Implementation of Reading Interventions in Introductory Chemistry and Its Impact on Student Performance

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IMPLEMENTATION OF READING INTERVENTIONS IN INTRODUCTORY CHEMISTRY AND ITS IMPACT ON STUDENT PERFORMANCE

by

Fatoumata Diawara

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Chemistry

at

The University of Wisconsin-Milwaukee

August 2023
ABSTRACT

IMPLEMENTATION OF READING INTERVENTIONS IN INTRODUCTORY CHEMISTRY AND ITS IMPACT ON STUDENT PERFORMANCE

by

Fatoumata Diawara

University of Wisconsin Milwaukee, 2023
Under the Supervision of Professor Anja Blecking, PhD

Research studies conducted in disciplinary literacy in the last 15 years have shown that students' reading comprehension is as much a predictor of student success in college science courses as in students' math skills (O’Reilly & McNamara, 2007). However, college STEM programs often focus solely on teaching STEM content, assuming students' reading comprehension skills have been developed in high school. Thus, only a few examples of reading interventions for students in STEM programs have been reported.

College-level science texts present distinctive challenges for students with lower reading skills and can significantly affect student comprehension of scientific content. This issue hits close to home since a significant portion of students who enroll in introductory chemistry at the University of Wisconsin-Milwaukee (UWM) do not meet the college readiness reading level, which puts them at an immediate disadvantage.

For the reasons above, this research's broader purpose is to help close this equity gap and create equal opportunities for success in introductory chemistry for students of various incoming reading abilities.
In particular, this study investigates the impact of online pre-instruction reading assignments on student learning in introductory chemistry, as measured by student performance on the final exam. Focusing on the support of students with lower reading abilities, the design of my reading intervention draws from educational learning theories, instructional strategies (Alpanahi, 2014), and delivery methods known to be effective for lower performers (O’Reilly & McNamara, 2007).

Aside from text manipulation using Lexile measures to create accessible text, this study also investigates student challenges based on visual images and graphs, difficulties that may affect students with lower reading abilities to a more significant extent (Erin et al., 2011; Mayer, 2009).
Dedication

This dissertation is dedicated to my beloved daughter, Mariam Iman Sylla, my gentle, patient, respectful, and supportive husband, Mohamed Dit Mody Sylla. To the one who paved the way, supports me, and pushes me to be great, Dr. Manthia Diawara, and to the most kind and supportive, Dr. Janice R Welsch.
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<th>Description</th>
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<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>NoRA</td>
<td>No Reading Assignment</td>
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<tr>
<td>RAS</td>
<td>Reading Assignment Scaffolded</td>
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<tr>
<td>RA</td>
<td>Reading Assignment</td>
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<tr>
<td>RASIA</td>
<td>Reading Assignment Scaffolded with Image Redesign and Audio</td>
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<tr>
<td>STEM</td>
<td>Science Technology Engineering and Math</td>
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<tr>
<td>ACT</td>
<td>American College Testing</td>
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<tr>
<td>ZPD</td>
<td>Zone of Proximal Development</td>
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<tr>
<td>CLT</td>
<td>Cognitive Load Theory</td>
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<tr>
<td>CTML</td>
<td>Cognitive Theory of Multimedia Learning</td>
</tr>
<tr>
<td>CLS</td>
<td>Classroom Salon</td>
</tr>
<tr>
<td>UWM</td>
<td>University of Milwaukee-Wisconsin</td>
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<tr>
<td>IRB</td>
<td>Institutional Review Board</td>
</tr>
<tr>
<td>SAS</td>
<td>Statistical Analysis System</td>
</tr>
<tr>
<td>APA</td>
<td>American Psychological Association</td>
</tr>
<tr>
<td>AERA</td>
<td>American Educational Research Association</td>
</tr>
<tr>
<td>NCME</td>
<td>National Council on Measurement in Education</td>
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<tr>
<td>DIF</td>
<td>Differential Item Functioning</td>
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<tr>
<td>IRT</td>
<td>Item Response Theory</td>
</tr>
<tr>
<td>MH</td>
<td>Mantel-Haenszel</td>
</tr>
<tr>
<td>ACS</td>
<td>American Chemical Society</td>
</tr>
<tr>
<td>LMS</td>
<td>Learning Management System</td>
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<tr>
<td>ICC</td>
<td>Item Characteristic Curve</td>
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ACKNOWLEDGMENTS

I want to thank my creator for the possibility of making it to the finish line. I also want to express my gratitude to many people who contributed to the success of my doctoral studies. To my principal advisor Dr. Anja Blecking, thank you for your time and assistance with this dissertation. I want to thank the committee members, Dr. Kristen Murphy, Dr. Xiaohua Peng, Dr. Alan W Schwabacher, and Dr. Nicholas R Silvaggi, for their feedback and for making time out of their busy schedules for milestone meetings, pre-defense, and defense meetings. I want to thank Dr. Bo Zhang for his help and input with statistics. I would like to thank Dr. Maria Shevyrev Shteynbuk for allowing me to collect data in her course. I would also like to thank Leah Elizabeth Johnson for all her help. I would like to extend my gratitude to the chemistry department staff and all the other students for all their help.

Finally, I would like to thank my family for always encouraging me to go beyond my boundaries, for always being supportive of all my decisions, for keeping me mentally stable, for making me laugh when I was sad, for the love and respect, and for always believing in me.
CHAPTER 1: INTRODUCTION

Organization of the Dissertation

The following dissertation is organized into eight chapters. The first chapter provides information on the organization and rationale of the research. The second chapter contains a literature review that will serve as the foundation for arguments made in this dissertation about prior work. The third chapter contains information on the design of the reading assignments and the methods used during the study. Chapters four to seven each have a single study and include a rationale, methodology, results, and discussion, each specific to the study. Chapter eight is the concluding chapter, where the overall findings, implications for teaching, and future research on all the studies will be discussed.

The study in chapter four is based on an ANOVA analysis of the impact of the reading assignments on the student's final exam mean performances. This was done to investigate the difference in student exam performance means in the different groups: (the students who did not receive a reading assignment NoRA (No reading assignment), the students who received a reading assignment without the different Lexile levels RA (reading assignment), the students who received the reading assignments at different Lexile levels without image or audio redesign RAS (reading assignment with scaffolds), the students who received the reading assignments at different Lexile levels with image and audio redesign RASIA (reading assignment with scaffolds, image, and audio redesign).

The study in chapter five is based on two methods used to detect Differential Item Functioning (DIF). The Cochran-Mantel-Haenszel and Logistic Regression are both non-IRT
approaches. DIF was done to assess whether the students who received reading assignments performed better on the exam items than comparable students who did not.

The study in chapter six is based on a pre-survey and a post-survey. The pre-survey aimed to identify how students engaged with the textbook, their strategies, and their difficulties while using it. The post-survey aimed to identify if the reading assignments supported the students learning. A Spearman correlation was done to determine the relationship between the students' self-reported data on the pre-survey and post-survey and the grade obtained in the course.

The study in chapter seven is based on semi-structured interviews. These semi-structured interviews aimed to gather in-depth information and insights on the changes made to the reading assignments (the overview, the image redesign, and the added audio).

Together, these four studies show the importance of differentiated instruction, scaffolding, pre-lecture instruction, assessing reading comprehension, Lexile-level, and multimedia learning. These studies show that students can succeed in their courses when provided with the necessary tools.

The last chapter consists of all the studies' overall conclusions and implications.

Rationale

There have been multiple studies done to determine why reading comprehension is essential for student success, and research has also shown that students are graduating high school and not prepared for scientific literature (ACT, 2019).

College STEM programs often focus solely on teaching STEM content, assuming that students' reading comprehension skills have been developed in high school. Thus, only a few
examples of reading interventions for students in STEM programs have been reported. This study addresses how equal opportunities can be created for everyone by providing underperforming students with the tools to succeed.

Reading comprehension is essential in learning any discipline and in the future of the learner in college and even the workforce. It can be described as the ability to extract and construct meaning by actively engaging with written language. It consists of three elements: the reader, the text, and the activity or purpose for reading” (Snow, 2002). It is also a critical component of nationwide standardized tests.

Surprisingly, a great number of students graduate high school underprepared for college or the workforce. This shows that even though students graduate from high school, they must still be qualified and ready for college (Gewertz, 2011). The need for college reading instruction is there because, as we all know, reading is fundamental. According to the College Board, over one-third of students who graduated from high school in 2018 were not ready for college or career-level reading (ACT, 2018). In the 2018 nationwide assessment, more than 37% of students in 12th grade performed below grade-level expectations for reading competency (U.S. Department of Education, 2018). Students who do not comprehend what they are reading are at higher risk of failing college courses or even dropping out. Students in the US lag behind their international peers on several academic measures, particularly on measures of reading comprehension (Perie, Grigg, & Donahue, 2005; Snow, 2002).

To appreciate the importance of reading comprehension, it is crucial first to comprehend its meaning. Reading comprehension can be described as the ability to extract and construct meaning by actively engaging with written language. It consists of three elements: the reader,
the text, and the activity or purpose for reading (Snow, 2002). Pearson and Hamm (2005) also summarized early research that mentioned reading comprehension having multiple components that would appear depending on the formats used to present the material and how the reader was asked to indicate their understanding of the material that was read.

The above statement proves that students face multiple challenges regarding reading comprehension. In the chemistry course, these challenges are increased because students are now exposed to new vocabulary, and the technical writing style is different. It makes it hard for students to approach the subject because they may need the necessary content knowledge to comprehend chemistry text (Bennet & Brett, 2013).

Students may be assigned reading and spend much time studying and reading. Courses at the college level, especially those in college settings, do not focus on reading comprehension. This is because instructors assume students have been prepared for college. According to (White, 2004), first-year students finish their first year with little to no reading comprehension. Studies have shown many ways students can be helped to succeed. Guiding students can help them because they need to be given a purpose to focus on the information in a passage; they need to stimulate their thinking and be assisted with the essential concepts and vocabulary (White, 2004).

Knowing a student's background is especially important because it helps understand their academic level. When the student’s background is understood, instructors may need to produce ways to help the students succeed.

Lectures have been known to help students better understand what they found overwhelming in a textbook because, during lectures, instructors review the overview of the
essential information from the textbook. Lectures can be important when students are introduced to a large and cohesive body of knowledge (Parker, 1993). According to Goldenberg (1992) discussion has also been used to improve reading comprehension; class discussions are such a valuable part of the learning experience that many instructors have advocated for more frequent use of them. When Choi and Johnson (2005) investigated the potential of a constructivist approach to context-based video instruction to enhance learning, like comprehension, they found a significant difference in the learners’ motivation. The constructive approach is an educational theory and an instructional approach that emphasizes active learning. The attention of the learner was more on video-based learning than text-based learning. One must have active reading skills to become a critical reader and have good thinking skills (White, 2004). Therefore, assigning homework to students is essential because it helps slightly close the gap in performance caused by reading comprehension. Many other methods have been used to help learners with reading comprehension.

While there has been much research on reading comprehension, Lexile measure is a specific number given to a text by the Lexile analyzer, a computer software program. This number represents the text’s difficulty. The number is followed by L (Lexile) (Lennon et al., 2004). It has yet to be used to measure reading comprehension at the university level. Educators in K-12 education try to increase student understanding of the scientific text by introducing text at different Lexile levels Davison and Kantor (1982). Students are assigned books or magazines that meet their Lexile level. However, college students need this opportunity. Even if it is known that a great number of introductory college students come into college underprepared for college instruction, they are still all assigned the same Lexile level textbook, and the lower
performers are overwhelmed by the information in the textbook. This reinforces students’ view of chemistry as a difficult subject, such that it is a subject that only some students would like to major in (Sirhan, 2007).

Students also face challenges with visual images and graphs. These difficulties mainly affect students with lower reading abilities (Sirhan, 2007). Such challenges include understanding concepts from illustration; deciding in what order images should be studied, how to judge the pertinent and superfluous information in the illustrations; determining which pieces of information from the graphics are related; integrating the related pieces of information; and difficulty in extracting essential information from graphs, symbolic representations, and mathematical expression (Erin et al., 2011). (Mayer, 2009) who believed that learning is better understood when presented in pictures and words than in words alone, identified 15 multimedia principles based on educational psychology that instructors could use to help their students succeed. Because of the specific linguistic features, science textbooks are difficult to understand (Gomes et al., 2016).

There is much literature on reading comprehension; however, there is not much research that includes Lexile and how reading comprehension in STEM is essential because we know that students' reading comprehension is as much of a predictor of student success in college science courses as students' math skills (O’Reilly & McNamara, 2007). Students come into college and are presented with challenging science textbooks. These challenges range from understanding the scientific language in the text to understanding concepts from illustration, deciding in what order images should be studied, how to judge the pertinent and superfluous information in the illustrations, determining which pieces of data from the graphics are related, integrating the
related pieces of information, and difficulty in extracting essential information from graphs, symbolic representations, and mathematical expression (Erin et al., 2011). Lower-performing students are most affected by these challenges and switch majors or drop out of college.

This study aims to determine the impact of implementing pre-instruction reading assignments on introductory chemistry students’ exam performance while focusing mainly on lower-performing students.

There is an emphasis placed on educators to help their students’ progress and succeed in their different majors. However, as mentioned above, students graduate high school underprepared for college. This poses a significant problem in success and retention rates. STEM is among the leading majors with low retention and success rates (Sithole et al., 2017). This is due to many reasons, and one is students need to be provided with the necessary tools to succeed. First, knowing the student’s background (the schools they attended, what type of resources were available to them, their level of reading) is essential because it helps them understand their academic level. When the student’s background is understood, instructors may need to produce ways to help the students succeed.

This study is significant because, through quantitative and qualitative data analysis, it shows how Lexile is essential even in science courses because it helps the instructor understand the student’s level and what type of help, they can give the student to succeed. This study also shows the significance of pre-instructions reading, which helps students reduce their cognitive load, the amount of mental effort one puts on their brain when learning new material (Sweller, 2006). The study also shows that it is significant to understand that not all students learn the same way or at the same pace, so it is essential to provide learning tools to complete a task that
one is unlikely to achieve without assistance, whether through scaffolding material, multimedia learning, or even differentiated instruction. To gain the students’ insight into the assigned course textbook and the reading assignments, it was essential to administer pre-survey and post-surveys, asking the students questions about the course textbook and the reading assignments. The pre-survey helped the researcher understand the students’ backgrounds, their courses before college, how they engaged with the assigned chemistry textbook, and what strategies they used. The post-survey gave the researcher an insight into how many reading assignments the students completed and how helpful they found the reading assignments compared to the course textbook.

Research questions

This study has multiple research questions, and different analysis methods were used to answer these questions.

The investigation used to answer the main question on this study’s impact on students’ exam performance.

Is there a difference in the exam performance means of the students among the different groups (NoRA, RA, RAS, RASIA)?

* **NoRA**: Students who did not receive reading assignments

* **RA**: Students who received reading assignments with no scaffolds

* **RAS**: Students who received reading assignments with scaffolds except for audio and image redesign

* **RASIA**: Students who received scaffolded reading assignments with audio and image redesign
The research question used to answer questions on students’ performance on the final exam items.

Do students with different reading levels who receive reading assignments perform better on the final exam items than those who do not?

The research question used to answer the questions on the students’ insights on the course textbook and the reading assignments they were assigned.

Pre-Survey:

**Question 1.** What is the relationship between the grades students predicted they would obtain in the introductory chemistry course and their actual obtained course grade?

**Question 2.** What is the relationship between students’ engagement with the course textbook and the grade they obtained?

**Question 3.** What is the relationship between the students’ reading strategies when interacting with the course textbook and the grade they obtained?

**Question 4.** What is the relationship between the types of difficulties the students encountered when interacting with the course textbook and the grade they obtained?

Post-survey:

**Question 1.** What is the relationship between the grades students predicted they would obtain in the introductory chemistry course and their actual obtained course grade?

**Question 2.** What is the relationship between the number of reading assignments the students completed and the grade they obtained in the course?

**Question 3.** What is the relationship between the student’s thoughts on the features in the reading assignments that support their learning and the grade they obtained?
The research questions used to answer the question in the qualitative study on semi-structured interviews.

**Question 1:** what are students' perspectives on the multimedia illustrations in the textbook and reading assignments?

**Question 2:** How do students engage with the textbook? Does their engagement with the text lead to correct summaries?

**Question 3:** How do students perceive the structure of the reading assignment used during the interview regarding the main point and the overview, and do they understand the text?
CHAPTER 2: LITERATURE REVIEW

This study aimed to determine the impact of implementing pre-instruction reading assignments on introductory chemistry students’ exam performance while focusing mainly on lower-performing students.

Every year, educators are subjected to annual changes and are required to provide data on their students’ progress and Universities are also concerned with student retention. However, many students begin college underprepared for the college level coursework; the under-preparedness is mainly shown when the students take placement exams (Bettinger, 2009; Byrd, 2005). There is literature that helps explain what goes into retention for a specific subgroup of students. The literature generally posits several theoretical approaches to college student retention, most of which contribute independently to understanding college attrition (Attewell, Heil, and Reizel, 2011).

High schools are essential in preparing students for success in their post-graduate lives, whether in college or the workforce. However, as Arnold, Lu & Armstrong (2012), Aud et al. (2010), and Aud et al. (2013) suggest, high schools have come under scrutiny in recent years for not adequately preparing students for the challenges they may face after graduation. The US’s economic growth and societal strength depend on developing and educating its citizens (Dewey, 1916; Grossman, 2006). With a college degree, people can get higher-paying jobs, higher incomes, better health care, and better retirement and financial stability (Trostel, 2015). Universities admit students from different racial, socioeconomic, and cultural backgrounds. All these students have one objective in common: to succeed in college in hopes of a better life that will get them close to the American dream. However, obtaining a better life
is difficult because most students are underprepared for college. College readiness is also significant because, as (Conley 2011 p.1) defines it, as “the level of preparation a student needs to enroll and succeed without remediation in a credit-bearing general education course at a post-secondary institution that offers a baccalaureate degree or transfer to a baccalaureate program.”

**College Readiness**

College and career readiness is defined as the measure of behaviors, skills, and knowledge a student should have to succeed in a post-secondary education that may lead to suitable employment (Mishkind, 2014, p. 2).

Conley, 2011 p.1 defines it as “the level of preparation a student needs to enroll and succeed without remediation in a credit-bearing general education course at a post-secondary institution that offers a baccalaureate degree or transfer to a baccalaureate program.”

The American College testing company defines college readiness as “the attainment of knowledge and skills required for a student to enroll and succeed in credit-bearing first-year courses at a postsecondary institution” (ACT, 2018). Some researchers separate college readiness from career readiness, but some argue that the two overlap (Malin et al., 2017). Lee (2012) mentioned that college readiness is a narrow lens and that long-term outcomes should be measured in education. Whether defined together or separately, the message is the same regarding what is necessary for high school graduates. For quite some time, public high school graduation rates have been increasing. In 2018-2019, high school graduation rates increased by 52%; however, even with this increase, about 36 % of students of the students who took the ACT did not meet the college readiness benchmarks, according to the ACT exam (ACT, 2019...
p.2). This shows the need for schools to emphasize preparing students for post-secondary education. Barnes and Slate (2010) mentioned that many high school graduates in the U.S. in the 21st century are not academically prepared for the challenges of postsecondary education. There must be a more comprehensive definition of college readiness developed. It has been mentioned that for a student to succeed, they must meet the college readiness benchmarks. These benchmarks are minimum scores needed to show that a student can achieve a grade of C and higher in a non-remedial college course at a 75% chance. In 2019 only 37% of students who took the ACT met the college readiness benchmarks in the four subjects: mathematics, English, science, and reading (ACT, 2019). This was a 1% variation from the results reported in 2018, in which 38% of students met the college readiness benchmark. Researchers found that 77% of students who are higher achieving in high school complete college with a degree; however, only 37% of students who are lower performing in high school complete college by age 26 (Howell et al., 2010). This indicates that students are unaware of what they should do to succeed in college (Howell et al., 2010). A student being offered a standardized-based assessment as a means of college readiness may not help, especially if the test taken is not yet normed based on the student outcomes (Camara, 2013). A definition of college readiness was not given by Maruyama (2012), but the author argues that three principles should be part of the definition of college readiness:

- Principle 1: Benchmarks should be logical and consequential.
- Principle 2: Benchmarks should recognize and acknowledge their limitations.
- Principle 3: Benchmarks should employ various approaches, assessments, and formats, ideally using multiple measures.
College readiness aims to ensure that students are prepared for the academic difficulties they may encounter in college and help the students have a chance of succeeding. With students graduating high school underprepared for college, instructors must tailor instruction to meet the needs of the students, and this can be done through differentiated instruction.

**Differentiated instruction.**

Not all students learn the same way. Students will be able to succeed when given tools that meet their readiness level. According to Good (2006), expecting students to learn the same “what” within the same “when” and “how” is unreasonable. Learners can attain their potential by being provided opportunities that are consistent with their abilities and attributes (Al-Shaboul et., al 2021). Differentiated instruction is a form of instruction made for a student's individual needs. Tomlinson (2014) argues that differentiation is not a strategy but a way to think about interactions between learners and teachers. When instruction is differentiated, one recognizes students' background knowledge, language preferences when learning, readiness, interests, and how they respond. Tomlinson (2014) argues that the theoretical framework of differentiated instruction is based on three different theories. The first theory is called The Learning Style theory, and it emerges from the learner’s ability to grasp information (Tomlinson, 2014). The material instructed is presented to the learner’s many bits of intelligence (Pritchard, 2009). The second theory, which is Vygotsky’s (1934/1986) Zone of Proximal Development (ZPD) Theory, comes from the understanding that people learn when they are taught at their level of readiness. And the third theory, Interest Theory proposes that students will be more interested when instruction is taught with minimum difficulty and
strategies that grab the learner's attention to the preferred learning style (Tomlinson, 2014; Torrance, 1995). Each theory has its own power but adds separate aspects to differentiated instruction. They add to Tomlinson’s earlier findings (2001) that identified three curricular elements that can be differentiated: content, products, and process.

- **Content:**
  - Many elements and materials can be used to support instructional content.
  - Learning goals and objectives should be aligned.
  - Instruction is principle-driven and concept-focused; instructors may need to focus on concepts, principles, and skills that students need to learn. While the instructional content should cover the same concepts for all the students, it should also be tailored in complexity to meet the diverse learning abilities in the classroom.

- **Process:**
  - Flexible grouping should be used consistently.
  - Students and teachers benefit from classroom management. To successfully implement differentiated instruction, instructors may need to consider organization and instructional strategies that are tailored to the diverse needs of their students.

- **Products:**
  - An initial and ongoing assessment of student readiness and growth is essential.
  - Students should be active and responsible explorers.
  - Expectations and requirements for the student responses should be varied.

According to Guild & Garger (1998), differentiated instruction can be made possible for instructors if they clarify the key concepts and generalizations to ensure that all learners obtain
great understandings that will help them get the foundation for future learning. Instructors may need to use assessment as a teaching tool to expand and not just measure instruction. Critical and creative thinking should be emphasized as a goal in the lesson design. It is essential to have all learners engaged, and there should be a balance between tasks selected by students and those assigned by the instructor. While differentiated instruction is an approach to teaching that involves tailoring instruction to meet the needs of the learners, scaffolds can help support learners as they work through a challenging task. Another effective way to meet the diverse needs of students is to use scaffolding within differentiated instruction.

**Scaffolds**

Many researchers have argued that scaffolding gives an advantageous framework for assisting students with difficulties (Hannafin et al., 1999). The goal of scaffolding is to aid learners in gradually developing their understanding and ability to complete a task independently. It is particularly useful when learners face a new concept or task beyond their current level of understanding or skill. Scaffolding was introduced in 1976 by Bruner as a process to support teachers or peers in providing learning tools to complete a task that a novice is unlikely to achieve without assistance. This concept of scaffolding was based on the (Zone of Proximal Development) ZPD, defined by Vygotsky (1978) as the area between a learner’s current ability and what a learner can accomplish when given the right instructional conditions. In the zone of proximal development (ZPD), scaffolding is most effective because it provides the necessary support to help learners bridge the gap between their current level of understanding and their potential. Scaffolding can take many forms, including modeling, feedback, questioning, and providing guidance and support. The process of scaffolding involves breaking
down complex tasks into smaller, more manageable ones by providing guidance and support as learners work through each step and gradually withdrawing support as learners become more confident. When creating a task, instructors may need to avoid designing tasks that are too easy, as this may result in disengagement and boredom for the learner. The task cannot be challenging because the learner cannot reach their potential if it is very easy; the learner does not benefit from it. The instructor needs to get the students to work in the “zone” and give them the support that enables them to develop. The dynamics of scaffolding depend on the cycles of adjustments made to meet the learners; performances, the duty demands, and the level of scaffolding (Pea, 2004, p. 44). These dynamic cycles guide the learners’ autonomous performance, which refers to learners’ ability to carry out a task effectively on their own without relying on external guidance or support.

With the learner getting close to reaching the intended learning goal, scaffolding must be removed by the instructor (Collins et al. 1989). As the learners internalize cognitive processes and finish a task without outside help, scaffolding is removed by the instructors. Instructors use scaffolds to help learners master a task. Learners should benefit from scaffolds and experience a decrease in extraneous cognitive load (Van Merrenbor & Sweller, 2005). Extraneous cognitive load weighs on the working memory and causes unnecessary distractions, content, and difficulties for the learner (Burning et al., 2011).

In a variety of studies, students have been provided with educational scaffolds and evaluated by instructors’ causes while focusing on the ZPD of progress. Research on the concept of scaffolding now includes not only individual instructors and student exchanges. According to Puntambekar et al., 2005, technology-based resources and tools are now part of
scaffolding, such as peer interaction and discussions. Ge & Land (2003) also argue that peer interactions are encompassed in scaffolding. According to Kim et al. (2011), teacher-enhanced scaffolds like formal or informal assessments, guided activities, and modeling are also additional scaffolding strategies. This shows that scaffolding appears in many ways depending on the multiple types of support given to help students engage in an inquiry-based learning activity. For example, providing background information can help students understand better the specific information in the assigned task. According to Lin Tzu-Chiang et al. (2012), researchers should focus their scaffolding goals and effect on the design of scaffolding, like detecting the learners’ ZPD change through constant assessment and including many forms of scaffolding into instruction due to many ZPDs that the learners hold in the classroom. Scaffolding can provide a helpful starting point for active learning by providing information using prior knowledge to guide the active learning process.

**Reading Strategies**

Success in reading and comprehending is not only dependent on an individual’s language proficiency but also on their use of strategic behaviors, as noted by Scarborough (2001). Reading strategies are purposeful actions taken by the reader to achieve specific goals. In this study, the goal is to read and comprehend. According to Paris et al., (1991) and researched by Blachowicz and Ogle (2017) and Coiro and Dobler (2007), reading strategies generally used are:
- Summarizing
- Inferencing
- Predicting
- Background knowledge activation
- Connecting
- Questioning
- Visualizing

These strategies uniquely impact successful reading, as shown by studies done on each strategy. Summarizing is known as a meaning-based strategy that promotes the memory of the text (Pourhosein Gilakjani & Sabouri, 2016). According to Honig et al., (2000), for summarizing to be done correctly, the reader must recognize the elements in the story, which stimulates the reader to understand what is happening in the text. In the study presented in this thesis, reading assignments were designed with questions that asked students to summarize a passage for the purpose of reading comprehension.

Inferencing helps in understanding beyond literal words. According to Pourhosein et al., (2016), Making inferences involves combining information from the text with prior knowledge to derive meaning. It was also noted by Attaprechakul, (2013) that inferencing aids readers in finding the meaning of words that are unfamiliar and understanding what is happening beyond the literal words that are composed in the text. When it comes to predicting, it enables readers to form hypotheses and assessments (Pourhosein et al., 2016). It was suggested by Gillet and Temple, (1994) that effective readers with strong comprehension skills tend to evaluate their initial assumptions and revise them according to when they come across evidence in the text that contradicts their predictions.

Background knowledge activation helps readers comprehend new information (Pourhosein et al., 2016). According to Anderson et al. (1977), schema theory suggests that people construct
a set of cognitive frameworks or knowledge structures as they acquire knowledge about the
world. These mental representations continue to evolve and adapt as individuals acquire new
information through their experiences and reading, which allows the reader to comprehend
what the text is about. There are many definitions for connecting; in this study, connecting was
done by finding the key information in texts earlier and connecting it to new content. According
to Frid & Friesen, (2020), connecting new information to background knowledge helps in noting
key information and understanding. Questioning focuses attention and enables comprehension
repair which is the process of recognizing and rectifying difficulties in understanding when a
person is reading. When learners ask appropriate questions, it helps the reader to focus on the
information that is important (Wood et al., 1995).

Visualizing helps in memory (Pourhosein et al., 1995) noted that visualizing requires the
reader to create a mental picture of what they are reading. While effective reading strategies
can significantly improve reading comprehension, it is also important when reading occurs. It
has been shown that pre-instructional reading can further enhance students' ability to
comprehend and retain information from texts.

**Pre-Lecture instruction**

Cognitive load theory and schema learning theory have been suggested to explain why it
is beneficial to assign learning material before lecture. Schema learning theory suggests that
knowledge is mostly acquired when new information can be added to existing knowledge
networks containing multiple cognitive constructs called schemas (Bartlett, 1932). A schema
organizes new knowledge, giving a framework for future reference and understanding
(Anderson & al., 1977). When students receive reading material, they activate the type of
schema they think is required, and if they must read a passage and answer questions about the main idea, they stop and ask themselves what they think should be the main points (Resnick, 1985). Many studies on reading and writing have investigated schemas. (McVee, Dunsmore, & Gavelek, 2005).

Cognitive load theory (CLT) refers to the number of demands placed on the information processing system, particularly the working memory (Mayer, 2012). The theory also CLT further explains using schemas is what makes learning new reading material difficult. It explains that when too much information is put into the working memory, this may lead to failure in processing and comprehending new reading material (Sweller, 1994). There are three types of cognitive load, intrinsic load, germaine, and extraneous load. Intrinsic load stems from the number of demands placed on the working memory by the unchanged properties of the knowledge to be obtained, and extrinsic load stems from the unwanted load placed on the working memory by irrelevant content (Bruning et al., 2011).

When students are assigned pre-class assignments, they are more prepared, increasing the clarity and usefulness of the class, which also increases attendance (Stelzer et al., 2010); (Deslauriers et al., 2011). Pre-lecture instruction is also helpful to students with a low level of topic knowledge because these students do not grasp which specific ideas are significant right away; with pre-lecture instruction, they can be oriented in the right direction toward the important ideas in the scientific text. When students are assigned pre-lecture assignments, they are asked to “summarize or explain”; these pre-lecture assignments have shown that the students will adjust their reading strategies based on the purpose of the reading assigned (Braten & Samuelstuen, 2004). Ozungor & Guthrie, (2004) argued that research based on
elaborative interrogation questions, questions embedded in a text specifically after a paragraph, a sentence, or a section, show that these questions help with learning on both the factual and conceptual levels for different ability groups.

McNamara et al., (2009) argued that for students to comprehend a science text thoroughly, they need to have an elevated level of inferencing, which is difficult for those with low prior knowledge levels. Research done on pre-lecture instruction shows that assigning pre-reading instructions to students influences their reading behaviors or strategies. Specifically, instructions influence what students focus on when reading the text, as measured by the reading times, patterns their eyes fixate on, and even reports from thinking aloud. (Braten & Samuelstuen, 2004). Pre-lecture instruction and reading comprehension are closely linked, as both strategies aim to equip students with the necessary background knowledge and skills to engage with new material. Pre-lecture instruction can improve reading comprehension by providing learners with a framework for approaching new material.

Reading comprehension

Reading comprehension is the process of extracting and constructing meaning through Simultaneous interaction and involvement with written language (Snow, 2002). The Rand reading study group (Snow, 2002) reported three interaction factors for successful reading comprehension: the reader, text, and purpose. Figure 2.1 shows the connection. These three factors are what make a successful reader. The reader uses their cognitive abilities attention, memory, critical analytic ability, the process of inferring, visualization); motivation (a purpose for reading, interest in the content, self-efficacy as a reader); knowledge (vocabulary and topic knowledge, linguistic and discourse knowledge, knowledge of comprehension strategies); and
experiences. These attributes vary considerably among readers and even within an individual reader as a function of the particular text being read and the reading activity. The features of a written text greatly affect comprehension. When reading, the reader creates different representations of the text that are crucial for understanding, such as the exact wording of the text, the meaning behind it, and how information is processed. Electronic text poses challenges to comprehension, such as limited annotation abilities, but it can also provide helpful tools like links to definitions or supplementary material. The reading activity involves a purpose or task, processing the text, and outcomes within a specific context. Text processing includes decoding, linguistic and semantic processing, and self-monitoring, all dependent on the reader's capabilities and text features. Each processing element has varying importance based on the type of reading. The outcomes of reading include increased knowledge, problem-solving, and engagement with the text, with long-term outcomes being improved comprehension, increased knowledge, and engagement relevant to educators. The context in which reading is often taught is a classroom setting, but the learning process extends beyond the classroom and is influenced by the sociocultural environment in which children live and learn (Kirby, 2003). Literacy and learning are cultural activities that reflect how a cultural group or discourse community (a group of individuals who share common goals within a specific field) interprets the world and transmits information. Sociocultural differences are often correlated with group differences based on income, race, ethnicity, native language, or neighborhood (Kirby, 2003). Much research has been done on reading comprehension, leading to multiple theories' development
McNamara and Magliano (2009) reviewed nine major reading comprehension theories comprehensively. The theories may differ in the content they emphasize, but they describe comprehension as a process of building meaning as the reader interacts with the text. Importantly inferences or connections should be made between text segments so the reader can form a reasonable mental representation of the text's content (Graesser et al., 1994).

In the study in this dissertation, one of the goals is to help students form meaningful connections with ideas to help them learn science. Duschl et al. (2007) proposed important attributes learners need to reach proficiency in science reading. The first was “to know, use and interpret scientific explanations of the natural world.” Making relevant and meaningful connections between ideas is a significant part of the progression of disciplinary understanding. The organization of conceptual structures is one attribute that differentiates novices from experts. Beginners have their knowledge fragmented or not connected (Biggs & Collis, 1982; DiSessa, 2006); experts' knowledge is structured and organized around central concepts and principles in a way that helps their way of thinking and allows them to use their knowledge in new situations (Chi et al., 1981). Students who take a science course are assigned a textbook to engage with scientific ideas. However, studies have shown that students struggle to organize
and make meaningful conceptual structures or even coherent mental models while reading scientific texts (Roth & Anderson, 1988). Scientific texts contain much information, are abstract, and have a lot of specialized terms (Yager, 1983; Fang, 2005).

Familiar words in other books can have different meanings in a scientific text. As opposed to text with narrative, scientific texts have several expository text structures like cause-and-effect patterns, classification, and more, which are unfamiliar to students (Meyer, 1975). To better understand reading comprehension, we must introduce Lexile, which can match readers with texts appropriate for their reading level. This leads to improving reading comprehension and engagement (Pearson et al., 2005). While reading comprehension and the Lexile measure various aspects of reading ability, they are very closely related because a reader’s comprehension is impacted by the difficulty level of the text they are reading, as measured by the Lexile.

**The Lexile level.**

The Lexile framework is an approach to reading comprehension that educators, parents, and readers can implement. It comprises two components, the Lexile measure, and the Lexile scale. The Lexile measure is a specific number given to a text by the Lexile analyzer, a computer software program. The number is followed by L (Lexile) (Lennon et al., 2004). These numbers represent the difficulty level of the text. Each text’s score is not dependent on another text, so the Lexile text measure puts texts on a sliding scale of difficulty (Lennon et al., 2004). The score can be used to match readers with appropriate texts, ensuring that they will not be overwhelmed by challenging texts or lose interest by easy ones. The other component is the Lexile scale which is a developmental scale for reading. This scale ranges from 200L to 1700L
and measures the readers’ reading comprehension ability. This allows educators to select texts that are not only at the appropriate reading level but also appropriate in terms of complexity. Since both components came from the same sliding scale, which uses a numbering system, the same scores can be paired. (Lennon et al. 2004). When a text and the reader are appropriately matched, the reader can comprehend at about a 75 percent rate. By using the Lexile framework, educators can develop teaching strategies and materials that meet students’ individual needs. This ensures that the students are being challenged but not overwhelmed. It also helps educators track student progress over time and identify where students may need more support. Table 2.1 shows the Lexile number assignment (Lennon et al., 2004).

Table 2.1: Lexile number assignment per grade. Source: (MetaMetrics)

<table>
<thead>
<tr>
<th>Grade</th>
<th>College and Career-Ready Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190L - 530L</td>
</tr>
<tr>
<td>2</td>
<td>420L – 650L</td>
</tr>
<tr>
<td>3</td>
<td>520L - 820L</td>
</tr>
<tr>
<td>4</td>
<td>740L - 940L</td>
</tr>
<tr>
<td>5</td>
<td>830L - 1010L</td>
</tr>
<tr>
<td>6</td>
<td>925L - 1070L</td>
</tr>
<tr>
<td>7</td>
<td>970L - 1120L</td>
</tr>
<tr>
<td>8</td>
<td>1010L - 1185L</td>
</tr>
<tr>
<td>9</td>
<td>1050L - 1260L</td>
</tr>
<tr>
<td>10</td>
<td>1080L - 1335L</td>
</tr>
<tr>
<td>11 &amp; 12</td>
<td>1185L - 1385L</td>
</tr>
</tbody>
</table>
Publishers have used the Lexile framework (see Figure 2.2), making it easy for educators and parents to select suitable reading materials for their students in the classroom or at home (Stenner, 2012).

Figure 2.2: Example of books with Lexile levels (Andrew J. Milson, Ph.D.)

Multimedia Learning

As of now, multimedia learning and instruction is well established in higher education. During the time of Covid-19, many schools had to find ways to keep children learning and interacting with their teachers, professors, and peers; the solution was often multimedia learning. According to Mayer's cognitive theory of multimedia learning (CTML), Figure 2.3 illustrates the different steps of how memory works.
Mayer (2001) argued that learners usually process information in more depth when pictures and words are shown together than when they are shown separately.

Moreover, he described this as the multimedia principle. “Just putting in pictures with words does not improve learning; that is, all multimedia presentations are not equally effective” (Mayer 2005. p.31). Words and pictures should be organized; if not, the presentation may create multimedia messages that hinder learning instead of amplifying it, thus compromising the student’s ability to process information successfully (Mayer & Jackson, 2005). One of the primary purposes of CTML is to help learners develop successful multimedia messages drawn from how the individual’s brain works and how they process information cognitively (Mayer, 2001). The kind of information a learner processes and the types of knowledge they may create can vary considerably. To be specific, knowledge can be factual; for example, when knowledge is affiliated with terms and details. It can be conceptual, as when it is affiliated with classifications, principles, generalizations, categories, models, theories, and
structures. Knowledge can be procedural, for example, as when it is affiliated with methods, techniques, and skills.

Finally, knowledge can be metacognitive, as when affiliated with strategies, cognitive tasks, and self-knowledge (Anderson et al., 2001; Mayer, 2011). From the viewpoint of CTML, the instructor has a role as a cognitive guide to help the learners build knowledge by leading them toward the precise information, they need to pay specific attention to and helping them organize information cognitively (Mayer 2001, 2021). Mayer (2011) suggested three theoretical assumptions that instructors may need to use to help learners accomplish meaningful learning outcomes: The dual-channel assumption, the limited capacity assumption, and the active processing assumption.

**The dual-channel assumption:**

Under the dual-channel assumption for information that an individual sees and hears to make sense, they must use different processing channels (Mayer, 2001). The information shown through animation, readable text, videos, pictures, and all other visual representations processed through the visual information channel. However, when information is presented through narration, verbal explanation, or other sounds it is processed through the auditory information channel (Mayer, 2001). In their study in a meta-analysis of 43 non similar studies, which explored the impact on student learning of showing information through visual and auditory-based channels. Ginns (2005) reported results that were consistent with the notion that whether students process information through visual or audio can significantly affect how they cognitively process and remember that information.
The limited capacity assumption:

The limited capacity assumption states that there is a limit to the information an individual's brain can process through visual and audio channels simultaneously (Mayer, 2001). The brain processes part of a presented material as shown by the sensory representation and not the exact copy of the material presented (Mayer, 2005a, p.35). When this happens, the working memory selects sensory representation which a human pays attention to (Baddeley, 1986; Mayer, 2005a). However, the amount of information stored in the working memory is limited, so learners must use metacognitive strategies (Mayer, 2005a).

The active processing assumption

When individuals can pay attention to the essential parts of the material presented, organize information in a coherent mental structure, and combine it with their prior knowledge, they can construct knowledge meaningfully (Mayer, 2001). According to CTML, the learning process is intentional and cognitively intensive, not passive, CTML conceptualizes individuals as “active processors who seek to make sense of multimedia presentations” (Mayer, 2005a, p.36).

Instructors must be strategic when they implement instructional designs using multimedia learning. There are three goals they should achieve (Mayer, 2005; Mayer, 2021):

1. Help learners reduce extraneous cognitive load!
2. Support learners in controlling their key cognitive processing!
3. Assist learners in generative cognitive processing!

The learner also must engage in five cognitive processes to attain meaningful learning from the words and pictures (Mayer, 2010):
1. Choose relevant words that the verbal working memory can process.
2. Choose relevant images that the visual working memory can process.
3. Sort out words into a verbal model.
4. Sort out images into a pictorial model.
5. Use prior knowledge to combine verbal and pictorial representations.

With extensive research done on more than 100 studies, Mayer (2021) then identified 15 Multimedia learning principles; I will focus on five principles in this study. These five principles are presented in Table 2.2.

Table 2.2: Multimedia principles of interest to this study. (Mayer 2010).

<table>
<thead>
<tr>
<th>Multimedia Principles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial contiguity principle</td>
<td>People learn best Images and words that go together are presented close to each other rather than far part on the same page</td>
</tr>
<tr>
<td>Temporal contiguity principle</td>
<td>People learn best when images and words are shown simultaneously instead of successively</td>
</tr>
<tr>
<td>Modality principle</td>
<td>People learn best from narrations and graphics, instead of animation and on-screen text</td>
</tr>
<tr>
<td>Multimedia principle</td>
<td>People learn best from words and images than words alone</td>
</tr>
<tr>
<td>Voice principle</td>
<td>People learn best when the narration in multimedia lessons is delivered in a friendly human voice instead of a machine voice.</td>
</tr>
</tbody>
</table>
CHAPTER 3: DESIGN OF THE READING ASSIGNMENTS AND METHODS

Design of the reading assignments

Introduction:

Studies have shown that pre-instruction reading helps students reduce their cognitive load (Sweller, 2006). When students are assigned pre-class assignments, they are more prepared, thus increasing the clarity and usefulness of the class, which also increases attendance (Stelzer et al., 2010; Deslauriers et al., 2011). Pre-lecture instruction is also helpful to students with a low level of topic knowledge because these students do not grasp which specific ideas are significant right away; with pre-lecture instruction, they can be oriented in the right direction toward the ideas that are significant in the scientific text. When students are assigned pre-lecture assignments, they are asked to “summarize or explain; this means the students will adjust their reading strategies based on the purpose of the reading assigned (Braten & Samuelstuen, 2004). Reading assignments were scaffolded at different Lexile levels to provide students with pre-lecture material that would prepare them for lecture. When the material is scaffolded, it provides the necessary support to help learners bridge the gap between their current level of understanding and their potential. In this study, reading assignments were designed and assigned to students at different Lexile levels. The reading assignments were adjusted to the Lexile level of the reader, so that they could have a better chance on reading comprehension. Questions were embedded in the reading and summarizing tasks were used to promote active reading strategies. Scaffolding can take many forms, including modeling, feedback, questioning, and providing guidance and support. The reading assignments were designed to help students prepare for the lecture before it was presented in
class and help the lower-performing students attain the level of comprehension they could not attain on their own.

Design of the reading assignments:

Reading assignments were designed from the course textbook *Introduction to Chemistry* by Bauer, Birk, and Marks (2006). Based on the introductory chemistry course curriculum, the researcher had permission from the publisher, McGraw Hill, to use the textbook excerpts for this research. Twelve concepts were selected from the textbook, and each was made into a reading assignment. Three different versions of the text were designed at three different Lexile levels. In addition to the original, which measured at a Lexile level of 1060L – 1180L, the text was also converted into a lower Lexile level (940L – 1080L) and a higher Lexile Level (1170L – 1280L). No Lexical changes were made to the original text. Appendix G shows all the reading assignments in different Lexile levels. Table 3.1 shows the chapters used for the reading assignments.

Table 3.1: Chapters used for the reading assignment.

<table>
<thead>
<tr>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Theory</td>
</tr>
<tr>
<td>Modern Model of an Atom</td>
</tr>
<tr>
<td>Molecular Shapes</td>
</tr>
<tr>
<td>Covalent Bonding</td>
</tr>
<tr>
<td>Ionic Bonding</td>
</tr>
<tr>
<td>Periodic Trends</td>
</tr>
<tr>
<td>Properties and Changes</td>
</tr>
<tr>
<td>Formula Calculations</td>
</tr>
<tr>
<td>Solutions</td>
</tr>
<tr>
<td>Chemical Reactions</td>
</tr>
<tr>
<td>Limiting Reactants</td>
</tr>
<tr>
<td>Gases</td>
</tr>
</tbody>
</table>
The Lexile framework is a tool used to calculate a text's difficulty or a student's comprehension level. Lexile measures allow Researchers to match a text's complexity with the student's reading ability. In this study, chemistry text from a college-level textbook was translated into a lower Lexile level by replacing complex words with commonly used ones, making sentences and paragraphs shorter and more accessible, removing unnecessary details from the text, and using simple verbs/adjectives. The contrary was done to translate text into a higher Lexile level than the original textbook. Table 3.2 explains the strategies used to change the Lexile levels of the reading assignments. Figure 3.2 shows an example of a low Lexile level paragraph and a high Lexile level paragraph. A Lexile analyzer, software by MetaMetrics was utilized to determine the final Lexile levels of the reading assignments (Lennon, 2004).

Table 3.2: Strategies used to increase or lower Lexile levels.

<table>
<thead>
<tr>
<th>Lower level (940L – 1080L)</th>
<th>Higher Level (1170L – 1280L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shorter sentences</td>
<td>Longer sentences</td>
</tr>
<tr>
<td>Shorter paragraphs</td>
<td>Longer paragraphs</td>
</tr>
<tr>
<td>Easy and commonly used verbs/ adjectives</td>
<td>Complex/rarely used verbs/adjectives</td>
</tr>
<tr>
<td>More frequent words</td>
<td>Less frequent words</td>
</tr>
<tr>
<td>More explanations with short sentences on images</td>
<td>Less or longer sentences on images</td>
</tr>
</tbody>
</table>
An atom is made up of a smaller particle called a subatomic particle. The subatomic particles are Proton, neutron, and electron. In the late 1800s, researchers developed instruments and techniques to detect subatomic particles. The instruments and techniques could also show their numbers and arrangements in atoms.

A subatomic particle is a smaller particle found inside an atom. These subatomic particles are the proton, neutron, and electron. It was not until the late 1800s that researchers developed instruments and techniques capable of detecting subatomic particles and revealing their numbers and arrangements in atoms.

A subatomic particle is a smaller particle found inside an atom; there are more than 40 known; however, only three are of interest in chemical behavior. These subatomic particles are protons, neutrons, and electrons. It was not until the late 1800s that researchers developed instruments and techniques to detect subatomic particles and reveal their numbers and arrangements in atoms.

<table>
<thead>
<tr>
<th>Low Lexile 960L</th>
<th>Original Lexile 1080L</th>
<th>High Lexile 1280L</th>
</tr>
</thead>
<tbody>
<tr>
<td>An atom is made up of a smaller particle called a subatomic particle. The subatomic particles are Proton, neutron, and electron. In the late 1800s, researchers developed instruments and techniques to detect subatomic particles. The instruments and techniques could also show their numbers and arrangements in atoms.</td>
<td>A subatomic particle is a smaller particle found inside an atom. These subatomic particles are the proton, neutron, and electron. It was not until the late 1800s that researchers developed instruments and techniques capable of detecting subatomic particles and revealing their numbers and arrangements in atoms.</td>
<td>A subatomic particle is a smaller particle found inside an atom; there are more than 40 known; however, only three are of interest in chemical behavior. These subatomic particles are protons, neutrons, and electrons. It was not until the late 1800s that researchers developed instruments and techniques to detect subatomic particles and reveal their numbers and arrangements in atoms.</td>
</tr>
</tbody>
</table>

Figure 3. 1: Comparison of a Low and High Lexile levels paragraph.

It is important to note that the text content did not change when the text complexity (Lexile level) changed. The Lexile adjustment was only done to make text more accessible for students with lower reading ability. The higher-Lexile text was created to determine its effect for students with reading abilities higher than expected for college readiness. This study utilized the ACT reading score of students as a measure of incoming reading abilities. While this is not an ideal measure, especially since the test does not measure reading comprehension of science text, it was the only measure available. It is also important to mention that there is no known correlation between the Lexile measure and student performance on the ACT Reading test.

In this study, students were matched with low, original, or high Lexile levels based on their ACT reading scores. The benchmark for college readiness is 22, and about 45% of students have scores below this benchmark (ACT, 2019). Therefore, students with a lower ACT reading score received the lower Lexile text, the original chemistry text was assigned to students around the college readiness benchmark (21-25), and students with an ACT reading score above
a reading ACT of 26, received the higher Lexile text. Table 3.3 shows the ACT reading scores corresponding to this study’s three Lexile level groups.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>ACT reading score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Lexile</td>
<td>20 or less</td>
</tr>
<tr>
<td>Medium-Lexile</td>
<td>21 – 25</td>
</tr>
<tr>
<td>High-Lexile</td>
<td>26 and greater</td>
</tr>
</tbody>
</table>

As mentioned previously, the chemistry content for reading assignments was chosen based on the course curriculum. Each of these reading assignments mainly had conceptual questions embedded in them. In chemistry, most conceptual questions are composed of three forms of representation, macroscopic, particle, and symbolic, and these three forms are used with chemical information (Bowen, 1998). Conceptual questions are questions that make use of the learner’s understanding of chemical ideas associated with the question. Conceptual questions can be used as vehicles for learners to practice actively. This can be done by assessing things they do not understand about the fundamental ideas of chemical phenomena and analyzing information to select the necessary information (Nurrenbern & Robinson, 1998). According to Fang (2005), science texts are often conceptually dense and contain specialized or technical terms. Best et al. (2005), explained that in-depth comprehension of science texts frequently requires an elevated level of inferencing on the reader’s part, which is difficult for those with low levels of prior knowledge.
**Image redesign and audio addition:**

Images from the original textbook were redesigned by replacing some images with easily accessible and comprehensive images. In case images did not explain (See Figure 3.2 below), descriptive text was added. The original text did not explain the contents of the images very well, and not all the students comprehended what the image was meant to convey. The descriptive text provided more insight. Words and pictures should be organized; if not, it may create multimedia messages that hinder learning instead of amplifying it, compromising the student's ability to process information (Mayer & Jackson, 2005) successfully.

As previously described, Mayer (2010) showed that audio narrations have been shown to help learners comprehend images and text by hearing the audio being delivered by a friendly voice, with the voice principle, People learn best when the narration in multimedia lessons is delivered in a friendly human voice instead of a machine voice. Therefore, as part of this study, the audio narration delivered by a friendly female voice was added to selected images to support students who prefer this mode of content delivery. Figure 3.2 shows an example of the redesigned image with audio narration.

Carbon has an atomic number of 6. The 1s orbital will get 2 electrons, the 2s will get 2 electrons and the remaining 2 electrons will go into the first 2p orbitals.

Figure 3.2: Example of redesigned image with audio narration.
Before the adjustment, the text underneath the image was: The boxes represent orbitals, and the arrows represent electrons.

**The chapter overview:**

In her book “the thesis and the book, Eleanor Harman et., al (1976), mention the importance of chapter overviews and how to use them to create a coherent and compelling narrative. A chapter overview was added at the beginning of each reading assignment, to help readers understand what to expect in the text. Chapter overviews aid readers in focusing on the main points and facts that the text has. Figure 3.3 shows an example of the atomic theory reading assignment overview.

**The evolution of the atomic theory**

**What to expect in this chapter:**

The first part of this chapter introduces John Dalton's atomic theory from 1808; he was an English school teacher and hobby scientist. With his theory, he revived the idea that matter consists of incredibly small particles called atoms, a theory that found its origins in ancient Greece but had been neglected for over 2000 years.

At the time Dalton published his theory, the existence of subatomic particles was not known. Subatomic particles “live” inside of atoms and are considerably smaller than atoms, they are critical in the sense that they determine the properties of individual elements.

The second part of this chapter will talk about experiments that have been conducted after 1808, these experiments have accidentally or intentionally shown the existence of subatomic particles (cations, anions, or neutrons).

Based on these discoveries, the model of what an atom looks like has been revised a couple of times. Please note that models are often not an accurate mirror of the truth, models change if new information becomes available.

Figure 3. 3: Overview of the atomic theory.
Multiple steps were taken to make the reading assignments more accessible to the lower performing students. Figure 3.4 outlines the steps. This includes designing scaffolded text at different Lexile levels, based on the course textbook, redesigning the illustrated text, adding audio narration and an overview, and posting the reading assignments on learning platforms.

Figure 3.4: Steps taken to make the reading assignments more accessible to the lower-performing students.

Table 3.4 shows the steps taken in designing the reading assignments and the expansion of the study.
Table 3.4: Steps taken in designing the reading assignments and expanding the study.

<table>
<thead>
<tr>
<th>Time period of data collection</th>
<th>Section</th>
<th>Interventions implemented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2018</td>
<td>403</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). They were posted on Classroom Salon (CLS). A survey on textbook use was developed.</td>
</tr>
<tr>
<td>Spring 2019</td>
<td>402</td>
<td>Low Lexile level students were assigned medium Lexile reading assignments. The rest got RAs corresponding to their Lexile levels. They were posted on CLS.</td>
</tr>
<tr>
<td></td>
<td>403</td>
<td>High Lexile level students were assigned medium Lexile level reading assignments. The rest got RAs corresponding to their Lexile levels. They were posted on CLS.</td>
</tr>
<tr>
<td>Fall 2019</td>
<td>403</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). They were posted on Canvas. A survey on the reading assignments was developed.</td>
</tr>
<tr>
<td>Spring 2020 (the start of COVID-19 and online exams)</td>
<td>403</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned. Students receive an online exam instead of a paper exam.</td>
</tr>
<tr>
<td></td>
<td>404</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned. Students receive an online exam instead of a paper exam.</td>
</tr>
<tr>
<td>Fall 2020</td>
<td>403</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, audio narration and an overview were also added. Students receive an online exam instead of a paper exam.</td>
</tr>
<tr>
<td></td>
<td>404</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, audio narration and an overview were also added. Students receive an online exam instead of a paper exam.</td>
</tr>
<tr>
<td>Spring 2021</td>
<td>401</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, audio narration and an overview were also added. Students receive only one part of the online exam instead of two parts (Final 1 and Final 2).</td>
</tr>
<tr>
<td></td>
<td>402</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, audio narration and an overview were also added. Students receive only one part of the online exam instead of two parts (Final 1 and Final 2).</td>
</tr>
<tr>
<td>Fall 2021 (Back to paper exams)</td>
<td>401</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, an overview was added but no audio narration was added. Students receive a paper exam.</td>
</tr>
<tr>
<td></td>
<td>402</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, audio narration and an overview were also added. Students receive a paper exam.</td>
</tr>
<tr>
<td>Spring 2022</td>
<td>401</td>
<td>Reading assignments were assigned according to the Lexile levels of students (Low, Medium, High). Illustrations were redesigned, audio narration and an overview were also added. Students receive a paper exam.</td>
</tr>
</tbody>
</table>
Methods

Design

Chapters four, five, and six contain studies based on quantitative data analysis. One of the main objectives of quantitative research is to comprehend what the world describes as it relates to material phenomena that are being observed, emphasizing the occurrences in the quantitative dimension (Draper, 2004). For a quantitative method to be applied, researchers must show the study data for applying statistical calculations (McCusker & Gunaydin, 2015). Quantitative data analysis was used for this data because relationships among different variables of interest were being investigated (Patten & Newhart, 2017). Patten & Newhart (2017) also mentioned that quantitative research design can permit a generalization of study results from a sample to a population.

Previously gathered data was used to determine if the ACT scores were significant predictors of the final exam scores. Nonexperimental research permits the exploration of the relationship between the variables of interest without presenting a treatment or a lot of other observations (Fortson et al., 2015). The experimental data in chapter four consisted of four independent variables no reading assignments (NoRA), Reading assignments (RA), Reading assignments scaffolded (RAS), and reading assignments scaffolded with image redesign and audio (RASIA), and the dependent variables Final exam one score, designed by the ACS (American Chemical Examination Institute) and consisting of forty-four multiple choice questions and the final exam two, designed by the course instructor consisting of forty-five multiple questions. The experimental data in chapter five consisted of two independent variables, no reading assignments (NoRA) and Reading assignments scaffolded (RAS)—the dependent variables were final exam one and final exam two items. The experimental data in
chapter six consisted of self-reported data as independent variables and the course grade obtained as the dependent variable. An experimental design was appropriate because experimental designs call for independent variables to be controlled and involve random assignment to different groups to rigorously evaluate any changes that happen (Hamer & Collinsin, 2014).

The study done in chapter seven is based on qualitative research analysis. One of the main objectives of qualitative research is to give insights into the reason underlying quantitative research results (Slavica et al., 2000). In this study, quantitative data was collected before the qualitative data collection began. Semi-structured interviews were conducted for qualitative research. During these interviews, students were given a reading assignment not yet covered in class and asked to summarize the text. The interviews also investigated students’ preferences about the text accompanying images. The students were asked about the placement of the text next to the image and their understanding of the illustrations. The semi-structured interviews gave more insight into the findings from the quantitative data; however, the number of participants was low, limiting the findings' usefulness.

**Introduction to Chemistry course**

The Introduction to Chemistry course introduces students to general inorganic chemistry. This course is designed for students with little to no prior science training. This course comprises three hours of lecture and one hour of discussion per week. When students complete this course, they can enroll in General Chemistry I, and General chemistry for Engineers. General Chemistry is a two-semester course designed to help students learn about the nature of the material universe. The first part of this course is based on the principles that
determine the composition, properties, and structure of matter. General chemistry for
Engineers is based on the modern principle of chemistry with a focus on applications in the
engineering field.

Data collection and cleaning

Data collection for this study began in the Fall of 2018 and continued until the Spring of
2022. The data was collected from students with the same course instructor. All the students
were in the introductory chemistry course Chem-100. 861 students participated in this study.
Of these students, 550 were females, and 311 were males. The study participants participated
in 5 to 12 reading assignments, had an ACT reading score on record, and completed final exams
one and two. Statistical analysis was done on students who participated in 9-12 and 5-8; this
option was not chosen because it not only decreased the sample size but also excluded a
significant number of students needed. The data collected was a combination of different
semesters, so if any student took the course more than once, their data was removed from the
semesters in which they repeated the course. Any data that was missing was deleted using both
Excel and SAS software. During data collection, engagement data was collected based on the
number of letters that students submitted in comment boxes. However, this was not included
in the study because after conducting a statistical analysis, there was no significant difference in
how the students engaged among the different Lexile-levels.

A schedule was obtained from the course instructor to post the reading assignments
aligned with the lecture schedule. A reading assignment was posted a week before the topic
was to be covered, so the students could read and answer the embedded questions before
seeing the subject in lecture. If they had questions on a reading assignment, these questions
were sent to their course instructor so she could address them. Students were graded on completing the reading assignments, and their grades were communicated at the end of the semester.

The reading assignments were posted on an online platform. From Fall 2018 to Spring 2019, the reading assignments were posted on Classroom Salon (CLS). This platform was shut down due to server problems, and in the Fall of 2019, we moved to post the reading assignments on Canvas, a university platform. Canvas is a web-based learning management system or LMS. Universities, educators, institutions, and students can use it to access and manage their courses and learning materials and communicate about achieving and developing skills and learning methods (Canvas UWM). Students could highlight, annotate, comment, and answer questions on CLS. However, the reading assignments were posted as quizzes with embedded questions and text on Canvas. On Canvas, the students could not highlight or annotate. A comment section question was added for students' questions or comments about the reading assignment.

Students were manually added to their group on CLS and Canvas with their respective Lexile level reading assignments. Three groups were created for the posting of the reading assignments. RA1 was low Lexile, RA2 was Medium Lexile, and RA3 was high Lexile.
Ethical Considerations

It is essential to protect the confidentiality and privacy of the students participating in a study. Procedures that ensured the confidentiality and privacy of the research participants were maintained during this study. Data was collected, managed, and saved on Microsoft OneDrive, which is password protected but also requires a two-step authentication process to log in. The backup of the data was also stored on a password-protected computer. After the completion of the study, data was kept using the same security measures. UWM requires that data taken from individuals should follow the Institutional Review Board (IRB) rules. This study followed UWM’s IRB guidelines for human subjects. Students who participated in this study were asked to sign IRB forms, see Appendix A. According to Check et al. (2014), certificates of confidentiality such as IRB are essential for keeping the privacy of research participants and the confidentiality of their data.
CHAPTER 4: AN ANOVA ANALYSIS OF THE IMPACT OF READING ASSIGNMENTS ON STUDENT EXAM MEAN PERFORMANCE.

In this study, an ANOVA analysis was done to assess the impact of reading assignments on student final exam mean performance in the introductory chemistry course. The rationale behind the quantitative study will be presented, along with the methods, data analysis, results, discussion, limitations, conclusion, and implications. Descriptive statistics are also shown to give the reader a basic understanding of the data.

**Background and rationale**

In his Schema Theory, Piaget provided compelling evidence for the effectiveness of pre-reading activities that equip the reader with an outline for reading the text (Piaget, 1971). Because reading is one of the main ways students can attain and retain knowledge, when instructors assign reading assignments, they expose the students to various ideas and perspectives on the subject. This can lead to a better and deeper understanding of the subject, leading to better performance in the course (Alipanahi & Mahmoudi, 2014).

As mentioned in chapter 2, reading comprehension is vital for student success. However, students are graduating high school underprepared for college. In 2019 only 37% of students who took the ACT met the college readiness benchmarks in the four subjects: mathematics, English, science, and reading ACT, (ACT, 2019). These benchmarks are minimum scores needed to show that a student can achieve a grade of C and higher in a non-remedial college course at a 75% chance. Researchers found that 77% of students who are higher achieving in high school complete college with a degree; however, only 37% of students who are lower achieving in high school complete college by age 26 (Howell et al., 2010). This may indicate that students are unaware of what they should do to succeed in college (Howell et al.,...
Rixse (1985) argued that general chemistry is an essential course in many STEM degrees, and how students perform in this course determines the outcomes in their future chemistry courses and even other scientific endeavors. Looking at the fundamental nature of chemistry education, it is essential to identify students who are at risk early on so that interventions are implemented early for concepts that are deficient for these students. If offered early, these interventions can lead to the students who are at risk performing comparably to those who are not considered at risk (Ralph et al., 2019).

Data reported to the University made it clear that many students were coming into college with ACT reading scores below the benchmark. In this study, reading assignments were designed through differentiated instruction. Differentiated instruction reflects an understanding that not all students learn the same way (Tomlinson, 2001). However, they can achieve the level of success if given the tools that meet their readiness level. Reading assignments were designed with scaffolds because they help learners gradually develop their understanding and ability to complete a task independently (Hannafin et al., 1999). The reading assignments were scaffolded to the Lexile levels of each student based on their incoming ACT reading scores. While there is no direct link between the Lexile and the ACT score, assigning the reading assignments this way made sense because the students would be exposed to text that was at their reading level. Moreover, as the results will show, lower ACT reading scores performed significantly higher on their exam scores when assigned a reading assignment at their Lexile level.

The reading assignments were assigned before lecture to help the students be more prepared, which would allow the lecture to be clearer and more useful to them. Braten &
Samuelstuen, (2004) argued that when students were assigned assignments before lecture, it helped them, especially those with a low level of topic knowledge because these students cannot grasp the significant ideas right away. However, the pre-lecture assignment orients them in the right direction toward the significant ideas in the scientific text. When the students are asked to summarize or explain, it has been shown that they will adjust their reading strategies based on the purpose of the reading assigned. Questions in the reading assignments that asked students to summarize and explain have been used to help students with attention and increase comprehension and retention of the course material (Freeman et al., 2014).

Kosslyn et al., (2017) argued that active learning was effective in helping students think deeply about the information and altered how students stored, organized, and retrieved information. When people learn without understanding, they tend to forget, making it difficult to use the information in the future. Learning should include both skill application and knowledge acquisition. This means instructors must change how they approach teaching to include more active learning opportunities.

Even if the results from the image redesign and audio addition did not yield significant results for the lower-performing students, it is still essential to have included the multimedia theory in this study because, according to Mayer (2001), people usually process information in more depth when pictures and words are shown together than when they are shown separately.

Moreover, Mayer (2005) described this as the multimedia principle. “Just putting in pictures with words does not improve learning; that is, all multimedia presentations are not equally effective” (Mayer, 2005. p.31). Words and pictures should be organized; if not, it may
create multimedia messages that hinder learning instead of amplifying it, compromising the student's ability to process information (Mayer & Jackson, 2005) successfully.

**Methods and data collection**

Data was from students who participated in 5 – 12 reading assignments, completed both parts of the final course examination, and had an ACT reading score. Data was analyzed in SAS Version 9.4. An ANOVA (analysis of variance) was used to investigate if there was a difference in student exam performance means in the different groups: the students who did not receive a reading assignment NoRA (No reading assignment), the students who received a reading assignment without the different Lexile levels RA (reading assignment), the students who received the reading assignments at different Lexile levels without image or audio redesign RAS (reading assignment with scaffolds), the students who received the reading assignments at different Lexile levels with image and audio redesign RASIA (reading assignment with scaffolds, image, and audio redesign). The purpose of the ANOVA analysis was to evaluate if there was a statistically significant difference among the means of the different groups, and to determine which combinations were the most significant. The post hoc Tukey test was conducted to compare the means of the different groups. The Tukey test was developed to compute the honestly significant difference between the exam means using a statistical distribution called the q distribution (Abdi & Williams, 2010). A post hoc test is crucial because it helps identify which groups are significantly different after the ANOVA analysis (Tanner, 2012). The SAS code for this analysis can be found in appendix B.

The experimental data consisted of four independent variables (NoRA, RA, RAS, RASIA) and the dependent variables (Final Exam Part One, created by the ACS Examinations Institute
and consisting of forty-four multiple choice questions, and the Final Exam Part Two, designed by the course instructor and consisting of forty-five multiple questions. An experimental design was appropriate in this case because experimental designs call for independent variables to be controlled and involve random assignment to different groups to rigorously evaluate any changes that happen (Hamer & Collinson, 2014).

The group (No reading assignments NoRA) data was obtained from the Fall 2017 and Spring 2017 semesters. This data was from students taught by the same instructor. In the Spring of 2018, students were given the original reading assignments (Medium Lexile). This is the group labeled RA; these reading assignments were not put into different Lexile levels. Then from Fall 2018 to Spring 2022, the reading assignments were scaffolded into the different Lexile levels (RA1, RA2, RA3). The group labeled RAS (reading assignment scaffolded) is the group of students who received reading assignments at different Lexile levels. These reading assignments did not have audio or image redesign. The reading assignments labeled RASIA (reading assignments scaffolded with image and audio redesign) had the respect Lexile levels, audio, and image redesign.

Validity and reliability of the data

When analyzing variance, we need to check the assumptions. One such assumption is that observations are randomly selected from a normal population. A one-way ANOVA was done to answer the question. Generally, studies have shown that Type I and Type II errors for the omnibus-F test will not be affected much by the deviations from normality (Cody & Smith, 2005). After using SAS, for the results that were skewed, the Kruskal-Wallis test was used. Another assumption of ANOVA is that all sample of the population should have the same
variance. The robustness of the test depends on the extent of the differences between the variances of the groups and if the group sample sizes are the same. The omnibus F-test is robust to deviations from homogeneity of variance if the sample sizes are equal and not exceedingly small ($n_j < 5$ per group). If sample sizes are unequal, the robustness will depend on which groups are associated with which variances (Maxwell et al., 2003). The Levene’s test was done to test the homogeneity of variance. The third assumption of the ANOVA procedure is that all the samples should be drawn independently from each other within each sample. Table 4.1 shows the normality of final exam part one and part two for the four groups at each Lexile level.

Table 4.1: Normality of final exam part one and part two for the four groups at each Lexile level.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>Group</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>NoRA</td>
<td>29.11</td>
<td>0.41</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>29.81</td>
<td>-0.14</td>
<td>-0.89</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>26.50</td>
<td>-0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>39.62</td>
<td>0.21</td>
<td>-0.46</td>
</tr>
<tr>
<td>Medium</td>
<td>NoRA</td>
<td>26.04</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>21.33</td>
<td>-0.05</td>
<td>-0.32</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>18.00</td>
<td>-0.30</td>
<td>-0.33</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>40.09</td>
<td>-0.08</td>
<td>-0.06</td>
</tr>
<tr>
<td>High</td>
<td>NoRA</td>
<td>30.17</td>
<td>-0.16</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>46.94</td>
<td>-0.69</td>
<td>-0.24</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>28.63</td>
<td>-0.05</td>
<td>-0.999</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>34.08</td>
<td>-0.32</td>
<td>0.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>Group</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>NoRA</td>
<td>30.67</td>
<td>0.58</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>33.76</td>
<td>0.05</td>
<td>-0.49</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>28.63</td>
<td>0.27</td>
<td>-0.16</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>38.58</td>
<td>0.06</td>
<td>-0.76</td>
</tr>
<tr>
<td>Medium</td>
<td>NoRA</td>
<td>30.88</td>
<td>0.12</td>
<td>-0.31</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>29.44</td>
<td>-0.40</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>26.29</td>
<td>-0.9</td>
<td>-0.16</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>41.21</td>
<td>-0.19</td>
<td>-0.27</td>
</tr>
<tr>
<td>High</td>
<td>NoRA</td>
<td>34.93</td>
<td>-0.04</td>
<td>-0.27</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>25.46</td>
<td>-0.93</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>36.66</td>
<td>0.07</td>
<td>-0.59</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>28.78</td>
<td>-0.18</td>
<td>0.05</td>
</tr>
</tbody>
</table>
To show the power of the sample size required for this study, a G*Power version 3.2 analysis was done. G*power 3.2 provides researchers with effect size calculators, graphs, and power analysis that they are interested in (Faul et al., 2009). A sample size of 861 at a 95% significance level, with four groups, with a medium effect size. G*Power indicated that the power would be 99%. Alpha was set to 0.05 to minimize Type I error from occurring. When alpha is set at a lower number, for example, 0.01, there would be a larger possibility that the null hypothesis would be incorrectly rejected (Gelman, 2008).

Research question

Is there a difference in the exam performance means of the students among the different groups (NoRA, RA, RAS, RASIA) by Lexile level?

Null hypothesis:

There is no significant difference in the exam performance means of the students among the different groups (NoRA, RA, RAS, RASIA).

Alternative Hypothesis:

There is a significant difference in the exam performance means of the students among the different groups (NoRA, RA, RAS, RASIA).

Results

The different independent variables were:

1. Students who did not receive reading assignments (No RA)
2. Students who received reading assignments with no scaffolds (RA)
3. Students who received reading assignments with scaffolds (RAS)
4. Students who received scaffolded reading assignments with audio and image redesign (RASIA)

Data was collected from 861 students. The data contained 318 students in the low Lexile level, 348 students in the medium Lexile level, and 195 students in the high Lexile level. Table 4.2 shows the descriptive statistics of the data in more detail.

Table 4.2: Descriptive statistics of the data used.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>Group</th>
<th>Sample sizes</th>
<th>Variable</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>NoRA</td>
<td>104</td>
<td>Final 1</td>
<td>21.17</td>
<td>5.40</td>
<td>11.50</td>
<td>36.50</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>21.05</td>
<td>5.56</td>
<td>11.00</td>
<td>35.50</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>60</td>
<td>Final 1</td>
<td>22.45</td>
<td>5.29</td>
<td>13.50</td>
<td>20.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>24.52</td>
<td>5.61</td>
<td>14.00</td>
<td>33.50</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>75</td>
<td>Final 1</td>
<td>26.57</td>
<td>4.90</td>
<td>15.50</td>
<td>36.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>26.07</td>
<td>4.68</td>
<td>17.00</td>
<td>45.50</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>79</td>
<td>Final 1</td>
<td>23.90</td>
<td>5.95</td>
<td>12.64</td>
<td>36.00</td>
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<td>22.93</td>
<td>5.93</td>
<td>10.75</td>
<td>40.75</td>
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<td>NoRA</td>
<td>140</td>
<td>Final 1</td>
<td>22.66</td>
<td>4.99</td>
<td>10.00</td>
<td>35.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>22.18</td>
<td>5.34</td>
<td>10.00</td>
<td>33.00</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>39</td>
<td>Final 1</td>
<td>26.55</td>
<td>4.22</td>
<td>19.50</td>
<td>34.00</td>
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<td>Final 2</td>
<td>28.99</td>
<td>4.96</td>
<td>18.50</td>
<td>37.00</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>108</td>
<td>Final 1</td>
<td>27.35</td>
<td>4.09</td>
<td>18.00</td>
<td>35.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>27.24</td>
<td>5.19</td>
<td>16.00</td>
<td>39.00</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>61</td>
<td>Final 1</td>
<td>30.01</td>
<td>5.97</td>
<td>19.00</td>
<td>39.82</td>
</tr>
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<td></td>
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<td>Final 2</td>
<td>26.38</td>
<td>5.83</td>
<td>15.00</td>
<td>37.58</td>
</tr>
<tr>
<td>High</td>
<td>NoRA</td>
<td>63</td>
<td>Final 1</td>
<td>25.58</td>
<td>5.39</td>
<td>13.00</td>
<td>36.00</td>
</tr>
<tr>
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<td>Final 2</td>
<td>23.40</td>
<td>5.74</td>
<td>10.50</td>
<td>35.50</td>
</tr>
<tr>
<td></td>
<td>RA</td>
<td>28</td>
<td>Final 1</td>
<td>26.67</td>
<td>6.91</td>
<td>14.00</td>
<td>36.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>27.73</td>
<td>4.09</td>
<td>17.00</td>
<td>34.50</td>
</tr>
<tr>
<td></td>
<td>RAS</td>
<td>60</td>
<td>Final 1</td>
<td>28.23</td>
<td>4.62</td>
<td>19.50</td>
<td>35.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>26.83</td>
<td>6.18</td>
<td>16.00</td>
<td>42.00</td>
</tr>
<tr>
<td></td>
<td>RASIA</td>
<td>44</td>
<td>Final 1</td>
<td>31.34</td>
<td>5.87</td>
<td>17.24</td>
<td>40.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final 2</td>
<td>27.20</td>
<td>5.41</td>
<td>14.83</td>
<td>36.68</td>
</tr>
</tbody>
</table>

Low Lexile level results:

The ANOVA test showed a statistically significant difference in the exam performance mean of the students who received the different treatments at the Low Lexile level. For Final Exam Part One, F (3,314) = 12.57, p<0.0001. The Tukey post hoc results showed that the students who received scaffolded reading assignments (RAS) performed significantly highest on
their final exam. For Final Exam Part Two, F (3,314) = 12.07, p<0.0001. The Tukey post hoc results showed that the students who received scaffolded reading assignments (RAS) performed significantly higher on their final exam than those who did not receive a reading assignment (NoRA) and those who received scaffolded reading assignments with audio and image redesign (RASIA). A $R^2$ of 0.107, indicating about 10% of the total variability in the Final Exam Part One score is due to the treatment the students received. A $R^2$ of 0.103, indicating about 10% of the total variability in the Final Exam Part Two score is due to the treatment the students received. The ANOVA results for Final Exam Part One and Two are presented in Table 4.3; the Tukey post hoc results are presented in Table 4.4. Figure 4.1 shows the exam means based on treatment.

Table 4. 3: Low Lexile Final Exam Part One and Part Two ANOVA results.

<table>
<thead>
<tr>
<th>Type of exam</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Final Exam Part One</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between groups</td>
<td>3</td>
<td>1173.144</td>
<td>391.048</td>
<td>12.57</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Within groups</td>
<td>314</td>
<td>9769.397</td>
<td>31.112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>317</td>
<td>10942.547</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Final Exam Part Two</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between groups</td>
<td>3</td>
<td>1190.561</td>
<td>396.853</td>
<td>12.07</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Within groups</td>
<td>314</td>
<td>10321.242</td>
<td>32.870</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>317</td>
<td>11511.803</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4: Post hoc results for the low Lexile level students.

<table>
<thead>
<tr>
<th>Group</th>
<th>Final Exam Part One means</th>
<th>Final Exam Part Two means</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NoRA</td>
<td>21.17</td>
<td>21.05</td>
</tr>
<tr>
<td>2. RA</td>
<td>22.45</td>
<td>24.52</td>
</tr>
<tr>
<td>3. RAS</td>
<td>26.57</td>
<td>26.07</td>
</tr>
<tr>
<td>4. RASIA</td>
<td>23.90</td>
<td>22.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Final Exam Part One</th>
<th></th>
<th>Final Exam Part Two</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NoRA</td>
<td>0.7065</td>
<td>&lt;0.0001*</td>
<td>0.0199*</td>
<td>1. NoRA</td>
</tr>
<tr>
<td>2. RA</td>
<td>0.0002*</td>
<td>0.4238</td>
<td>2. RA</td>
<td>0.0065*</td>
</tr>
<tr>
<td>3. RAS</td>
<td>0.0002*</td>
<td>0.0224*</td>
<td>3. RAS</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>4. RASIA</td>
<td>0.0199*</td>
<td>0.4238</td>
<td>4. RASIA</td>
<td>0.2910</td>
</tr>
</tbody>
</table>

p-value <0.05*, NoRA: no reading assignment, RA: reading assignment, RAS: reading assignment scaffolded, RASIA: reading assignment scaffolded with image and audio redesign.

Figure 4.1: Distribution of Final Exam Part One and Part Two means at Low Lexile level.

Medium Lexile level results:

The ANOVA test showed a statistically significant difference in the mean exam performance of the students who received the different treatments in the medium Lexile level.

For Final Exam Part One, F (3,344) = 19.40, p<0.0001. The Tukey post hoc results showed that the students who received scaffolded reading assignments (RAS) performed significantly higher on their final exam than those who did not (NoRA). For Final Exam Part Two, F (3,344) = 19.27,
p<0.0001. The Tukey post hoc results showed that the students who received scaffolded reading assignments (RAS) performed significantly higher on their final exam than those who did not receive a reading assignment (NoRA). A R² of 0.144 indicating that about 14% of the total variability in the Final Exam Part One score is due to the type of treatment the students received. A R² of 0.141 indicating that about 14% of the total variability in the Final Exam Part Two scores is due to the type of treatments the students received. The ANOVA results for Final Exam Part One and Part Two are presented in Table 4.5; the Tukey post hoc results are presented in Table 4.6. Figure 4.2 shows the exam means based on treatment.

Table 4. 5: Medium Lexile Final Exam Part One and Part Two ANOVA results.

<table>
<thead>
<tr>
<th>Type of exam</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Exam Part One</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between groups</td>
<td>3</td>
<td>1850.563</td>
<td>604.322</td>
<td>19.01</td>
<td>&lt;0001</td>
</tr>
<tr>
<td>Within groups</td>
<td>344</td>
<td>10823.407</td>
<td>32.786</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>347</td>
<td>13001.756</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Exam Part Two</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between groups</td>
<td>3</td>
<td>1809.690</td>
<td>603.230</td>
<td>19.40</td>
<td>&lt;0001</td>
</tr>
<tr>
<td>Within groups</td>
<td>344</td>
<td>10698.306</td>
<td>31.099</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>347</td>
<td>12507.996</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. 6: Post hoc results for the medium Lexile level students

<table>
<thead>
<tr>
<th>Group</th>
<th>Final Exam Part One means</th>
<th>Final Exam Part Two means</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NoRA</td>
<td>22.66</td>
<td>22.18</td>
</tr>
<tr>
<td>2. RA</td>
<td>26.55</td>
<td>28.99</td>
</tr>
<tr>
<td>3. RAS</td>
<td>27.35</td>
<td>27.24</td>
</tr>
<tr>
<td>4. RASIA</td>
<td>30.01</td>
<td>26.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Final Exam Part One</th>
<th>Final Exam Part Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.NoRA</td>
<td>2.RA</td>
</tr>
<tr>
<td>1.NoRA</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>2.RA</td>
<td>0.0069*</td>
</tr>
<tr>
<td>3.RAS</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>4.RASIA</td>
<td>&lt;0.0001*</td>
</tr>
</tbody>
</table>

p-value <0.05*, NoRA: no reading assignment, RA: reading assignment, RAS: reading assignment scaffolded, RASIA: reading assignment scaffolded with image and audio redesign.
High Lexile level results:

The ANOVA test showed a statistically significant difference in the mean exam performance of the students who received the different treatments at the high Lexile level. For Final Exam Part One, $F(3,191) = 9.34, p<0.0001$. The Tukey post hoc results showed that the students who received scaffolded reading assignments with audio and image redesign (RASIA) performed significantly higher on their final exam than those who received the other treatments. For Final Exam Part Two, $F(3,191) = 5.46, p = 0.0013$. The Tukey post hoc results showed that the students who received any reading assignment performed significantly higher on their final exam than those who did not receive a reading assignment (NoRA). A $R^2$ of 0.127, indicating that about 13% of the total variability in the Final Exam Part One mean score is due to the treatment the students received. A $R^2$ of 0.079 indicates that about 8% of the total variability in the Final Exam Part Two score is due to the type of treatment the students received. The ANOVA results for Final Exam Part One and Part Two are presented in table 4.7; the post hoc results are presented in table 4.8. Figure 4.3 shows the exam means based on treatment.
Table 4. 7: Low Lexile Final Exam Part One and Part Two ANOVA results

<table>
<thead>
<tr>
<th>Type of exam</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Exam Part One</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between groups</td>
<td>3</td>
<td>854.146</td>
<td>284.715</td>
<td>9.34</td>
<td>&lt;0.0001</td>
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<tr>
<td>Within groups</td>
<td>191</td>
<td>5823.576</td>
<td>30.489</td>
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<tr>
<td>Total</td>
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<td>6677.723</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Exam Part Two</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between groups</td>
<td>3</td>
<td>536.548</td>
<td>178.849</td>
<td>5.46</td>
<td>0.0013</td>
</tr>
<tr>
<td>Within groups</td>
<td>191</td>
<td>6254.195</td>
<td>32.744</td>
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<td></td>
</tr>
<tr>
<td>Total</td>
<td>194</td>
<td>6790.743</td>
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</tr>
</tbody>
</table>

Table 4. 8: Post hoc results for the high Lexile level students

<table>
<thead>
<tr>
<th>Group</th>
<th>Final Exam Part One means</th>
<th>Final Exam Part Two means</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NoRA</td>
<td>25.58</td>
<td>23.40</td>
</tr>
<tr>
<td>2. RA</td>
<td>26.67</td>
<td>27.73</td>
</tr>
<tr>
<td>3. RAS</td>
<td>28.23</td>
<td>26.83</td>
</tr>
<tr>
<td>4. RASIA</td>
<td>31.34</td>
<td>27.20</td>
</tr>
</tbody>
</table>

### Final Exam Part One

<table>
<thead>
<tr>
<th></th>
<th>1.NoRA</th>
<th>2.RA</th>
<th>3.RAS</th>
<th>4.RASIA</th>
<th>1.NoRA</th>
<th>2.RA</th>
<th>3.RAS</th>
<th>4.RASIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.NoRA</td>
<td>0.8251</td>
<td>0.1351</td>
<td>&lt;0.0001*</td>
<td>1.NoRA</td>
<td>0.0063*</td>
<td>0.0104*</td>
<td>0.0219*</td>
<td></td>
</tr>
<tr>
<td>2.RA</td>
<td>0.8251</td>
<td>0.8296</td>
<td>0.004*</td>
<td>2.RA</td>
<td>0.0063*</td>
<td>0.8561</td>
<td>0.8781</td>
<td></td>
</tr>
<tr>
<td>3.RAS</td>
<td>0.1371</td>
<td>0.8296</td>
<td>0.0096*</td>
<td>3.RAS</td>
<td>0.0104*</td>
<td>0.8561</td>
<td>1.0000</td>
<td></td>
</tr>
<tr>
<td>4.RASIA</td>
<td>&lt;0.0001*</td>
<td>0.0044*</td>
<td>0.0096*</td>
<td>4.RASIA</td>
<td>0.0219*</td>
<td>0.8781</td>
<td>1.0000</td>
<td></td>
</tr>
</tbody>
</table>

p-value <0.05*, NoRA: no reading assignment, RA: reading assignment, RAS: reading assignment scaffolded, RASIA: reading assignment scaffolded with image and audio redesign.

Figure 4. 3: Distribution of Final Exam Part One and Part Two means at high Lexile level.
Discussion

The research question was focused on the difference in student exam performance means among four groups (students who did not receive reading assignments, those that received reading assignments with no scaffolds, those that received scaffolded reading assignments, and those that received scaffolded reading assignment with audio and image redesign) by Lexile level. The results from this quantitative study show that scaffolding reading assignments is an effective way to improve student’s exam performance. While the scaffolded reading assignments with audio and image redesign did not have an impact on the low Lexile level students, the results from the medium and high Lexile level students show that they have an impact on exam performance means. This may mean that adding audio and text to the image may have caused extraneous cognitive load on the low Lexile level students. The Tukey post hoc results show that students who received scaffolded reading assignments performed significantly better on their final exams compared to those who did not (NoRA) or those who received a reading assignment that was not scaffolded. At the low Lexile level, the R squared values of 0.107 and 0.103 for the Final Exam Part One and Part Two indicate that approximately 10% of the total variability in student exam mean performance can be attributed to the type of intervention they received. This means that only a small portion of the differences observed in the students’ exam performance means can be explained by the type of intervention they received, and other factors may have influenced the results.

At the medium Lexile level, the R-squared values of 0.144 for the two finals suggest that approximately 14% of the total variability in the student exam mean performance can be attributed to the type of intervention they received. This shows that scaffolded reading
assignments can have an even greater impact on the exam mean performance of students at the medium Lexile level.

At the high Lexile level, the R squared values of 0.127 and 0.079 for the Final Exam Part One and Part Two suggest that approximately 13% and 8% of the total variability in student’s exam performance can be attributed to the type of intervention they received. The results showed that students' performance increased when assigned scaffolded reading assignments. The low-performing students benefited the most in both Final Exams Part One and Part Two. There was a significant difference in exam performance among the four groups, and the low-performing students who received scaffolded reading assignments benefited the most. This revealed that when students can read and comprehend scientific text, when they are assigned this text at their Lexile level, with the appropriate scaffolds, differentiated instruction, and assigned as pre-lecture instruction, they perform better on their final exam scores in their science courses. The results on this central question did not provide significant results for all the interventions at the high Lexile levels for both Final Exams Parts One and Two.

Limitations

Like any other research, limitations could apply to the findings due to conditions of the experiment and sample. The data from this study was collected from only the University of Wisconsin-Milwaukee introductory chemistry students, which means the results cannot to generalized for all introductory chemistry students from other institutions. The chemistry textbook used in this course, from which the reading assignments were designed, may not be the same one used by other institutions. The content on the topics may be different compared to other institutions. However, according to Cromley & Synder-Hogan, (2010), because of the
similarities of the scientific texts used in all fields, success in one field, chemistry, can result in success in a student’s general chemistry literacy. Another limitation of this study was the sample size at certain levels. The study had three Lexile levels, so data had to be spread further. However, ANOVA analysis is robust to normality violations. A non-parametric method can be used if the ANOVA assumptions are violated.

**Implications and conclusions**

While the analysis of variance did not provide significant results for all the different implementations, the students who received low Lexile level reading assignments performed significantly higher on Final Exam Parts One and Two than the other implementations. The students who received reading assignments at medium and high Lexile levels also performed significantly higher on both final exam parts one and two when reading assignments were implemented versus when they were not (NoRA). These results show that implementing pre-instruction reading is beneficial to student exam performance no matter their incoming reading comprehension level. The Implementation of scaffolded pre-lecture reading assignments shows the highest learning gains for students with lower incoming reading abilities (below college level readiness).

An essential aim of educational research is to better comprehend the student learning process in a particular subject. The research must mainly investigate a component of the learning process to achieve this aim. This study investigated the impact of reading interventions (reading assignments) on student exam performance. By investigating the reading assignment, which is a component that can impact student exam performance, we were able to better
understand how to help students, mainly those with low reading abilities, succeed in an introductory chemistry course.

In introductory chemistry, students are assigned the textbook for the course and asked to read it prior to lecture. However, this leads to frustration because most students find the textbook challenging to comprehend. The results of this study show that if given the right tools, students can perform better in their courses. The Cognitive Load Theory and schema learning theory have both been suggested to explain how beneficial it is to assign pre-lecture learning material. Schema learning theory suggests that knowledge is mainly acquired when new information can be added to schemas: existing knowledge networks containing multiple cognitive constructs (Bartlett, 1932). Assigning reading assignments at the student’s appropriate Lexile level before the topic is covered in lecture is beneficial. This helps the students better understand the concepts and retain the information. This proportionally minimal change can significantly impact student exam performance and encourage students to continue with STEM education.
CHAPTER 5: DETECTION OF GROUP-RELATED DIFFERENTIAL ITEM FUNCTIONING (DIF) ON FINAL EXAM PART ONE AND TWO ITEMS

Background and rationale

When an educational program is designed, the primary goal is to attain the highest efficiency of the program through good design and well-organized measurement instruments (Royse et al., 2009). When a measurement instrument is well developed, it has a prominent place in educational programs because it measures the efficiency of the program through educational outcomes. The book Standards for Educational, Psychological Testing (Standards) characterized a test as “a device or procedure in which a sample of an examinee's behavior in a specified domain is obtained. Subsequently, they are evaluated and scored using a standardized process” (Plake, 2014, p.2.)

The development and analysis of standardized tests, and even other tests have been directed by the Standards, which were developed by the American Educational Research Association (AERA), the American Psychological Association (APA), and the National Council on the Measurement in Education (NCME). The Standards highlight validity, reliability, and fairness in test development and testing applications such as test administrations (Plake, 2014). Validity is the degree to which evidence and theory support the test score interpretations for the proposed use of tests (Plake, 2014, p.11). Reliability is the consistency of scores across replications of a testing procedure, regardless of whether the consistency is estimated or reported (Plake, 2014, p.33).

Fairness is a significant validity issue and should be considered in all testing processes, such as test development or test score interpretation (Plake, 2014).
The issues of test fairness may stem from test bias, which can be defined as invalidity or systematic errors in the test measurement for the members of a given group (Camilli & Shepard, 1994, p.4). Systematic errors in the measurement provide an unfair benefit to one of the subgroups, creating an unequal opportunity for test-takers. Measures to eliminate Differential Item Functioning have been used to reduce measurement bias and improve testing. Differential Item Functioning (DIF) happens when test takers of equal ability differ in their probabilities of answering a test item correctly as a function of group membership (Plake, 2014, p.51). DIF analyses are critical in ensuring the test’s quality because biased items have an adverse effect on its validity.

DIF can be categorized as uniform or non-uniform. With uniform DIF an item favors one group over the other consistently, and an item will show non-uniform DIF when the difference in item performance amongst groups are not consistent across different levels of the underlying ability that is being measured (Swaminathan & Rogers, 1990). The Cochran-Mantel-Haenszel method and the logistic regression method are non-IRT approaches. The Cochran-Mantel-Haenszel method is the most popular DIF detection method used, it compares group members that have been matched by their ability, and gives odds ratios and chi-square statistics and detects uniform DIF. The logistic regression method detects both uniform and non-uniform DIF. For both methods, data must include item responses (1= correct, 0 = incorrect), group membership (NoRA = 0, RAS = 1), and the ability (total test score) variables. Logistic regression also involves an interaction variable that combines the ability and the group. While the logistic regression method is more general and flexible than the Mantel-Haenszel, it includes the
interaction term which can have a detrimental effect on power, if the item is only exhibiting uniform DIF.

Differential Item Functioning analysis was done to assess whether the students who received reading assignments performed better on the exam items than those who did not. This was done to determine if students in one group were more likely to get an exam item correct than students with comparable ability levels in another group (Plake, 2014, p.2). DIF is studied among two groups of exam takers. A comparison group, referred to as the reference group, and the interest group called the focal group, can show two types of DIF: uniform DIF and non-uniform DIF. When items persistently favor one group over the other, and the item characteristics curves (ICC) which are graphical representations that show the relationship between the examinee’s probability of getting an item correct and the underlying ability. The ICC are parallel for both groups, then there is uniform DIF. However, with non-uniform DIF, items show if the group is believed to have a higher probability of getting a correct answer change at different levels of the underlying “trait”, and the item characteristic curves intersect. (Swaminathan & Roger, 1990; Camilli & Shepard, 1994). Figure 5.1 shows the graphic representation of uniform and non-uniform DIF.
There is a direct relationship between DIF and test validity. If a test accurately measures the constructs it claims, then it is valid (Ackerman, 1992). This can be due to the group differences in the primary dimension (Ackerman, 1992). A test validation process must be done to ensure the test is fair for the test takers. Cole & Zieky (2001) argued that a test is fair if it does not overpredict or underpredict how groups members perform. Moreover, predictive bias is how accurate a test is in predicting which group will succeed over another group (Jain et al., 2015). The same assessment should not be used for all test takers because it brings on inequalities in the opportunities to learn (Jain et al., 2015).
Mantel-Haenszel Method

Many methods have been used to detect DIF. The Mantel-Haenszel (MH) is one of the most popular analysis methods used to detect DIF. It is a method based on a contingency table. This method is non-parametric. The MH procedure compares group members that have been matched on ability as measured by their total score on the exam. The odds ratios estimator ($\alpha_{MH}$) can be found by using the contingency table. See table 5.1. (Scheuneman & Bleistein, 1989)

Table 5.1: MH contingency table.

<table>
<thead>
<tr>
<th>Group</th>
<th>Correct (1)</th>
<th>Incorrect (0)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (R)</td>
<td>A$_j$</td>
<td>B$_j$</td>
<td>N$_{Rj}$</td>
</tr>
<tr>
<td>Focal (F)</td>
<td>C$_j$</td>
<td>D$_j$</td>
<td>N$_{Fj}$</td>
</tr>
<tr>
<td>Total</td>
<td>M$_{ij}$</td>
<td>M$_{0j}$</td>
<td>T$_j$</td>
</tr>
</tbody>
</table>

When $\alpha_{MH} = 1$, this means that the exam item does not have DIF, and an equal proportion of the reference group and focal group test takers answered the item right. When $\alpha_{MH} > 1$, more of the reference group test takers answered the item correctly, and a greater number of the focal group test takers answered the item incorrectly. This shows that the item favors the reference group. On the contrary, when $\alpha_{MH} < 1$, the item favors the focal group (Dorans & Holland, 1993). To put items into three categories of DIF, the estimator is converted to the MH delta-difference (MH D-DIF) scale by using: $\Delta \alpha_{MH} = -2.35 \ln(\alpha_{MH})$. MH D-DIF scale allows DIF to be interpreted as negligible, moderate, and large. The three categories are presented in Table 5.2. With the odds ratio estimator converted onto the MH D-DIF scale, the estimates are instantly explained as the difference between item difficulties for the focal and
reference group (Dorans & Holland, 1993). When $\ln \alpha$ is positive, the item is distinctively difficult for the test takers in the focal group. When controlling for the ability, the Mantel-Haenszel tests the null hypothesis that there is no difference in item performance between the reference and focal groups. An item has DIF when the effect size of the DIF is considered moderate or large. An item is said not to have DIF when the effect size of the DIF is considered negligible or nonexistent. Below are the limits and categories.

Table 5. 2: MH-DIF scale.

<table>
<thead>
<tr>
<th>MH-DIF</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>MH-DIF</td>
</tr>
<tr>
<td>$1 &lt;</td>
<td>MH-DIF</td>
</tr>
<tr>
<td>$</td>
<td>MH-DIF</td>
</tr>
</tbody>
</table>

To test the null hypothesis, which states that an item does not have DIF ($\alpha_{MH}=1$), the Mantel-Haenszel chi-square statistic ($X^2_{MH}$) is determined. It is said to follow the chi-square distribution with one degree of freedom (Angoff, 1993; Holland & Thayer, 1988).

Logistic Regression Method

Cox presented the logistic regression technique in 1958 (Swaminathan & Rogers, 1990). The logistic regression uses three methods that a computed and compared to detect DIF. Model 3 is the full model; this contains the main effects and an interaction term; $Y = b_0 + b_1 (\text{Ability}) + b_2 (\text{Group}) + b_3 (\text{Ability} \times \text{Group})$. Model 2 is a reduced model that includes the main effects; $Y = b_0 + b_1 (\text{Ability}) + b_2 (\text{Group})$. Model 1 is another reduced model with a main effect; $Y = b_0 + b_1 (\text{Ability})$. To identify non-uniform DIF, model 3 and model 2 are compared. If non-uniform DIF is detected, model 3 and model 1 are compared to check for uniform DIF. If there is no uniform DIF, then there is no DIF detected. The proc-Logistic procedure was used in SAS 9.4
software for the logistic regression. The likelihood ratio test chi squares can be used to evaluate the model comparisons in logistic regression (Zhang, 2015).

The odds ratio estimates can be used to determine which items favor NoRA (no reading assignments) or RAS (reading assignments scaffolded). The focal group was coded with 0, and the reference group with 1 (Abedalaziz, 2010). If the significant odds ratio is greater than 1, DIF favors the focal group, and if the odds ratio is less than one, DIF favors the reference group.

**Methods and data analysis**

The Mantel-Haenszel and Logistic Regression methods were used in this study. This was done to determine if students from the group who did not receive reading assignments had a greater probability of getting an exam item correct than those who received reading assignments with different reading levels. The exams were final exams, the first being a final exam prepared by the American chemical society (ACS), composed of forty-four multiple choice questions, and the second one from the course instructor, consisting of forty-five multiple choice questions. The sample size in this study is treated as a low limit of what sample sizes are acceptable for DIF analysis (Zieky, 1993). There was an even distribution in sample size between the focal and reference groups. Only sample sizes that are unbalanced to 90% for the reference group and 10% for the focal group would cause a discrepancy that would affect DIF detection for the Mantel-Haenszel analysis (Sedivy & Zhang, 2009). Type I error rates were determined by simulating no DIF conditions. Uttaro & Millsap (1994) demonstrated that the Mantel-Haenszel method showed different Type I error rates depending on the length of the exams. Their results showed that Type I error was more inflated with a test that had 20 items than one with 40 items.
The study was based on textbook topics that were used in creating the reading assignments. The finals were checked for items that corresponded to the reading assignments. Table 5.3 shows the items corresponding to each reading assignment topic. SAS 9.4 was the software used for the analysis. Data was provided on a scale of 0 for incorrect and 1 for correct responses.

Uniformity of the odds ratio across the strata is one of the assumptions of the Mantel-Haenszel method (Holland & Wainer, 2012). The Breslow-Day test checks if the odds ratios are uniform across the strata. This test statistic shows the homogeneity well when the number of the strata is small and when the stratum is large (Driana, 2007; Holland & Wainer, 2012). To overcome the limitations of the Mantel-Haenszel method in detecting non-uniform DIF, Plenfield (2003) suggested using the Breslow-day test. A suggestion of using the Breslow-Day and Mantel-Haenszel tests in combination with limitations was presented by Plenfield (2003). When the combined decision rule is made, an item is said to have no DIF when both the Breslow-Day and Mantel-Haenszel tests fail to reject the null hypothesis. The SAS code for the DIF analysis can be found in Appendix C.

Table 5.3: Items corresponding to each reading assignment topic.

<table>
<thead>
<tr>
<th>Reading Assignments</th>
<th>Final Exam Part One</th>
<th>Final Exam Part Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Theory</td>
<td>8, 19, 23, 24</td>
<td>11, 12</td>
</tr>
<tr>
<td>Modern Model of an Atom</td>
<td>14</td>
<td>13, 14</td>
</tr>
<tr>
<td>Molecular Shapes</td>
<td>15</td>
<td>19, 20, 21, 22, 23</td>
</tr>
<tr>
<td>Covalent Bonding</td>
<td>16, 17, 18</td>
<td>5, 7, 17, 18, 21</td>
</tr>
<tr>
<td>Ionic Bonding</td>
<td>17</td>
<td>13, 14, 15, 17, 18, 21</td>
</tr>
<tr>
<td>Periodic Trends</td>
<td>20, 21</td>
<td>12, 16, 25, 35</td>
</tr>
<tr>
<td>Properties and Changes</td>
<td>31, 32, 34, 35, 36, 37</td>
<td>4, 5, 6, 8, 43</td>
</tr>
<tr>
<td>Formula Calculations</td>
<td>1, 2, 4, 9, 10</td>
<td>26, 27, 28, 29, 30, 31, 39, 41, 42</td>
</tr>
<tr>
<td>Solutions</td>
<td>26, 27, 28, 29, 30, 43</td>
<td>8, 32, 33, 34</td>
</tr>
<tr>
<td>Chemical Reactions</td>
<td>12, 13</td>
<td>36, 37, 38, 39</td>
</tr>
<tr>
<td>Limiting Reactants</td>
<td>N/A</td>
<td>40</td>
</tr>
<tr>
<td>Ideal Gases</td>
<td>6, 7, 11, 40</td>
<td>43, 44, 45</td>
</tr>
</tbody>
</table>
Research question:

Do students with different reading levels who receive scaffolded reading assignments perform better on the exam items than those who do not?

Null hypothesis:

There is no significant difference in exam item performance between the focal and reference groups when controlling for ability.

Results

The purpose of conducting a differential item functioning analysis was to assess whether the students who received reading assignments performed better on the exam items than those who did not. This was done to determine if students in one group were more likely to get an exam item correct than students with comparable ability levels in another group.

Variables:

1. Exam items
2. Focal group: Students who did not receive reading assignments.
3. Reference group: Students who received reading assignments at different Lexile levels.

Descriptive statistics:

Table 5.4 represents the frequency distribution for the final exams. The sample was distributed between 307 (59%) students who did not receive a reading assignment (NoRA) and 213 (41%) students who received a reading assignment at their Lexile levels (RA).

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoRA</td>
<td>307</td>
<td>59</td>
</tr>
<tr>
<td>RAS</td>
<td>213</td>
<td>41</td>
</tr>
<tr>
<td>Total</td>
<td>520</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5.4: Frequency distribution of the final exams for DIF analysis.
For this Mantel-Haenszel analysis, a PROC FREQ procedure in SAS 9.4 was done. A PROC LOGISTIC procedure in SAS 9.4 was done for the logistic regression analysis.

Table 5.5 and Table 5.6 show the results of the Mantel-Haenszel and logistic regression procedures for the exam items. The CMH statistics value shows that students who received a reading assignment performed significantly differently on items than those who did not receive a reading assignment after controlling for the ability. If the odds ratio is higher than 1, the item’s DIF favors RAS (reading assignments scaffolded), and if the odds ratio is less than 1, the DIF favors the NoRA (No reading assignment). Logistic regression was done to identify uniform and non-uniform DIF. The Breslow-Day test results suggest that the odds ratios between the two groups vary significantly across strata. To interpret the logistic regression results, the p-value for the interaction should be examined for non-uniform DIF. If this is not statistically significant, the p-value for the main effect of the model with the group and total scores should be examined for uniform DIF. If both p-values of the interaction and the main effect are not statistically significant, then there is no evidence of DIF.

Table 5.5: Cochran-Mantel-Haenszel and Logistic Regression Analysis result for items that showed DIF on Final Exam Part One item.

<table>
<thead>
<tr>
<th>Reading Assignments</th>
<th>Item</th>
<th>CMH p-value</th>
<th>CMH Chi-squared</th>
<th>CMH odds ratio</th>
<th>LR uniform p-value</th>
<th>LR non-uniform p-value</th>
<th>Breslow-Day p-value</th>
<th>Type of DIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Theory</td>
<td>23</td>
<td>0.0173</td>
<td>1.86</td>
<td>2.60</td>
<td>0.00119**</td>
<td>0.103</td>
<td>0.69</td>
<td>uni</td>
</tr>
<tr>
<td>Modern Model of the Atom</td>
<td>14</td>
<td>0.0269</td>
<td>4.90</td>
<td>0.5424</td>
<td>0.000506**</td>
<td>0.0123</td>
<td>0.10</td>
<td>uni</td>
</tr>
<tr>
<td>Ideal Gases</td>
<td>7</td>
<td>0.9609</td>
<td>0.262</td>
<td>1.26</td>
<td>0.0589</td>
<td>0.000409**</td>
<td>0.4633</td>
<td>Non-uni</td>
</tr>
</tbody>
</table>

Note: uni: uniform, non-uni: non-uniform. P-value <.001**.

Items 23 (Atomic theory), and 14 (Modern model of the atom), showed evidence of uniform DIF, and item 7 (Ideal gases) showed evidence of non-uniform DIF. Only 7% of the Final Exam Part One items exhibited DIF. Item 23 showed DIF favoring the group with the students
who received scaffolded reading assignments. Item 14 showed DIF in favor of the group with students who did not receive reading assignments, and there was no DIF favor for item 7.

Table 5.6: Cochran-Mantel-Haenszel and Logistic Regression Analysis result for items that showed DIF on Final Exam Part Two items.

<table>
<thead>
<tr>
<th>Reading Assignments</th>
<th>Item</th>
<th>CMH p-value</th>
<th>CMH Chi-squared</th>
<th>CMH odds ratio</th>
<th>LR uniform p-value</th>
<th>LR non-uniform p-value</th>
<th>Breslow-Day p-value</th>
<th>Type of DIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern Model of the Atom</td>
<td>13</td>
<td>0.015</td>
<td>6.39</td>
<td>2.07</td>
<td>0.00171**</td>
<td>0.0218</td>
<td>0.6023</td>
<td>Uni</td>
</tr>
<tr>
<td>Molecular Shapes</td>
<td>23</td>
<td>6.21e-08**</td>
<td>29.3</td>
<td>0.126</td>
<td>1.53e-09**</td>
<td>0.249</td>
<td>0.3223</td>
<td>Uni</td>
</tr>
<tr>
<td>Covalent Bonding</td>
<td>21</td>
<td>0.0103</td>
<td>6.58</td>
<td>2.47</td>
<td>0.0008**</td>
<td>0.294</td>
<td>0.824</td>
<td>Uni</td>
</tr>
<tr>
<td>Periodic Trends</td>
<td>12</td>
<td>4.95e-05**</td>
<td>16.5</td>
<td>3.72</td>
<td>5.07e-07**</td>
<td>0.188</td>
<td>0.8301</td>
<td>Uni</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>6.29e-11**</td>
<td>42.7</td>
<td>0.1</td>
<td>3.82e-11**</td>
<td>3.77e-06**</td>
<td>0.4424</td>
<td>Uni</td>
</tr>
<tr>
<td>Properties and Changes</td>
<td>4</td>
<td>4.62e-05**</td>
<td>16.6</td>
<td>3.42</td>
<td>6.61e-06**</td>
<td>0.839</td>
<td>0.9752</td>
<td>Uni</td>
</tr>
<tr>
<td>Formula Calculations</td>
<td>28</td>
<td>9.40e-05**</td>
<td>15.3</td>
<td>0.279</td>
<td>3.71e-05**</td>
<td>0.921</td>
<td>0.2796</td>
<td>Uni</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>3.56e-04**</td>
<td>12.8</td>
<td>3.11</td>
<td>2.22e-04**</td>
<td>0.519</td>
<td>0.9427</td>
<td>Uni</td>
</tr>
<tr>
<td>Chemical Reactions</td>
<td>36</td>
<td>2.32e-08**</td>
<td>31.2</td>
<td>8.03</td>
<td>1.21e-07**</td>
<td>0.211</td>
<td>0.6921</td>
<td>Uni</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>7.88e-13**</td>
<td>51.3</td>
<td>0.0826</td>
<td>9.95e-14**</td>
<td>0.485</td>
<td>0.0841</td>
<td>Uni</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>5.63e-11**</td>
<td>42.9</td>
<td>0.079</td>
<td>2.33e-11**</td>
<td>0.0545</td>
<td>0.0772</td>
<td>Uni</td>
</tr>
<tr>
<td>Limiting Reactions</td>
<td>40</td>
<td>3.05e-03**</td>
<td>8.77</td>
<td>0.339</td>
<td>2.66e-04**</td>
<td>0.766</td>
<td>0.22</td>
<td>Uni</td>
</tr>
</tbody>
</table>

Note: NA: not applicable, uni: uniform, non-uni: non-uniform. P-value < 0.001**

Items 13 (Modern model of the atom), 23 (Molecular shapes), 21 (Covalent bonding), 12, 35 (Periodic trends), 28,42 (Formula calculations), 36,37,39 (Chemical reactions) and 40 (Limiting reactants) all showed evidence of uniform DIF. Indicating that 27% of the items in the Final Exam Part Two exhibited DIF. Items 13,21,12,4,42, and 36 showed DIF favoring the group with the students that received scaffolded reading assignments. Items 23,35,28,39,37, and 40 showed DIF favoring the group with the students who did not receive reading assignments. The natural log odds ratio was calculated to classify the DIF level for the items that showed DIF in Final Exam Parts One and Two. The estimator was converted to the MH delta-difference (MH D-DIF) scale using: \( \Delta \alpha_{\text{MH}} = -2.35\ln(\alpha_{\text{MH}}) \). Table 5.7 shows the items with DIF categorization.
Table 5.7: The items with DIF categorization based on MH-DIF.

<table>
<thead>
<tr>
<th>DIF category</th>
<th>Final Exam Part One items</th>
<th>Final Exam Part Two items</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Negligible)</td>
<td>AT (23)</td>
<td>MM (13), FC (42), PT (12), CB (21), PC (4), CR (36),</td>
</tr>
<tr>
<td>B (Moderate)</td>
<td>MM (14)</td>
<td>NA</td>
</tr>
<tr>
<td>C (Large)</td>
<td>NA</td>
<td>PT (35), FC (28), CR (37), LR(40), MS(23), CR(39)</td>
</tr>
</tbody>
</table>


Discussion

The research question from the DIF analysis asked if there was a difference in exam item performance between the students of the same ability who received a reading assignment at their Lexile level and those who did not receive a reading assignment. The research question was analyzed using the Cochran-Mantel-Haenszel and logistic regression methods to detect the difference between the two groups (RAS and NoRA) on the final exams. Final Exam Part One consisted of 44 items, and Final Exam Part Two consisted of 45 items. The results of the final exam part one show that a small percentage of the exam items exhibited DIF. This suggests that the exam was fair overall because there was no systematic advantage or disadvantage for any specific group of students. However, it is important to talk about the items that showed DIF. Items 23 and 14 showed evidence of DIF, with item 23 favoring the group of students who received scaffolded reading assignments. It 23 was a conceptual item, aligns with the questions in the reading assignments. These findings may also suggest that these items may have been easier for students who received the scaffolded reading assignments. Item 7 showed evidence of non-uniform DIF. This may suggest that the item did not favor any group. It is important to
revise these items to ensure they measure what they intended to measure and to avoid potential bias against a particular group of students. The results of Final Exam Part Two show that items 13, 21, 12, 4, 42, and 36 showed DIF in favor of the group with students who received scaffolded reading assignments, while items 23, 35, 28, 37, 39 and 40 showed DIF in favor of the group of students who did not receive reading assignments. This suggests that the scaffolded reading assignments may have influenced student exam performance on some items while having no impact on others. The results suggest that scaffolded reading assignments increase student’s exam item performance in mostly conceptual questions that overlap with topics discussed in the reading assignments. In the context of reading assignments, items that showed DIF may need to be revised. Using the natural log odds ratio and MH-DIF scales, the items were classified based on their DIF level for the items that showed DIF in final exams parts one and two. DIF of the items that favor the group of students who received scaffolded reading assignments was categorized as negligible DIF, which means there was little to no difference in how the students responded to the items. This information can be useful for educators in identifying potential bias in exams and ensuring that all students are given a fair and equal opportunity to demonstrate their knowledge and skills.

Limitations

When using a traditional DIF method, researchers and educators must agree on the items and attributes that cause DIF (Fan, 1998). Studies done by Mendes-Barnett and Ercikan (2006) found different results when studying DIF. Many other problems exist when it comes to analyzing items for DIF. The first one is the underlying cause of DIF is unknown (Stricker & Emmerich, 1997). The sample size ratio can also impact the conditions of Type 1 error; power
and estimating parameters can yield conflicting results in how DIF is identified (Lei et al., 2006). In this study, the ratio was not 50/50, and the sample size is treated as a low limit of what sample sizes are acceptable for DIF analysis. Only sample sizes that are unbalanced to 90% for the reference group and 10% for the focal group would cause a discrepancy that would affect DIF detection for the Mental-Haenszel analysis (Sedivy & Zhang, 2009).

Conclusions and Implications

This study aimed to determine if students in one group (RAS) were more likely to get an exam item correct than students with comparable ability levels in another group (NoRA). This study used the Mantel-Haenszel and the logistic regression methods to detect DIF. Statistical DIF was identified in the Mantel-Haenszel method; however, due to the limitations of this method, which is only able to identify uniform DIF, the logistic regression method was also used to identify both uniform and non-uniform DIF. The results from both methods were compared and critically analyzed to flag the items for DIF under both methods for probable sources of DIF. The items were analyzed with different methods so that the researcher could capture the many dimensions of DIF. The items were evaluated from the Mantel-Haenszel and logistic regression method to determine whether the items functioned differently between groups.

Most of the items in the Final Exam Part Two exhibited DIF, which indicates that the exam may not have been entirely fair for all the students. Six items exhibited DIF in favor of the students who received and completed reading assignments, which in a 45-item exam makes a difference of more than one grade. It is important to address the items that showed evidence of DIF in order to ensure fairness for all the students in classes where the reading assignments are implemented. We can conclude that the results of this study suggest that scaffolded
reading assignments can be effective in improving student performance in introductory chemistry. Educators should be given opportunities to learn about item attributes that can function differently based on the students’ group. Educators should also be educated on the implications of differential item functioning. Universities can develop curriculums that help train prospective teachers to identify DIF.
CHAPTER 6: SURVEYS ON STUDENT TEXTBOOK USE AND STUDENT PERCEPTIONS OF READING ASSIGNMENTS

Background and rationale

The use of surveys is a common strategy for collecting student data in chemistry courses (Brucks & Towns, 2013) conducted a national survey in general chemistry to measure laboratory goals. The goals were research experience, group work and communication, data and error analysis, the connection between lab and lecture, transferable skills, and writing. This investigation helped create a measurable learning goal that could be used to assess and improve the quality of general chemistry laboratory instruction. Surveys are commonly used in chemistry education research.

This study's purpose was to develop surveys that would help the researcher understand how students engage with and use the course textbook, what strategies they use and what difficulties they encounter when reading chemistry text. The researcher also wanted to know if students perceived the assigned reading assignments as helpful and supportive of student learning. The goal of the following data analysis then was to determine if there was a relationship between the students' self-reported pre-survey and post-survey data and the grade obtained in the course. College students find chemistry to be complicated (Sirhan, 2007), but the introductory and general chemistry sequence is essential to many STEM degrees, both at UWM and elsewhere. Student performance in these courses often correlates with the outcomes in their future chemistry courses and even other scientific endeavors Rixse, (1985). It is essential to understand how students engage with the textbook to provide the appropriate resources for their success.
In many college chemistry courses, textbooks are one of the primary teaching aids and sources from which students learn. Textbooks are also known to help instructors’ topic selection and, furthermore, provide an orientation on how a topic is taught (Martinez-Garcia et al., 2006). Many instructors rely on textbooks to decide what and how to teach, so it seems that knowing what their students struggle with, how they engage, and what strategies they use, is important, especially since science textbooks are known to be quite challenging for students. In his 1996 book, “The Chemistry Classroom” Herron mentions that “teaching chemical language is like teaching a foreign language and limiting discussion to the culture in which that language is spoken.” This is a direct connection to the different representations (symbolic, macroscopic, and particle-level) Johnstone, (1991) that students encounter in chemistry and the media (text, images, audio) in which scientific information is delivered. According to the cognitive theory of multimedia learning, learners engage in three critical cognitive processes, selecting incoming verbal information, organizing, and integrating. This theory suggests that an explanation is better presented in words and pictures together (Mayer, 1997).

**Methods and data collection**

Experimental quantitative survey data was used to determine the relationship between the students’ self-reported data on the pre-survey and post-survey and the grade they obtained in the course. A quantitative research method was used because this study focused on measuring the statistical relationship between the dependent and independent variables (Yilmaz, 2013). Descriptive statistics are presented for the comprehension of the data.

A Spearman correlation was done to determine the relationship between the dependent and independent variables. Spearman’s correlation is a nonparametric measure
determining the relationship between two ranked variables. It is computed analogously to Pearson’s $r$ correlation, except on ranked values of each variable, rather than the actual values. Like Pearson’s, Spearman’s correlation also ranges from $-1$ to $1$. Where $1$ indicates a perfect monotonic increasing relationship, and $-1$ a perfect decreasing monotonic relationship. Zero indicates there is no monotonic relationship between the variables. However, it does not require linearity of the two variables and does not assume that the variables are measured on an interval or ratio scale (Choi et al., 2010).

Correlation analyses are one of the most used statistical methods, ranging from general to specific problems (Hair, 2009). This analysis included one dependent variable, the grade obtained in the course, four independent variables for the presurvey, and three independent variables for the post-survey. A quantitative correlational survey was a desirable choice because the researcher in the (Lodico et al., 2010) study used a survey to determine the relationships between the different variables (Lodico et al., 2010, p.224). When a correlational study is done, it provides a numerical exposition of attitudes, trends, or opinions of a selected population (Creswell, 2008).

Data was obtained by administering a pre-survey and post-survey to determine the students' opinions and attitudes about the course textbook (pre-survey) and the assigned reading assignments (post-survey). The pre-survey and the post-survey can be found in Appendix D. Surveys were distributed online using Qualtrics, an online platform, allowing users to create surveys, distribute them, and analyze the responses (UWM Qualtrics). Throughout eight semesters, students received a link to the surveys through their UWM emails and the course Learning Management system. The course instructor was asked to give the survey
participant extra credit, and students earned five extra credit points for completing each survey.

The raw data from the survey was collected, cleaned, and a statistical analysis was done for each question. Descriptive statistics analysis was done to determine the percent and frequency of each question on a Likert scale. A Spearman correlation was then done to determine the relationship between each question and the grade obtained in the course.

Data was collected from 517 students (pre-survey) and 402 students (post-survey). The pre-survey data consisted of 183 low Lexile level students, 205 medium Lexile level students and 129 high Lexile level students. The post-survey consisted of 146 low Lexile level students, 157 medium Lexile level students and 99 high Lexile level students. The study also included students who participated in 5-12 reading assignments, had an ACT reading score, and completed both final exam parts one and two. Since the surveys were distributed through Qualtrics, we were able to remove the students who only skimmed through the surveys by looking at the time it took to complete each survey item. Duplicates were also removed in the cases where students submitted the same survey more than once. The cleaning process was also validated by the main professor and other graduate students who were familiar with the study.

The response rates on the pre-survey and post-survey were approximately 62%. However, only certain data was retained for analysis (see above). Only students with a recorded ACT Reading score, who had participated in the reading assignments, and who had completed the course were included in the study.
The surveys allowed the students to express their opinion on the course's assigned course textbook and reading assignments. Students were asked to select the response that best described their experience with the course textbook and the reading assignment according to a Likert scale. With the pre-survey, the students had to indicate how they engaged with the textbook, what strategies they used, the difficulties they had while reading the textbook, and what grade they expected to obtain in this course. In the post-reading assignment, the students were asked to indicate how many reading assignments they participated in, how they helped them, and what grade they expected to obtain in the course. Students took the pre-survey at the beginning of the semester starting Fall of 2019 and the post-survey at the very end of the semester, in fact the post-survey was closed after the students were done with their final exams. To increase the response rate students received email reminders.

SAS 9.4, a statistical package, was used to analyze the survey data. Means and standard deviations are computed for the survey items. The SAS code for Spearman correlation can be found in Appendix E.

When developing the surveys, it was assumed that the survey respondents would give honest responses to the questions, and that the responses would be reflective of the students’ perceptions of the textbook and reading assignments. The following research questions will be addressed.
Research questions:

Pre-Survey:

**Question 1.** What is the relationship between the grades students predicted they would obtain in the introductory chemistry course and their actual obtained course grade?

**Question 2.** What is the relationship between students’ engagement with the course textbook and the grade they obtained?

**Question 3.** What is the relationship between the students’ reading strategies when interacting with the course textbook and the grade they obtained?

**Question 4.** What is the relationship between the types of difficulties the students encountered when interacting with the course textbook and the grade they obtained?

Post-survey:

**Question 1.** (Same as pre-survey) What is the relationship between the grades students predicted they would obtain in the introductory chemistry course and their actual obtained course grade?

**Question 2.** What is the relationship between the number of reading assignments the students completed and the grade they obtained in the course?

**Question 3.** What is the relationship between the student’s thoughts on the features in the reading assignments that support their learning and the grade they obtained?

**Student survey responses**

On the pre-survey, students responded to Likert scale questions for the presurvey that were later grouped into four categories:
1. Expected grade: students selected the letter grade they expected to receive in the course.

2. Engagement with the course textbook: students indicated how frequently they used the course textbook for a variety of purposes.

3. Strategies used while engaging with the textbook: students indicated how frequently they engaged in a variety of reading behaviors while reading the textbook.

4. Difficulties encountered while engaging with the textbook: students indicated how strongly they agreed or disagreed with statements describing challenges with chemistry text.

The Likert scale questions for the post-survey were grouped into three categories:

1. Expected grade.

2. The number of reading assignments completed: students indicated the approximate number of reading assignments they had completed over the semester.

3. Opinions about features in the reading assignments: students indicated how strongly they agreed or disagreed with statements about the helpfulness of various aspects of the reading assignments and the effect of the reading assignments on their learning.

The responses were coded 1 to 5 to facilitate data analysis. Table 6.1 shows the different responses and their corresponding codes.
Table 6.1: Codes for survey responses.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Response</th>
<th>Code</th>
<th>Response</th>
<th>Code</th>
<th>Response</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (Always)</td>
<td>5</td>
<td>A (Strongly agree)</td>
<td>5</td>
<td>10 – 12 RA</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>B (Most of the time)</td>
<td>4</td>
<td>B (Somewhat agree)</td>
<td>4</td>
<td>7 – 9 RA</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>C (About half the time)</td>
<td>3</td>
<td>C (Neither agree nor disagree)</td>
<td>3</td>
<td>4 – 6 RA</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>D (Sometimes)</td>
<td>2</td>
<td>D (Somewhat disagree)</td>
<td>2</td>
<td>1 – 3 RA</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>E (Never)</td>
<td>1</td>
<td>E (Strongly disagree)</td>
<td>1</td>
<td>NA</td>
<td>1</td>
</tr>
</tbody>
</table>

Results:

The purpose of conducting a Spearman correlation was to determine the relationship between the students' self-reported data on the pre- and post-survey and the grade obtained in the course.

For all analyses, the dependent variable was the grade the students obtained in the course.

The independent variables obtained in the pre-survey were the following:

- Expected grade.
- Student engagement with the course textbook.
- Strategies used while engaging with the textbook.
- Difficulties encountered while engaging with the textbook.

Similarly, the independent variables obtained from the post-survey were the following:

- Expected grade.
- The number of reading assignments completed (self-reported)
- Opinions on features in the reading assignments

Pre-survey and Post survey self-reported grade results:

On the pre-survey, the results show that the majority (70%), of low Lexile students indicated that they expected to obtain a grade of B in the course. Most (60%) of the medium
Lexile students also indicated a B for the grade they expected to obtain in the course, and the largest portion (43%) of the high Lexile students answered that they expected to obtain an A in the course. These results are further shown in Table 6.2 and Figure 6.1.

The results of the pre-survey show that students with higher Lexile levels have higher expectations for their grades in the course. These results are consistent with the literature showing a positive relationship between reading ability and academic achievement (Pluck, 2018). It should also be noted that the low Lexile students had relatively high expectations for their grades, with the majority expecting to receive a B. This could be due to multiple factors, such as a desire to do well in the course.

Table 6.2: Frequency (%) table for pre-survey on the self-reported grade at different Lexile Levels.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>Frequency (% of students in each Lexile group)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (183)</td>
<td>5 (A) 4 (B) 3 (C) 2 (D) 1 (F)</td>
</tr>
<tr>
<td>Medium (205)</td>
<td>28 (A) 60 (B) 12 (C) 0 (D) 0 (F)</td>
</tr>
<tr>
<td>High (129)</td>
<td>43 (A) 38 (B) 19 (C) 0 (D) 0 (F)</td>
</tr>
</tbody>
</table>

Figure 6.1: Histogram of pre-survey self-reported grade

On the post-survey, for the self-reported grade, a smaller, though a sizeable portion of the low Lexile students (41%), indicated a B for the grade they expected to obtain in the course.
A similar portion of medium (49%) and high Lexile students (44%) also indicated that they expected to receive a B in the course. These results are presented in Table 6.3 and Figure 6.2. The results from the post-survey show that despite some variations between the Lexile levels, the majority of the students still expected to receive a B for their grade in the course. This could suggest that, overall, students’ expectations for their grades remained relatively consistent throughout the course.

Table 6.3: Frequency (%) for post-survey on the self-reported grade at different Lexile Levels.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>Frequency (% of students in each Lexile group)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (146)</td>
<td>5 (A) 41 38 10 1</td>
</tr>
<tr>
<td>Medium (157)</td>
<td>24 49 26 1 0</td>
</tr>
<tr>
<td>High (99)</td>
<td>26 43 29 0 0</td>
</tr>
</tbody>
</table>

Figure 6.2: Histogram of post-survey self-reported grade

**Student textbook engagement**

When students were asked how often they engaged with the textbook, the largest portion of the students at all Lexile levels, 46% of the low Lexile students, 39% of the medium Lexile students, and 30% of the high Lexile students answered that they “sometimes” did so. The results suggest that there may not be a clear relationship between how often students engage with the textbook and the grade they obtained in the course at the different Lexile
levels. This is shown by the fact that students at all the Lexile levels indicated that they only sometimes engaged with the textbook. It is also interesting to note the difference in specific types of engagement between the students at different Lexile levels. For example, low and medium Lexile level students were more likely to refer to the textbook for help with homework problems, while high Lexile students were more likely to read about concepts they were struggling with. Table 6.4 and Figure 6.3 show these results.

Table 6.4: Frequency (%) table for the student textbook engagement at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>Frequency (%) of students in each Lexile group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 (Always)</td>
</tr>
<tr>
<td>Low (183)</td>
<td>8</td>
</tr>
<tr>
<td>Medium (205)</td>
<td>7</td>
</tr>
<tr>
<td>High (129)</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 6.3: Histogram of the student textbook engagement with the textbook.

It is interesting to note the difference in specific types of engagement between the students at different Lexile levels. For example, low and medium Lexile level students were more likely to refer to the textbook for help with homework problems, while high Lexile students were more likely to read about concepts they were struggling with. Table 6.5 shows the ways in which the students at different Lexile levels were the most engaged while using the course textbook.
Table 6.5: Results from the specific types of engagement at different Lexile levels

<table>
<thead>
<tr>
<th>Lexile-level</th>
<th>Type of engagement</th>
<th>Always</th>
<th>Most of the time</th>
<th>About half the time</th>
<th>Sometimes</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Read more about concepts you are struggling with</td>
<td>8</td>
<td>8</td>
<td>21</td>
<td>42</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Find and solve practice problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Read about topics before they are covered in lecture</td>
<td>4</td>
<td>17</td>
<td>8</td>
<td>29</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Find and solve practice problems</td>
<td>8</td>
<td>8</td>
<td>17</td>
<td>46</td>
<td>21</td>
</tr>
<tr>
<td>Medium</td>
<td>Read about topics before they are covered in lecture</td>
<td>14</td>
<td>8</td>
<td>14</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Look up the definitions to unfamiliar words in the glossary</td>
<td>18</td>
<td>11</td>
<td>14</td>
<td>21</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Refer to the textbook for help in solving homework problems</td>
<td>7</td>
<td>25</td>
<td>11</td>
<td>39</td>
<td>18</td>
</tr>
<tr>
<td>High</td>
<td>Read more about concepts you are struggling with</td>
<td>10</td>
<td>40</td>
<td>10</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Read about topics before they are covered in lecture</td>
<td>15</td>
<td>20</td>
<td>15</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Look up the definitions to unfamiliar words in the glossary</td>
<td>10</td>
<td>20</td>
<td>15</td>
<td>15</td>
<td>40</td>
</tr>
</tbody>
</table>

For the low Lexile students, this was to read more about concepts they were struggling with (something 42% of the students reported doing “sometimes”) and to find and solve practice problems (46% of the low Lexile students reported doing so “sometimes”). A large portion of the low Lexile students (42%) also reported that they “never” read about topics before they were covered in lecture.

Similarly, 39% of the medium Lexile students “never” read about topics before they are covered in lecture, and 36% reported “never” looking up the definitions to unfamiliar words in the glossary. The most frequently reported behavior for this group was to refer to the textbook for help in solving homework problems, which 39% reported “sometimes” doing.

By contrast, 40% of the high Lexile students read more about concepts they were struggling with “most of the time”, and 30% reported that they “sometimes” read about topics after they were covered in lecture (though 30% also reported that they “never did so.”)
to the medium Lexile students, 40% of the high Lexile students reported that they “never” looked up the definitions to unfamiliar words in the glossary.

The differences in the results could reflect variations in learning styles or strategies among students with different reading abilities. Overall, the results suggest that instructors may need to consider a variety of factors beyond simply encouraging students to engage with the textbook to support their learning and academic success. This could include providing targeted support and resources to help students with specific areas of difficulty or providing different types of learning materials to accommodate diverse learning styles.

**Strategies used by the students while using the textbook.**

Students were also asked to indicate how often they used reading strategies while reading their course textbook. Many of the low Lexile level students (23%) answered that they “sometimes” used the strategies; but the largest portion of both the medium Lexile (30%) and high Lexile (32%) students reported “sometimes” using them. The results suggest there may be some relationship between the strategies that students use and their reading comprehension ability. These results are presented in table 6.6 and figure 6.4.

Table 6.6: Frequency (%) table for the student strategy use while using the course textbook at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile-Level</th>
<th>Frequency (% of students in each Lexile group)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (183)</td>
<td>5 (Always) 4 (most of the time) 3 (About half the time) 2 (Sometimes) 1 (Never)</td>
</tr>
<tr>
<td>Medium (205)</td>
<td>35 22 10 23 10</td>
</tr>
<tr>
<td>High (129)</td>
<td>22 9 20 30 19</td>
</tr>
</tbody>
</table>
A large minority (40%) of the low Lexile level students “never” wrote questions and comments in the margins of the text or on a separate piece of paper; but 38% of the students reported that they “sometimes” worked through practice problems, and 35% “always” took notes on the reading on a separate piece of paper.

Similarly, 34% of the medium Lexile level students “never” wrote questions and comments in the margins of the text or on a separate piece of paper, and 32% “never” wrote notes and comments explaining pictures, diagrams, and graphs. Of the medium Lexile level group, 30% reported that they “sometimes” read the whole chapter all the way through.

While a large portion (35%) of the high Lexile level students reported that they re-read certain sections of the chapter, 42% “never” highlighted important information, like main ideas or definitions; and 49% “never wrote questions and comments in the margins of the text; or on a separate piece of paper. The results show that there were differences in the specific strategy used by the students at different Lexile levels. For example, high Lexile level students were more likely to read the whole chapter all the way through and highlight important information,
while low Lexile level students were more likely to take notes on the reading on a separate piece of paper.

There may also be a relationship between the most used strategy students used when interacting with the course textbook and the grades they obtained, at least in combination with student reading ability. For example, high Lexile level students who highlighted important information and wrote questions and comments in the margins of the textbook obtained higher grades in the course than those that did not. On the other hand, low-Lexile level students who never wrote questions and comments in the margins of the text or took notes on a separate piece of paper obtained lower grades than those that did.

These results show that instructors may need to take more individualized approaches to supporting student learning and engagement based on their reading level and specific strategies and resources to help the students develop effective strategies for interacting with the textbook, which could potentially improve their academic performance. These specific strategies are shown in table 6.7.
Table 6. 7: Results of the specific types of strategies at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile-level</th>
<th>Type of strategy</th>
<th>Always</th>
<th>Most of the time</th>
<th>About half the time</th>
<th>Sometimes</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Write questions and comments in the margins of the text, or on a separate piece of paper</td>
<td>17</td>
<td>8</td>
<td>12</td>
<td>23</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Work through practice problems</td>
<td>22</td>
<td>22</td>
<td>10</td>
<td>38</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Take notes on the reading on a separate piece of paper</td>
<td>35</td>
<td>22</td>
<td>10</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>Medium</td>
<td>Write questions and comments in the margins of the text, or on a separate piece of paper</td>
<td>10</td>
<td>15</td>
<td>14</td>
<td>27</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Write notes and comments explaining pictures, diagrams, and graphs</td>
<td>10</td>
<td>25</td>
<td>15</td>
<td>18</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Read the whole chapter all the way through</td>
<td>20</td>
<td>18</td>
<td>23</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>High</td>
<td>Re-read certain sections of the chapters</td>
<td>13</td>
<td>18</td>
<td>18</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Highlight important information, like main ideas or definitions</td>
<td>23</td>
<td>23</td>
<td>8</td>
<td>4</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Write questions and comments in the margins of the text, or on a separate piece of paper</td>
<td>16</td>
<td>13</td>
<td>11</td>
<td>11</td>
<td>49</td>
</tr>
</tbody>
</table>

**Difficulties the students encountered while using the course textbook.**

The pre-survey asked students to agree or disagree with statements about the difficulties they encountered when interacting with the course textbook. A large portion of the low (48%), medium (48%), and high Lexile (63%) students indicated that they “somewhat agreed” with statements expressing difficulties with chemistry text. The majority of the students, regardless of their Lexile level, reported facing difficulties while using the textbook, such as taking a long time to read the text, focusing on the words, skimming over images, and finding the information overwhelming. This suggests that difficulties with the textbook may be a common barrier to success in the course for all the students, regardless of their reading level. Such difficulties may contribute to lower grades as they can prevent students’ ability to fully understand the material and complete the assignments accurately.
These results are presented in Table 6.8 and Figure 6.5.

Table 6.8: Frequency (%) table for the difficulties students encountered while using the course textbook at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile-Level</th>
<th>Frequency (% of students in each Lexile group)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 (Strongly agree)</td>
</tr>
<tr>
<td>Low (183)</td>
<td>2</td>
</tr>
<tr>
<td>Medium (205)</td>
<td>21</td>
</tr>
<tr>
<td>High (129)</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 6.5: Histogram the students’ difficulty while using the course textbook at different Lexile levels:

About 43% of the low Lexile-level students “somewhat agreed” that it took them a long time to read chemistry texts, and similar portions “somewhat agreed” that they mainly focus on the words when they are reading a textbook and skim over graphs and images (48%), and that they look for other explanations to understand what is going on (42%).

The medium Lexile-level students showed a similar pattern. 45% “somewhat agreed” that it took them a long time to read chemistry text, and 51% “somewhat agreed” that they mainly focused on the words when reading a textbook and skimmed over graphs and images. As well, 48% “somewhat agreed” that there was so much information on one page of a chemistry textbook that they could get overwhelmed.
In a pattern similar to the low Lexile group, 53% of the high Lexile level students “somewhat agreed” that they mainly focused on the words when reading a textbook and skimmed over graphs and images, and 49% “somewhat agreed” that they had to look for other explanations to understand what was going on. However, 49% “somewhat agreed” that they recognized all the words in their chemistry textbook from classes or other reading. Table 6.9 shows the specific types of difficulties.

Table 6.9: Results of the specific types of difficulties at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile-level</th>
<th>Type of difficulty</th>
<th>Strongly agree</th>
<th>Somewhat agree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat disagree</th>
<th>Strongly disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>It takes me a long time to read chemistry texts</td>
<td>23</td>
<td>43</td>
<td>17</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>I mostly focus on the words when I am reading a textbook, and skim over graphs and images</td>
<td>2</td>
<td>48</td>
<td>27</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Look for other explanations to understand what is going on</td>
<td>25</td>
<td>42</td>
<td>23</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Medium</td>
<td>It takes me a long time to read chemistry texts</td>
<td>22</td>
<td>45</td>
<td>22</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>I mostly focus on the words when I am reading a textbook, and skim over graphs and images</td>
<td>8</td>
<td>51</td>
<td>21</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>There is so much information on one page of a chemistry textbook that I can get overwhelmed</td>
<td>21</td>
<td>48</td>
<td>12</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>High</td>
<td>I mostly focus on the words when I am reading a textbook, and skim over graphs and images</td>
<td>5</td>
<td>53</td>
<td>12</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Look for other explanations to understand what is going on</td>
<td>12</td>
<td>49</td>
<td>21</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>I recognize all the words in my chemistry textbook from classes or other reading</td>
<td>7</td>
<td>49</td>
<td>23</td>
<td>12</td>
<td>9</td>
</tr>
</tbody>
</table>

These results show that students at different Lexile levels encountered different types of difficulties. For example, low Lexile level students may become frustrated that it takes them a long time to read chemistry texts. This indicates that instructors and course designers may
have to be mindful of the specific difficulties that students at different reading levels may face and develop strategies to address them. Overall, the results suggest that encouraging students to engage more deeply with the course textbook and giving support to overcome the difficulties they face could lead to improved academic performance. It is important for instructors to consider these results when designing courses and supporting students to ensure they have the necessary resources and strategies to succeed.

The number of reading assignments completed.

The post-survey asked students to select the range corresponding to the number of reading assignments they had completed in the course. Most low- (74%), medium- (92%), and high-Lexile students (79%) answered that they completed 10-12 reading assignments. It is worth noting that completing a certain number of reading assignments does not necessarily guarantee a certain grade in the course. There may be other factors that influence students’ performance such as the level of engagement, and comprehension of the material. These results are presented in Table 6.10 and Figure 6.6.

Table 6. 10: Frequency (%) table for the number of reading assignments students completed at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile-Level</th>
<th>Frequency (%) of students in each Lexile group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 (10 – 12)</td>
</tr>
<tr>
<td>Low (146)</td>
<td>74</td>
</tr>
<tr>
<td>Medium (157)</td>
<td>92</td>
</tr>
<tr>
<td>High (99)</td>
<td>79</td>
</tr>
</tbody>
</table>
Students' thoughts on the features in the reading assignments that support their learning.

The post-survey asked students to agree and disagree with statements about the features in the reading assignments that supported their learning.

Large portions of low (49%), medium (45%), and high (59%) Lexile level students “somewhat agreed” with this statement. The results show that the majority of students across Lexile levels somewhat agree that the features in the reading assignments supported their learning. There was no difference in the responses of the students across different Lexile levels. These results are presented in Table 6.11 and Figure 6.7. It is interesting to see that students across all Lexile levels reported that the condensed format of the reading assignments worked for them and that the reading assignments helped them understand scientific concepts. These features may be particularly effective in supporting student learning.
Table 6.11: Frequency (%) table for student thoughts on the features in the reading assignments that support their learning at different Lexile levels:

<table>
<thead>
<tr>
<th>Lexile-Level</th>
<th>Frequency (% of students in each Lexile group)</th>
<th>5 (Strongly agree)</th>
<th>4 (Somewhat agree)</th>
<th>3 (Neither agree nor disagree)</th>
<th>2 (Somewhat disagree)</th>
<th>1 (Strongly Disagree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (146)</td>
<td></td>
<td>27</td>
<td>49</td>
<td>14</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Medium (157)</td>
<td></td>
<td>27</td>
<td>45</td>
<td>13</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>High (99)</td>
<td></td>
<td>15</td>
<td>59</td>
<td>12</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 6.7: Frequency (%) chart of students’ thoughts on the features in the reading assignments that support their learning.

73% of the low-Lexile students “somewhat” or “strongly” agreed that the language of the reading assignments was more accessible, 76% “somewhat” or “strongly” agreed that the condensed format worked for them, and 60% “somewhat” or “strongly” agreed that the reading assignments helped them understand scientific concepts.

72% of the medium-Lexile students “somewhat” or “strongly” agreed that the condensed format worked for them, and 62% “somewhat” or “strongly” agreed that the reading assignments helped them understand scientific concepts. 62% also “somewhat” or “strongly” agreed that the reading assignments helped them prepare for quizzes.
74% of the high-Lexile students “somewhat” or “strongly” agreed that the embedded questions helped them look deeper into the text and 65% “somewhat” or “strongly” agreed that reading prior to lecture helped them understand the material when it was presented in lecture. 68% of these students also “somewhat” or “strongly” agreed that the language of the reading assignments was more accessible. Table 6.12 shows the specific features that the students found helpful.

Table 6.12: The specific types of features at different Lexile levels.

<table>
<thead>
<tr>
<th>Lexile-level</th>
<th>Type of features</th>
<th>Strongly agree</th>
<th>Somewhat agree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat disagree</th>
<th>Strongly disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>I found the language of the reading assignment more accessible</td>
<td>23</td>
<td>49</td>
<td>18</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>The condensed format worked for me</td>
<td>27</td>
<td>49</td>
<td>14</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>The reading assignments helped me understand scientific concepts</td>
<td>17</td>
<td>42</td>
<td>18</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>Medium</td>
<td>The condensed format worked for me</td>
<td>27</td>
<td>45</td>
<td>13</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>The reading assignments helped me understand scientific concepts</td>
<td>23</td>
<td>39</td>
<td>18</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>The reading assignments helped me prepare for quizzes</td>
<td>31</td>
<td>38</td>
<td>17</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>High</td>
<td>I found the embedded questions helpful, they made me look deeper into the text</td>
<td>15</td>
<td>59</td>
<td>12</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Reading prior to lecture helped me understand the material when it was presented in lecture</td>
<td>3</td>
<td>18</td>
<td>32</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>I found the language of the reading assignment more accessible</td>
<td>29</td>
<td>35</td>
<td>21</td>
<td>12</td>
<td>3</td>
</tr>
</tbody>
</table>

There were some differences in the features that high Lexile level students found helpful, such as the embedded questions and reading prior to lecture. This may reflect the fact that high Lexile level students have more advanced reading skills and are more able to engage with more complex reading materials.
It is interesting to see that students across all Lexile levels reported that the scaffolded reading assignments worked for them and that the reading assignments helped them understand scientific concepts. These features may be particularly effective in supporting student learning.

Statistical analysis of the survey results

Pre-Survey:
Research question 1. What is the relationship between the grades students predicted they would obtain in the introductory chemistry course and the grade they obtained in the course?

The pre-survey obtained data from 183 low, 205 medium, and 129 high Lexile participants. The variables correlated were the Likert scale responses on what grade they anticipated obtaining in the course and the actual grade they obtained in the course.

For the low-Lexile group, this correlation was significant ($r_s = 0.20$ and $p<0.0001$), but the effect size of 4% was exceedingly small, which means that the association between the grade predicted and that obtained is small. The correlation for the medium-Lexile group was not significant. The high-Lexile group, however, did have a significant correlation ($r_s = 0.25$ and $p<0.0001$), with an effect size of 6%. This shows that the association between the grade predicted and that obtained is relatively moderate. Table 6.13 shows these correlations.

Table 6.13: Spearman correlations of anticipated and actual course grade for each Lexile level

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation ($r_s$)</th>
<th>$p$</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>183</td>
<td>0.20</td>
<td>&lt;0.001</td>
<td>Small</td>
</tr>
<tr>
<td>Medium</td>
<td>205</td>
<td>-0.035</td>
<td>0.3718</td>
<td>N.S.</td>
</tr>
<tr>
<td>High</td>
<td>129</td>
<td>0.25</td>
<td>&lt;0.001</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Note: $p<0.05^*$, N.S: Not Significant, $r$: correlation coefficient, N: number of observations
Research question 2: What is the relationship between how the students engaged with the course textbook and the grade they obtained?

The overall engagement scores were correlated with the obtained course grade at each Lexile group.

For both low and medium Lexile level students, the correlations were not significant, but indicated a negative association between student engagement with the course textbook and the actual grade obtained. For the high Lexile-level students, the correlation was also not significant, but indicated a positive association between student engagement with the course textbook and the actual grade obtained. Table 6.14 shows these relationships.

Table 6.14: Spearman correlations of textbook engagement and course grade for each Lexile level.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation ($r_s$)</th>
<th>$p$</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>183</td>
<td>-0.033</td>
<td>0.694</td>
<td>N.S.</td>
</tr>
<tr>
<td>Medium</td>
<td>205</td>
<td>-0.095</td>
<td>0.1492</td>
<td>N.S.</td>
</tr>
<tr>
<td>High</td>
<td>129</td>
<td>0.079</td>
<td>0.3865</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

Note: $p<0.05^*$, N.S.: Not significant, $r$: correlation coefficient, N: number of observations

Research question 3: What is the relationship between the students' highest used strategy when interacting with the course textbook and the grade they obtained?

The Likert scale responses on the students’ highest used strategy while engaging with the course textbook were correlated with the actual grade they obtained. For the low-Lexile group, this correlation was significant ($r_s=0.092$ and $p=0.0083$) and indicated a positive association between students' highest used strategy while reading the course textbook and the actual grade obtained, though the extent of this association between these variables is exceedingly small. There was no significant correlation between the strategy students used...
while engaging with the course textbook and the actual grade obtained for members of the medium or high Lexile-level groups. Table 6.15 shows the correlations.

Table 6.15: Spearman correlations of most used reading strategy and course grade for each Lexile level

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation ($r_s$)</th>
<th>$p$</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>183</td>
<td>0.092</td>
<td>0.0083</td>
<td>Small</td>
</tr>
<tr>
<td>Medium</td>
<td>205</td>
<td>-0.002</td>
<td>0.9433</td>
<td>N.S.</td>
</tr>
<tr>
<td>High</td>
<td>129</td>
<td>0.049</td>
<td>0.2571</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

Note: $p<0.05^*$, N.s: Not significant, $r$: correlation coefficient, N: number of observations

Research question 4: What is the relationship between the highest type of difficulty the students encountered when interacting with the course textbook and the grade they obtained?

The Likert scale responses on the students' highest type of difficulty while using the course textbook were correlated to the actual grade they received in the course. For the low-Lexile group, this correlation was not significant, but indicated a negative association between the students' highest difficulty while using the course textbook and the actual grade they obtained. For both the medium- and high-Lexile groups, the correlation was significant ($r_s=0.08$ and $p=0.0267$, and $r_s=0.13$ and $p=0.0106$, respectively), and indicated a positive association between the type of difficulty the students mostly encountered while using the course textbook and the actual grade obtained. According to Cohen (1988), correlation coefficients of 0.08 and 0.13 represent weak effect sizes. Table 6.16 shows these correlations.
Table 6. 16: Spearman correlations of the type of difficulty mostly encountered when reading the course textbook and course grade for each Lexile level.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation ($r_s$)</th>
<th>$p$</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>183</td>
<td>-0.008</td>
<td>0.8559</td>
<td>N.S.</td>
</tr>
<tr>
<td>Medium</td>
<td>205</td>
<td>0.08</td>
<td>0.0267</td>
<td>Small</td>
</tr>
<tr>
<td>High</td>
<td>129</td>
<td>0.13</td>
<td>0.106</td>
<td>Small</td>
</tr>
</tbody>
</table>

Note: $p<0.05^*$, N.s: Not significant, $r$: correlation coefficient, N: number of observations

Post-survey:

Research question 1. What is the relationship between the grades students reported they would obtain in the introductory chemistry course and the grade they actually obtained in the course?

The post-survey included data from 146 low, 157 medium, and 99 high Lexile participants. The variables correlated were the responses on what grade they anticipated getting in the course and the actual grade they received in the course. This correlation was not significant for the low-Lexile participants, though it was significant for the medium ($r_s=0.24$ and $p=0.04$) and high-Lexile participants ($r_s=0.41$ and $p=0.016$). This indicated a positive association between the self-reported and actual grades obtained. Table 6.17 shows these relationships.

Table 6. 17: Spearman correlations of grade anticipated on the post-survey and actual grade obtained.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation ($r_s$)</th>
<th>$p$</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>146</td>
<td>0.19</td>
<td>0.1019</td>
<td>N.S.</td>
</tr>
<tr>
<td>Medium</td>
<td>157</td>
<td>0.24</td>
<td>0.04</td>
<td>Small</td>
</tr>
<tr>
<td>High</td>
<td>99</td>
<td>0.41</td>
<td>0.016</td>
<td>Small</td>
</tr>
</tbody>
</table>

Note: $p<0.05^*$, N.s: Not significant, $r$: correlation coefficient, N: number of observations
Research question 2. What is the relationship between the number of reading assignments the students completed and the grade they obtained in the course?

The responses on the number of reading assignments students completed were correlated with the actual grade they obtained in the course. For both the low and high Lexile group, these correlations were not significant, and indicated a negative association between the number of reading assignments completed and the actual grade students obtained in the course. For the medium Lexile group, the correlation was likewise not significant, but indicated a positive association. Table 6.18 shows these relationships.

Table 6.18: Spearman correlations of the number of reading assignments completed and actual grade obtained.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation (r_s)</th>
<th>p</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>146</td>
<td>-0.166</td>
<td>0.1580</td>
<td>N.S.</td>
</tr>
<tr>
<td>Medium</td>
<td>157</td>
<td>0.12</td>
<td>0.3</td>
<td>N.S.</td>
</tr>
<tr>
<td>High</td>
<td>99</td>
<td>-0.08</td>
<td>0.63</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

Note: p<0.05*, N.s: Not significant, r: correlation coefficient, N: number of observations

Research question 3. What is the relationship between students’ thoughts on the feature in the reading assignments that support their learning and the grade they obtained?

The Likert scale responses on the student’s thoughts on the reading assignment (if the reading assignments helped the students) were correlated with actual grade they obtained in the course. For the low Lexile students, this correlation was significant (r_s = -0.23 and p=0.05) and indicated a negative association between the student’s thoughts on the reading assignments and their actual grades in the course. According to Cohen (1988), a correlation coefficient of −0.23 represents a weak effect size.
For the medium and high Lexile groups, the correlations were not significant, but likewise suggested a negative association. Table 6.19 shows these associations.

Table 6.19: Spearman correlations of the feature that mostly helped the student from the reading assignments and actual grade obtained.

<table>
<thead>
<tr>
<th>Lexile Level</th>
<th>N</th>
<th>Correlation ($r_s$)</th>
<th>$p$</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>146</td>
<td>-0.23</td>
<td>0.05</td>
<td>Small</td>
</tr>
<tr>
<td>Medium</td>
<td>157</td>
<td>-0.13</td>
<td>0.26</td>
<td>N.S.</td>
</tr>
<tr>
<td>High</td>
<td>99</td>
<td>-0.06</td>
<td>0.6775</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

Note: $p<0.05^*$, N.S: Not significant, $r$: correlation coefficient, N: number of observations

Flow charts and tables investigating relationships and connections between student survey responses and the grades obtained:

To contribute to the survey results and the statistical analysis results, Sankey diagrams were constructed to show the relationship between the grade the students’ predicted and the grade they obtained in the course Figure 6.8, the relationship between the way students engaged with the textbook and the grade obtained in the course Figure 6.9, the relationship between the strategies the students used while using the course textbook and the grade obtained in the course Figure 6.10, the relationship between the difficulties the student encountered and the grade they obtained in the course Figure 6.11, and the relationship between the number of reading assignments the students completed and the grade obtained in the course Figure 6.12.

The results in Figure 6.8 show some discrepancies between the grade the students predicted and the grade they obtained in the course. 43% of the students in the high Lexile levels who predicted a final grade of A for themselves obtained the grade they predicted. This suggests that the students were able to evaluate their science performance. However, the
majority of the low Lexile level students who predicted a final grade of B seemed to overestimate themselves, as 27% of them obtained a final grade of D or F. None of the students in the Medium and High Lexile level predicted a grade of D or F and none of them obtained this grade which is a positive outcome from these two groups. The trend shows that as the Lexile level increases from low to medium to high, the percentage of students obtaining A and B grades also increases.

Note: green (A), Grey(B), Blue(C) and orange (D or F). The flow goes from the Lexile level to the predicted grade to the grade obtained.

Figure 6. 8: Sankey diagram of the relationship between the pre-survey predicted grade and the grade obtained.
Figure 6.9 shows that 36% of the low Lexile level students who had low engagement with the course textbook beside the assigned reading assignments obtained grades of D or F. None of the students in the medium and high Lexile levels received grades of D or F. It is important to note that 39% of the students in the low Lexile level who were highly engaged with the course textbook received higher grades.

Note: Green (High engagement), Grey (Average engagement), Blue (Low engagement). The flow goes from the Lexile level to the engagement, to the grade obtained.

Figure 6. 9: Sankey diagram of the relationship between the students’ textbook engagement and the grade they obtained in the course.
The results in Figure 6.10 show that 73% of the low Lexile level students who used strategies the most when using the course textbook obtained grades of A and B, this is similar with the medium (86%) and the high Lexile level (69%). In all the Lexile levels, students who use strategies the most when using the textbook, obtained higher grades than those with average strategy use. The students with low strategy use also obtained a grade of A and B, however most A and B grades are associated with high strategy use.

Note: Green (High strategy), Grey (Average strategy), Blue (Low strategy). The flow goes from the Lexile level to the strategy to the grade obtained.

Figure 6. 10: Sankey diagram of the relationship between the strategies the students used and the grade they obtained in the course.
In Figure 6.11 the results show that the majority of students who had high difficulty with the textbook obtained higher grades in all the Lexile levels. Among the students who found the course textbook difficult, 51% of the low Lexile level students, 36% of the medium Lexile student and 23% of the high Lexile level students obtained a grade of A respectively.

Note: Green (High difficulty), Grey (Average difficulty), Blue (Low difficulty). The flow goes from the Lexile level to the difficulty to the grade obtained.

Figure 6.11: Sankey diagram of the relationship between the difficulties the students’ encountered while using the textbook and the grade they obtained in the course.
The results in Figure 6.12 show that students who completed 10-12 reading assignments obtained higher grades (A and B), while those who completed fewer reading assignments obtained lower grades (C and D or F), at all the Lexile levels. 70% of the low Lexile level students, 78% of the medium Lexile level students and 81% of the high Lexile level students who completed 10 – 12 reading assignments obtained grades of A and B respectively.

Note: Green (10 – 12 reading assignments), Grey (7 – 9 reading assignments), Blue (4 -6 reading assignments), orange (1 -3 reading assignments). The flow goes from the Lexile level to the number of reading assignments completed, to the grade obtained.

Figure 6.12: Sankey diagram of the relationship between the number of reading assignments the students completed and the grade they obtained in the course.
Tables 6.20, 6.21, and 6.22 were created to understand how the number of reading assignments completed, the grade obtained, the text engagement, the strategy mostly used, and the difficulty the students mostly encountered while using the textbook were connected.

The findings in Table 6.20 shows that among the Low Lexile level students who completed 10-12 reading assignments, there was a high percentage of students who obtained a grade of A. These students encountered text difficulty and also engaged less with the textbook. This may mean that the students were able to overcome the difficulties that were presented in the text, which led to better performance. It should also be noted that these students also had high strategy use. This may suggest that when strategies are effectively used, it may lead to high performance.

However, most of the students who obtained a grade of B had low text engagement and low text difficulty. These students did, however, have high strategy use, which may have compensated for the low engagement and led to the achievement of a higher grade. The students would obtain a C had high text difficulty and high strategy use, which shows that they actively used strategies to help them with the text difficulty. However, they had low text engagement. The students who obtained a grade of D had low text engagement, high strategy use, and low difficulties. This shows that even though they used strategies and did not encounter difficulties, the low text engagement may have led to obtaining a lower grade.

The same pattern follows with the students who completed 7-9 reading assignments. The students who obtained a grade of A had low text engagement, high strategy use, and high text difficulty. Those that obtained a grade of B had low text engagement, high strategy use,
and high difficulty as well. The pattern is the same for the students who obtained a grade of C and D.

Table 6.20: The connection between the number of reading assignments completed, the grades obtained, the text engagement, strategy used, and the difficulty encountered while using the course textbook at the low Lexile level.

<table>
<thead>
<tr>
<th>RAs completed</th>
<th>Grade obtained (%)</th>
<th>Engagement (%)</th>
<th>Strategy (%)</th>
<th>Difficulty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Average</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>10-12 (110)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (34)</td>
<td>47</td>
<td>15</td>
<td>32</td>
<td>53</td>
</tr>
<tr>
<td>B (36)</td>
<td>84</td>
<td>8</td>
<td>8</td>
<td>39</td>
</tr>
<tr>
<td>C (8)</td>
<td>25</td>
<td>63</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>D (22)</td>
<td>50</td>
<td>14</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>7-9 (35)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (29)</td>
<td>60</td>
<td>10</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>B (17)</td>
<td>67</td>
<td>17</td>
<td>16</td>
<td>33</td>
</tr>
<tr>
<td>C (34)</td>
<td>33</td>
<td>58</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>D (20)</td>
<td>29</td>
<td>14</td>
<td>57</td>
<td>14</td>
</tr>
</tbody>
</table>

In Table 6.21, the grade distribution of the medium Lexile level students who complete 10-12 reading assignments is as follows: 41% received an A, 37% received a B, 15% a C, and 7% a D. The findings show that the students who completed 10-12 reading assignments, had high text engagement and high use of the reading strategies, obtained better grades in the course. However, even though some students experienced high difficulties while using the textbook, the results show that some were able to achieve a grade of A. The students who completed 7-9 reading assignments engaged less with the course textbook and had higher text difficulty. This may have contributed to the lower grade obtained. The results also show that some students reported high engagement (57%), low difficulty (57%) and high strategy use (57%). These results show that even if the students engaged with the course textbook, they were not aware of the difficulties with the textbook and may not have used the right strategies, because they
obtained a grade of D in the course. Many students reported text difficulty and obtained a D grade, which means these students were aware of the type of difficulty they encountered when using the textbook. They also knew what type of strategies to use even if they have low engagement. Unlike the low Lexile level students, the medium Lexile level students knew what they needed to obtain a higher grade.

Table 6.21: The connection between the number of reading assignments completed, the grades obtained, the text engagement, strategy used, and the difficulty encountered while using the course textbook at the medium Lexile level.

<table>
<thead>
<tr>
<th>RAs completed</th>
<th>Grade Obtained (%)</th>
<th>Engagement (%)</th>
<th>Strategy (%)</th>
<th>Difficulty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Average</td>
<td>High</td>
</tr>
<tr>
<td>10-12 (136)</td>
<td>A (41)</td>
<td>63</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>B (37)</td>
<td>54</td>
<td>12</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>C (15)</td>
<td>50</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>D (7)</td>
<td>70</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>7-9 (21)</td>
<td>A (24)</td>
<td>60</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B (76)</td>
<td>63</td>
<td>25</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 6.22 shows the results of high Lexile level students who completed 10-12 had low strategy use, low text engagement, and high difficulty with the course textbook. However, they obtained an A. Most students who also completed 10-12 reading assignments and obtained a B had high text engagement, low strategy use, and low difficulty with the course textbook. The majority of those who obtained a grade of C had high text difficulty, low engagement, and low strategy use. The students who completed 7-9 reading assignments had mostly low engagement, low strategy use, and high text difficulty, and none of these students obtained a grade of C or D. Like the students who completed 7-9 reading assignments, none of those who completed 4-6 reading assignments received a grade of C or D. The majority of the students who received a grade of A had low text engagement, low strategy use, and high difficulty. Those
who received a grade of B had High text engagement, high strategy use, and low difficulty. The majority of the students who obtained a D had low engagement, high strategy, and high difficulty. However, with high engagement and low difficulty, even if the strategies were low, the students who completed 6 -9 reading assignments obtained a grade of B. This shows that the high Lexile level students are also aware of the types of difficulties they have when using the textbook and the strategies to use, and how to engage with the textbook.

Table 6. 22: The connection between the number of reading assignments completed, the grades obtained, the text engagement, the strategy used, and the difficulty encountered while using the course textbook at the high Lexile level.

<table>
<thead>
<tr>
<th>Ras completed</th>
<th>Grade Obtained (%)</th>
<th>Engagement (%)</th>
<th>Strategy (%)</th>
<th>Difficulty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low     Average High</td>
<td>Low           Average High</td>
<td>Low     Average High</td>
<td></td>
</tr>
<tr>
<td>10-12 (81)</td>
<td>A (52)  60         16    24</td>
<td>45            19    36</td>
<td>36            31    33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B (30)  38         16    46</td>
<td>50            12    38</td>
<td>54            29    17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C (7)   100        0     0</td>
<td>33            17    50</td>
<td>33            17    50</td>
<td></td>
</tr>
<tr>
<td>7-9 (8)</td>
<td>D (11)  100        0     0</td>
<td>33            11    56</td>
<td>0             33    67</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A (75)  50         17    33</td>
<td>50            17    33</td>
<td>33            33    34</td>
<td></td>
</tr>
<tr>
<td>4-6 (10)</td>
<td>B (25)  0          0     100</td>
<td>100           0     0</td>
<td>50            0     50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A (30)  100        0     0</td>
<td>100           0     0</td>
<td>50            0     50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B (70)  29         14    57</td>
<td>56            19    25</td>
<td>57            13    30</td>
<td></td>
</tr>
</tbody>
</table>

Discussion

The surveys were designed to ask students if and how they read their textbooks. However, there have not been many studies correlating student responses to their course performance. This study surveyed introductory chemistry students, and a Spearman correlation was done to correlate their responses to their course grades. The pre-survey helped the researcher understand how students engage with the textbook, the strategies they use and the difficulties they encounter while using the textbook, and how this impacts their course
performance. The first pre-survey question asked if there was a relationship between the grades students mentioned they would obtain in the introductory chemistry course and the grade they obtained in the course. About 70% of the low Lexile students indicated getting a grade of B, and there was a significant correlation between the self-reported grade and the grade obtained. 43% of the high Lexile students reported a grade of A, which was also significant. 60% of the medium Lexile students also said a grade of B; however, this was not significant, and the association was negative. The results from Figure 6.8 (Sankey diagram) also that the majority of the students in all the Lexile levels were able to achieve the grades they predicted, which shows a good understanding of their academic performance and also their ability to assess their potential. It is important to note that students who predicted a grade of B overestimated themselves. There were some students in the medium and high Lexile levels who predicted a grade of D or F, but none obtained these grades which indicates a positive outcome. The trend of fewer students achieving the grade they predicted may be due to the increasing difficulty associated with higher reading levels.

The second question asked if there was a relationship between the way the students engaged with the course textbook and the grade they obtained in the course. The engagement was based on reading about topics after they are covered in lecture, reading about topics before they are covered in lecture, referring to the textbook for help in solving homework problems, reading more about concepts you are struggling with, finding, and solving practice problems, and looking up the definitions to unfamiliar words in the glossary. On average, all the Lexile levels were engaged with the textbook, sometimes low Lexile (46%), medium Lexile (39%), and high Lexile (30%). The low Lexile level students mainly engaged with the textbook by
reading about topics before they were covered in lecture, reading more about concepts you are struggling with and finding and solving practice problems. The medium Lexile level students read about topics before they were covered in lecture, referred to the textbook for help in solving homework problems and looked up the definitions of unfamiliar words in the glossary. The high Lexile level students read more about concepts they were struggling with, looked up the definitions to unfamiliar words in the glossary, and read about topics after they were covered in lecture. The findings in Figure 6.9 show that students who had low engagement with the textbook obtained higher grades compared to those with high and medium textbook engagement at all Lexile levels. These results are unexpected to what one might think, because low engagement with the course textbook should lead to low grades. However, there were also many Low Lexile level students who received grades of C, D or F despite their low textbook engagement. These findings show that while low textbook engagement may not have an effect on the academic performance of some students, it can have negative impact on students with lower reading levels.

The third question asked if there was a relationship between the students' strategies when interacting with the course textbook and the grade they obtained. The strategies were based on the following, reading the whole chapter all the way through, re-reading certain sections of the chapters, highlighting important information, like main ideas or definitions, taking notes on the reading on a separate piece of paper; writing questions and comments in the margins of the text, or on a separate piece of paper, writing notes and comments explaining pictures, diagrams, and graphs, Using the glossary, a dictionary, or other resources to find the definitions of unfamiliar words, working through practice problems in the text, and checking
the answers to practice problems. On average, the low Lexile sometimes (23%) used the strategies, and medium and high Lexile students sometimes (30%) and (32%) used the strategies. There was a significant correlation between the strategies and the grade for only the low Lexile. The strategies that the low Lexile level students mainly used were writing questions and comments in the margins of the text or on a separate piece of paper, working through practice problems and taking notes on the reading on a separate piece of paper. The medium Lexile level students wrote questions and comments in the text's margins or on a separate piece of paper, wrote notes and comments explaining pictures, diagrams, and graphs, and read the whole chapter through. The high Lexile level students read more about concepts they are struggling with, look up the definitions to unfamiliar words in the glossary and read about topics after they are covered in lecture. Figure 6.10 shows that students who used the strategies frequently when using the textbook, obtained higher grades compared to those with average strategy use. However, some students with low strategy use were able to achieve higher grades, which shows that other factors may have influenced their academic performance. This means that academic achievement is not only due to one specific thing. Factors such as engagement, strategies, the types of difficulties, the number of reading assignments completed and so much more can influence the student course performance.

The fourth question asked if there was a relationship between the types of difficulties, the students encountered when interacting with the course textbook and the grade they obtained. The difficulties were based on the students reports of the following: the amount of time it takes to read chemistry textbooks; looking for other explanations to understand what is going on; recognizing all the words in the chemistry textbook from classes or other reading;
finding it easy to interpret the symbols and math equations in the textbook; focusing on the words when reading a textbook; and skimming over graphs or images; getting test and quiz questions wrong due to misunderstanding what the question is asking; being overwhelmed by too much information on one page of a chemistry textbook; finding chemical formulas and equations in chemistry textbooks difficult to interpret; and thinking that the sentences in a chemistry textbook are too long. All three groups encountered difficulties using the textbook (approximately 45% of the time). There was a significant correlation between the perceived difficulty and the grade for the medium and high Lexile students. The difficulties that the low Lexile level students most encountered were that it took them a long time to read chemistry texts, that they mainly focused on the words when they were reading a textbook and skimmed over graphs and images; and that they looked for other explanations to understand what was going on. For the medium Lexile level students, it took them a long time to read chemistry texts, they mainly focus on the words when reading a textbook and skim over graphs and images, and there is so much information on one page of a chemistry textbook that they get overwhelmed. This shows that the low Lexile level students had challenges reading and comprehending the chemistry textbook, which shows a need for more accessible reading material for students with low reading abilities. The high Lexile level students primarily focused on the words while reading a textbook and skimmed over graphs and images. They recognized all the words in my chemistry textbook from classes or other readings but had to look for other explanations to understand what was happening. This reveals that students did not engage with the reading or use strategies, and that they encountered difficulties using the textbook. This shows that students with high reading abilities are able to make connections with their prior
knowledge and know what to look for in the course textbook. In their study, Kinsey & Munsayac (2002) found out that 93% of students in a psychology class reported that they read the whole course syllabus; however, only 22% followed the instructions in the syllabus that mentioned if the students emailed the instructor, they would get a bonus point. In Figure 6.11 the results show that all the students had difficulty with the textbook, however this did not affect the grade they obtained. This shows that some amount of difficulty or engagement with the course textbook may be beneficial for learning and academic performance, also these results show that students who encounter difficulties with the textbook are able to overcome the challenges and can perform better.

Based on the analysis of the data, the relationship between the self-reported grade and the grade obtained in the introductory chemistry course is weak for the low and medium Lexile level students. This means that even if there was a significant association between the reported grade and the grade obtained, there were other factors that influenced the final grade obtained. It is medium for the high Lexile level students. There is no statistically significant relationship between student engagement with the course textbook and the grade obtained in the course for all three groups of students. It is important to note that these results do not necessarily mean that self-reported grades and student engagement with the textbook do not affect academic performance.

The post-survey helped with understanding how the students engaged with the reading assignments and their thoughts on the features in the reading assignments that support their learning. The first post-survey question asked if there was a relationship between the grades students mentioned they would obtain in the introductory chemistry course and the grade they
obtained. On average, 41% of the low Lexile students indicated getting a grade of B, and there was no significant correlation between the self-reported grade and the grade obtained. 49% of the medium Lexile students reported a grade of B, and 44% of the high Lexile students reported a B grade, which was both significant. There was a positive association between the self-reported grades and the grade obtained for all the Lexile levels, however the effect sizes were weak for all the Lexile levels, and the coefficient of determination indicated that the extent of this association was exceedingly small. Therefore, while there is a statistically significant relationship between the self-reported grades and grade obtained, the effect size is small, which means that other factors influenced the grade obtained.

The second post-survey question asked about the relationship between the number of reading assignments the students completed and the grade they obtained in the course. 74% of the low Lexile responded 10-12, 92% of the medium Lexile 10-12, and 79% of the high Lexile 10-12. There was no significant correlation between the number of reading assignments completed and the course grade. Even though the results were not significant, Figure 6.12 shows that students who completed 10-12 reading assignments in all the Lexile levels obtained higher grades compared to those who completed fewer reading assignments. This shows that it is important to be consistent in completing the reading assignment, which leads to better academic performance.

The third post-survey question asked if there was a relationship between the student’s thoughts on the features in the reading assignments that support their learning and the grade they obtained. Approximately 45% of all the levels reported (somewhat agree) that the reading assignments helped support their learning. The correlation was not significant. For the low
Lexile level students, the highest features that supported their learning were that they found the language of the reading assignment more accessible, the condensed format worked for them, and the reading assignments helped them understand scientific concepts. For the medium Lexile level students, the condensed format worked for them, the reading assignments helped them prepare for quizzes, and the reading assignments helped them understand scientific concepts. The high Lexile level students found the embedded questions helpful; they made me look deeper into the text, they found the language of the reading assignment more accessible and reading prior to lecture helped them understand the material when it was presented in lecture. Even if the correlation was not statistically significant, approximately 40% of the students reported that the features in the reading assignments supported their learning, which shows the importance of scaffolding reading assignments and also assigning pre-lecture assignments.

The results obtained from the connection between the number of reading assignments, the grade obtained, text engagement, strategy use, and text difficulty showed that for the low Lexile level students, they were able to perform better when they completed 10-12 reading assignments despite encountering high difficulty while using the course textbook. Active use of reading strategy can help students achieve a better grade even if they had low text engagement. Strategy use and text engagement should be combined to help students achieve better grades.

For the medium Lexile level students, actively using reading strategies and high text engagement helped the students achieve better grades. Some students achieved higher grades
despite having high difficulty when using the course textbook. When may mean that frequent use of reading strategies can help overcome difficulties.

Low text engagement, low strategy use, and high difficulty did not prevent most of the high Lexile level students from obtaining higher grades. This may mean that other factors may have contributed to the success of these students. These factors could be prior knowledge or how they approached the reading. High Lexile level students had a solid foundation understanding and knowledge of the course material before taking the course. Their prior knowledge could have helped them comprehend the reading assignments and course textbook and overcome challenges with it. They may have used other effective reading strategies that may not have been captured by the provided surveys.

Limitations

This study was limited to opinions, attitudes, and perceptions of introductory chemistry students on using textbooks and reading assignments, and students may not have accurately reported their study behaviors. The study was limited to a population of introductory chemistry students and from only the University of Wisconsin-Milwaukee during specific semesters. As a researcher, I also acknowledge that there might be potential for bias in the responses the student gave.

Implications and conclusions:

Textbooks are a critical part of students learning. However, because of the specific linguistic features, science textbooks are difficult to understand (Gomes et al., 2016).

The results from the pre-survey and post-survey reveal that the low Lexile students generally obtained the grade they predicted, even if the percentage of accurate responses
decreased from the pre to the post-survey, and they encountered some text difficulties; they were able to perform better after completing 10-12 reading assignments. The results show that some students can achieve higher grades by not engaging much with the textbook or reading assignments or not always using the strategies asked. From the results of the presurvey, the students only engaged sometimes with the textbook, and the strategies were mostly used by the low Lexile students. The medium and Lexile level students never used the strategies. Also, the students engaged differently with the textbook. All the students reported encountering difficulties while using the chemistry textbook. The students in the lower Lexile who reported reading most of the time performed better in the course. When it comes to engagement with the reading assignments, most students read 10-12 reading assignments, and all the groups mentioned that reading assignments supported their learning. Even though it is generally believed that reading a textbook increases student learning, the results from the pre-survey showed that student-reported reading compliance was low. For example, in their study, Podolefsky and Finkelstein (2006) found that even if 97% of the students from introductory physics courses had access to the course textbook, only 37% reported using it regularly. In this study, 95% of the students reported having access to the course textbook; however, only about 10% said that they read the textbook regularly.

It is essential to examine the relationship between self-reported data on the use of the course textbook and the course grade obtained, as well as the relationship between self-reported data on the student’s thoughts on the reading assignments’ support of their learning and the course grade obtained. The findings in this study are intended to help instructors understand how students engage with the course textbook, what strategies they use, and what
types of difficulties they encounter. This could help instructors understand their students and know how to address their students' challenges while using science textbooks. The findings on the reading assignments could also help instructors improve when they design pre-lecture material.
CHAPTER 7: A QUALITATIVE STUDY ON SEMI-STRUCTURED INTERVIEWS

Background and rationale

According to Duschl, (2007 p.48,) doing science involves conceptual knowledge, scientific reasoning, understanding how scientific knowledge is produced, and participating in science. Even if it is known that introductory college students come into college underprepared for college instruction, they are still all assigned the same Lexile level textbook, and the lower performers could be overwhelmed by the information in the textbook. Consequently, chemistry can be viewed as a difficult subject, and only a few students choose it as their major. Students also face challenges with visual images and graphs. Such challenges include understanding concepts from illustration, deciding in what order images should be studied; judging the pertinent and superfluous information in the illustrations; determining which pieces of information from the graphics are related, integrating the related pieces of information, and extracting essential information from graphs, symbolic representations, and mathematical expression (Erin et al., 2011). These difficulties mainly affect students with lower reading abilities to a more significant extent. In this study, semi-structured interviews were conducted to understand how students read and comprehend chemistry. Focusing on students' text preferences. They were given a reading assignment not yet covered in class to read, summarize, and highlight. Through active learning strategies, students can interact with the reading material meaningfully. Active learning strategies have been used to help students with attention and increase comprehension and retention of the course material (Freeman et al., 2014). Kosslyn et al., (2017) argued that active learning was effective in helping students think deeply about the information and how students stored, organized, and retrieved information.
Studies in general chemistry found that underrepresented learners were likelier to stay in a STEM major than other well-represented peers if they performed better in the introductory course and got a passing grade (Harris, 2020).

A way to ensure active learning is by assigning pre-lecture assignments. In this study, students were asked to give their opinions on the text placement next to the images in textbooks; and about the illustrations in the reading assignments. This was done to help the researcher improve the reading assignment design and inform instructors about the students' preferences, which can help enhance textbook designs.

When students receive reading material, they activate the type of schema they think is required, and if they must read a passage and answer questions about the main idea, they stop and ask themselves what they believe should be the main points (Resnick, 1985).

To help learners comprehend and understand text, Mayer (2001) argued that people usually process information more in-depth when pictures and words are shown together than when they are shown separately. Words and pictures should be organized; if not, it may create multimedia messages that hinder learning instead of amplifying it, which would compromise the student's ability to process information (Mayer & Jackson, 2005) successfully. One of the primary purposes of CTML is to help individuals develop successful multimedia messages drawn from how the brain works and how information is processed cognitively (Mayer, 2001). The kind of information a learner processes and the types of knowledge they may create can vary considerably. To be specific; knowledge can be factual when affiliated with terms and details, it can be conceptual when it is affiliated with classifications, principles, generalizations, categories, models, theories, and structures; it can be procedural; when it is affiliated with
methods, techniques, and skills. Knowledge can also be metacognitive, for instance, when affiliated with strategies, cognitive tasks, and self-knowledge (Anderson et al., 2001; Mayer, 2011). From the viewpoint of CTML, the instructor has a role as a cognitive guide to help the learners build knowledge by leading them toward the precise information, they need to pay specific attention to and helping them organize information cognitively. (Mayer 2001, 2021).

In this study, semi-structured interviews were conducted to understand how students read and comprehend chemistry. For the purpose of the semi-structured interviews, a five-point Likert scale survey was developed to investigate how the students in introductory chemistry used their course textbook. Their input would help the researcher improve the reading assignments for future semesters. In this survey, students were asked questions on the multimedia representations, the textbook engagement, and their perception of the reading assignments. Although the surveys were used to assess the attitudes and expectations of the students, they did not effectively examine the in-depth attitudes and expectations.

**Methods and data collection**

**Survey:**

The survey was developed to allow the students to express their opinion on the course’s assigned textbook and reading assignments. The focus of the survey was on students’ preferences when it comes to multimedia representations, how the students engaged with the course textbook, and their perception of the assigned reading assignments. This survey can be found in Appendix D. For the efficiency of the data collection, most of the questions on the survey were closed-ended, 5-point Likert-type scale items. This survey was distributed through Qualtrics, and students were asked to select a response based on their preferences when it
comes to multimedia representations, how the students engaged with the course textbook, and their perception of the assigned reading assignments. This was done to allow the students to give some details. At the end of the survey, participants were asked to participate in the interview.

**Interview:**

The research was done using introductory chemistry students in the Fall of 2021. The study interviewed students on how they read and comprehended chemistry and focused on students' preferences about the course textbook. The introductory chemistry students were chosen because they represent incoming college students. During the last decades, research on science teaching and learning has focused on improving science education while emphasizing historical and philosophical perspectives related to science and including student-active learning practices (Boe et al., 2018).

Semi-structured interviews were conducted with introductory chemistry students. The interview process was selected to allow the participants the freedom to describe and elaborate on specific interview items. This enabled the interviewer to guide and direct all the responses provided by the students toward the main topic. The researcher helped facilitate the interview process with a series of questions directed and designed to gather information directly related to the research question in the study. The responses collected through the interview were intended to give the researcher detailed information that could be used during the analysis and help identify common themes among the interviewee's responses. The items in the interview were developed in a way that could contribute directly to answering the research questions. The responses collected through the interview were intended to give the researcher detailed
information that could be used during the analysis and help identify common themes among
the interviewee's responses.

According to McMillan and Schumacher (2010), one characteristic of qualitative
research is the naturally occurring behavior of the observers. In this study, the students were all
from the introductory chemistry course of the Fall of 2021 from the University of Wisconsin-
Milwaukee.

In this qualitative study, the sampling was done purposefully. Purposeful sampling
intentionally samples a group of people that can best inform the researcher about the research
phenomena being examined (Creswell & Poth, 2018). The data collected from
phenomenological studies is in the form of primarily personal, thoroughly done interviews so
that the essence of the experience perceived by the participant can be captured (McMillan &
Schumacher, 2010). The participants were all introductory chemistry students. Twelve students
participated in this study which is a good sample size to gather information for qualitative
research (Creswell, 2014). According to Creswell, (2014) & Dukes, (1984), it is recommended to
have three to ten participants; other researchers, such as Polkinghorne, (1989) recommended
conducting five to twenty-five in-depth interviews. The interviews were conducted on the
UWM campus, on the fourth floor of the chemistry building, in a room called the Science
House. Each interview began with informing the students what the interview was about, and
the participants were informed that they could stop the interview at any time if they wished to
participate no longer. The interview was recorded using a camcorder, and the researcher’s
iPhone was also used for more assurance.
UWM requires that data taken from individuals follow the Institutional Review Board (IRB) rules. This study followed UWM’s IRB guidelines for human subjects. Students who participated in this study were asked to sign IRB forms (see Appendix A). Certificates of confidentiality such as IRB are essential for keeping the privacy of research participants and the confidentiality of their data (Beskow et al., 2014). The data collected from the interview was stored on a password-protected computer, and numeric codes were used instead of the participant names.

The request to participate in the interview was sent to the student through the UWM emailing system and through a Qualtrics survey. The students were asked to participate in a reading survey, and they were asked in the survey if they were willing to participate in an interview on the textbook and reading assignments. After the students indicated they were interested in participating in the interview, they were told they would be compensated with an ACS study guide. Twelve students agreed to participate in the interviews. An e-mail was sent to the students who agreed to participate in the interview to schedule a time and date for the interview. The document contained information that explained what the students should expect during the interview and how long it would take. Data collection began from the week of the 12th to the week of the 14th in the Fall of 2021.

Purposeful sampling was done by conducting interviews with introductory chemistry students. A matrix table (See Table 7.1) was used to select the participants based on their level of performance in the course and their ACT reading scores. In the matrix, three categories of students were chosen: high-performance, low-performance, and those with No ACT score. The students were further divided within each category based on their ACT scores: high, low, or no
score. The numbers in the table represent the number of participants that were selected for the interview. By using the matrix, participants were purposefully sampled to provide valuable information on how they read and comprehend chemistry. This was done to ensure that the participants provided a more comprehensive understanding of chemistry.

<table>
<thead>
<tr>
<th></th>
<th>Low Performance</th>
<th>High Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High ACT</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Low ACT</strong></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>No ACT</strong></td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

According to McMillan & Schumucher, (2010), qualitative data analysis is primarily an inductive process where data is organized into categories, and the relationships and patterns are identified. Then according to Cresswell and Poth, (2018), three main analysis strategies, which include organization of the data, reducing the data into themes, and representing the data, are involved in qualitative research. Each interview was transcribed using Microsoft transcription software, and the data was analyzed using NVivo software. According to Saldana, 2016, NVivo is used to highlight significant statements and sentences that can provide an
understanding of how participants experience a particular phenomenon. The coding in NVivo refers to verbatim or literal coding. NVivo can capture the meaning of this phenomenon using the words that participants expressed because of its description.

After the audio transcription was done, the transcriptions were compared to the audio of the interviews to ensure accuracy. Transcription consists of accurate verbatim data following an interview (McMillan & Schumucher, 2010). After the interviews were transcribed, the next step was coding the information obtained from the students. The interview transcripts were entered into the NVivo software; this allows the researcher to begin an interactive and reflective data coding process, which allows for a close examination of the data, identifies common themes, provides a thematic analysis, and makes conclusions. The codes were entered into NVivo, which allowed the researcher to detect emergent themes. A theme emerges from coding, categorizing, and analyzing data (Saldana, 2016). Coding data begins by identifying segments of information that are relevant. Coding also allows for establishing any relevant relationships with the information presented; then, the codes are grouped to form categories, and the categories are used to find patterns. From the patterns and categories, significant themes related to the study emerge (McMillan & Schumucher, 2010).

Before coding, the researcher read the transcribed interviews to make sense of the data. This study used deductive coding, and a codebook was created based on the research questions. This method allowed the researcher to organize the text for the upcoming interpretation (Crabtree & Miller, 1992). Initially, ten broad code categories based on the theoretical framework were determined. Within each category, subcategories were developed based on research and interview questions. Table 7.2 shows the initial codes and subcategories.
<table>
<thead>
<tr>
<th>Main Codes</th>
<th>Subcategory codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>– Audio No</td>
</tr>
<tr>
<td></td>
<td>– Audio reason</td>
</tr>
<tr>
<td></td>
<td>– Audio yes helpful</td>
</tr>
<tr>
<td></td>
<td>– Audio yes unhelpful</td>
</tr>
<tr>
<td>Best Image</td>
<td>– Best image reason</td>
</tr>
<tr>
<td></td>
<td>– Image 1</td>
</tr>
<tr>
<td></td>
<td>– Image 2</td>
</tr>
<tr>
<td></td>
<td>– Image 3</td>
</tr>
<tr>
<td>Dissolving</td>
<td>– Both</td>
</tr>
<tr>
<td></td>
<td>– Macro</td>
</tr>
<tr>
<td></td>
<td>– Neither</td>
</tr>
<tr>
<td></td>
<td>– Particulate</td>
</tr>
<tr>
<td></td>
<td>– Reason dissolving</td>
</tr>
<tr>
<td>States of Matter</td>
<td>– Correct matter</td>
</tr>
<tr>
<td></td>
<td>– Incorrect matter</td>
</tr>
<tr>
<td></td>
<td>– Reason matter</td>
</tr>
<tr>
<td>Text placement</td>
<td>– Above</td>
</tr>
<tr>
<td></td>
<td>– Below</td>
</tr>
<tr>
<td></td>
<td>– Side</td>
</tr>
<tr>
<td></td>
<td>– Reason placement</td>
</tr>
<tr>
<td>Class reading engagement</td>
<td>– High engagement</td>
</tr>
<tr>
<td></td>
<td>– Low engagement</td>
</tr>
<tr>
<td></td>
<td>– No engagement</td>
</tr>
<tr>
<td>Main points</td>
<td>– Complete correct main point</td>
</tr>
<tr>
<td></td>
<td>– Gas law</td>
</tr>
<tr>
<td></td>
<td>– Incomplete correct main point</td>
</tr>
<tr>
<td></td>
<td>– Incorrect main point</td>
</tr>
<tr>
<td></td>
<td>– None</td>
</tr>
<tr>
<td></td>
<td>– Properties</td>
</tr>
<tr>
<td></td>
<td>– Relationships</td>
</tr>
<tr>
<td>Overview</td>
<td>– No overview</td>
</tr>
<tr>
<td></td>
<td>– Yes overview.</td>
</tr>
<tr>
<td></td>
<td>– Reason overview</td>
</tr>
<tr>
<td>Text experience</td>
<td>– High experience</td>
</tr>
<tr>
<td></td>
<td>– Medium experience</td>
</tr>
<tr>
<td></td>
<td>– Low experience</td>
</tr>
<tr>
<td>Text type</td>
<td>– Online text</td>
</tr>
<tr>
<td></td>
<td>– Print text</td>
</tr>
<tr>
<td>Written Summary</td>
<td>– Complete correct summary</td>
</tr>
<tr>
<td></td>
<td>– Incomplete correct summary</td>
</tr>
<tr>
<td></td>
<td>– Incomplete</td>
</tr>
</tbody>
</table>
Codes were not communicated to the participants in the interview but used for analysis; however, the interview questions' nature and direction were able to give in-depth descriptions of their collaborative learning experiences.

Member checking was used in parts of the interview during the interview. The process of member checking is when the researcher asks the participants in the study to verify the accuracy of the data collected for an increase in validity. When member check happens, researchers must report the findings and confirm the report's accuracy (Candela, 2019). While being interviewed, the researchers asked the participants to verify certain information.

According to Stiles, 1993, types of validity important to qualitative research include uncovering or self-evidence, coherence, testimonial validity, catalytic validity, reflective validity, and consensus among researchers. In this study, both accords among researchers and catalytic validity were addressed. Catalytic validity is explained as how the research focuses, energizes, and reorients the participants of the study (Stiles, 1993).

In this study, interrater or intercoder reliability was achieved by having the leading professor and another researcher assist in the data collection and analysis. According to Creswell 2014, interrater or intercoder reliability involves having independent coders or peers review and compare codes created by the researcher to determine their agreement level. This process increases the study's external validity and gives a broader perspective of the results; it also shows the consistency of the results. The leading professor, graduate student, and researcher reviewed the transcriptions and coded the data. After the data was coded, the results were compared, discrepancies were discussed, and a consensus was reached. This process is called investigator triangulation; when this process is used, more than one person is
used in the research (Denzin, 1970). Credibility and dependability are addressed during the process of triangulation. Credibility happens when results are accurate, trustworthy, and reasonable (McMillan & Schumucher, 2010). Also, trustworthiness in this study was attained by allowing another researcher and professor to review the transcribed notes after the interview.

**Research questions:**

**Question 1:** what are students' perspectives on the multimedia illustrations in the textbook and reading assignments?

**Question 2:** How do students engage with the textbook? Does their engagement with the text lead to correct summaries?

**Question 3:** How do students perceive the structure of the reading assignment used during the interview regarding the main point and the overview, and do they understand the text?

To answer these questions, 11 interview questions were developed through the lens of the theoretical framework in Chapter 2. The interview questions were presented to two other people, the leading professor and another graduate student working on a similar project for validation, and the three researchers came to a consensus that the questions were valid and useful as data-collection instruments. These interview questions were used as the data collection instrument. A practice interview was also done to help the researcher practice, strengthen the way the interview was designed, and test the instrument (Majid et al., 2017). The insights gained from the practice interview were utilized to improve and fine-tune the interview questions, which resulted in a well-designed instrument that could provide extensive data. The practice interview was done by interviewing another graduate student from the
chemistry department in the chemistry education division. This student had knowledge and experience with the type of data that was being collected.

**Research question 1: Multimedia Illustrations**

The first research question examined students' perspectives on the multimedia illustrations in the textbook and reading assignments. To deeply understand the students' perspectives, five interview questions were developed.

- **Interview question 1**: Did you use the audio option embedded in the text? Did you find the embedded audio narrative helpful?

- **Interview question 2**: Here is an image and some text describing the image. Where would you put the text and labels to make the image easier to understand?

- **Interview question 3**: What do you think this image shows?

- **Interview question 4**: In your personal opinion, which of the images below illustrate the process of dissolving best?
Interview question 5: Which image best describes the preparation of an aqueous solution (copper (II) sulfate in water)? Please choose the image that provides you with enough information about the solution preparation.

1. [Beaker with water, Copper (II) sulfate powder, Solution of water and copper (II) sulfate]

2. [A scientist pours copper (II) sulfate powder into a small beaker containing water. The copper (II) sulfate powder dissolves in the water to form a solution of water and copper (II) sulfate.]

3. [As the scientist starts pouring the blue copper (II) sulfate powder into the beaker containing water, it starts to dissolve, and a blue solution of water and copper (II) sulfate is formed. An equation of the process is written as such: \( \text{Cu}^{2+}\text{SO}_4^{2-}\cdot7\text{H}_2\text{O}(s) + \text{H}_2\text{O}(l) \rightarrow \text{Cu}^{2+}(aq) + \text{SO}_4^{2-}(aq) \) The blue solid means the copper (II) sulfate is a hydrate. That’s why the \( \text{H}_2\text{O} \) is added. When copper (III) sulfate pentahydrate reacts with water, the \( \text{Cu}^{2+} \) ions and the \( \text{SO}_4^{2-} \) ions dissociate. The products are aqueous \( \text{Cu}^{2+} \) and aqueous \( \text{SO}_4^{2-} \). The aqueous means they are in water.
Research question 2: Engagement

How do students engage with the textbook? Does their engagement with the text lead to correct summaries? To deeply understand how the students engaged with the textbook, four interview questions were developed.

- **Interview question 1**: When you read texts for school now, how do you do it?
- **Interview question 2**: Did you read textbooks or reading assignments much in your previous classes?
- **Interview question 3**: Do you have an online or print textbook?
- **Interview question 4**: What does it mean to write a summary? What do you usually include when you summarize?

Research question 3: Perception of the reading assignment

How do students perceive the overview and the structure of the reading assignment used during the interview? Do they understand the text and its main point? To deeply understand how the students perceive the structure of the reading assignment used during the interview regarding the main point and the overview, and if they understand the text. Two interview questions were developed.

- **Interview question 1**: Did you find the overview helpful in understanding what the reading assignment was about?
- **Interview questions 2**: What do you think are the main points a student should learn from this reading?
Results

The purpose of this qualitative study was to understand how introductory chemistry students read and comprehend chemistry. To understand this phenomenon, students were asked questions on the embedded audio, the choice of images, the state of matter, text placement, how they engaged with the course textbook, what the main point was in the reading used during the interview, and what type of textbook they have.

Research questions:

- **Question 1**: what are students' perspectives on the multimedia illustrations in the textbook and reading assignments?

- **Question 2**: How do students engage with the textbook? Does their engagement with the text lead to correct summaries?

- **Question 3**: How do students perceive the structure of the reading assignment used during the interview regarding the main point and the overview, and do they understand the text?

**Research Question 1: Multimedia Illustrations**

The first research question examined students' perspectives on the multimedia illustrations in the textbook and reading assignments. To deeply understand the students' perspectives, five interview questions were developed.

- **Interview question 1**: Did you use the audio option embedded in the text? Did you find the embedded audio narrative helpful?

Of the participants that used the audio, 50% of the participants reported not using the audio embedded in the text, and 50% reported using the audio and finding it helpful. Adding
audio narration helps students that learn from both audio and text; in this study, the narration was delivered by a friendly female voice, in accordance with multimedia principles. As Mayer (2010) stated, people learn best when the narration in multimedia lessons is delivered in a friendly human voice instead of a machine voice. High-and low-performing students showed equal preference for the audio. These results are also consistent with the results from the survey as 73% of the students reported finding the audio helpful in the survey. The relevant statement from participant AR402 suggests that some students may prefer audio over reading and find it easier to learn through listening. Even if the sample size was small, the results suggest that providing an audio option in reading materials may be beneficial for some students. This may be particularly useful for students who are auditory learners or who have difficulty with reading comprehension. It is also important to note that not all students may find the audio option helpful, and some may still prefer reading the text. Providing multiple options for accessing the same content, such as both text and audio formats, can help students with learning preferences and abilities. Table 7.3 provides supporting data for the audio code.

Table 7.3: Supporting statements for the Audio code.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR402 (High performance)</td>
<td>“I wish there was more audio. Actually, I wish there was an option to just have the whole thing read. But I’m more of an audio learner, so for me, it’s easier to listen to it than it is to sit there and try to read it”</td>
</tr>
</tbody>
</table>

Interview question 2: Here is an image and some text describing the image. Where would you put the text and labels to make the image easier to understand?
Of the participants, 7 preferred the text placed below the image. The main reason for this is that it allows for a natural reading flow, as students tend to read from top to bottom. Also, having the text below the image allows for easy reference to the image, as it reinforces what is being shown in the image. 4 students preferred the text placed above the image, and 1 preferred the text on the side of the image. The reason for the preference of the text on the side is not entirely clear, but it seems to be related to capturing attention. Regardless of the place the text is placed, students value having descriptive text next to the image. In the survey, about 42% of the high performers preferred the next to the image, and 44% of the low performers preferred the text next to the image or inside the image. As stated in the multimedia principle, People learn best from words and images than from words alone (Mayer 2010). Students have different preferences on where they would prefer the text placed. However, one thing that can be agreed upon is that both the high and low performers prefer having both the image and image description. Table 7.4 provides supporting data on the text placement.
Table 7.4: Supporting statements for the text placement.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subcode: Above</strong></td>
<td></td>
</tr>
<tr>
<td>EW404 (High performance)</td>
<td>“On top would work as well. I just, I don’t know why, I prefer it to the left and to the bottom of it. Um, I read like this, I mean most people do read down, yeah, Uhm, so that’s kind of nice, especially sometimes there are multiple pictures in textbooks, and so you know if there is another picture up here, it might, I might wonder, “are these both showing that?” or “which is this for?” Uhm, but having something either right next to, like on either side, usually has been less confusing to me than having it directly below or above the picture”.</td>
</tr>
<tr>
<td><strong>Subcode: Below</strong></td>
<td></td>
</tr>
<tr>
<td>LK404 (High performance)</td>
<td>“I would prefer it on the bottom. Just so I can see that and make assumptions on what I think it might be, and then when I look to the bottom, I’m like, “oh, this is what this image is showing,” ’Cause I feel like the universal—like, a figure, you always have the figure thing on the bottom, so that’s where I automatically look for information on it, too, instead of, like, searching around.”</td>
</tr>
<tr>
<td><strong>Subcode: Side</strong></td>
<td></td>
</tr>
<tr>
<td>WL404 (Low performance)</td>
<td>“I feel like it just captures your attention more a little bit here. If it’s, like, on the side, it’s like, weird, I don’t know”.</td>
</tr>
</tbody>
</table>

– **Interview question 3:** What do you think this image shows?

![Image of molecular structures]

Of the participants, 100% reported the correct states of matter. The participants recognized that the image showed the states of matter, solid, liquid, and gas. The students have seen this concept before in similar images and used their prior knowledge to answer the question; they are able to retrieve information from memory. The high-performing students provided more detailed descriptions of the states of matter, highlighting characteristics such as the structure of solids, the movement of molecules in the liquids, and the randomness of the gas particles. The low-performing students also demonstrated an understanding of the states of matter but provided less detailed descriptions. These results are consistent with the survey results as the majority of both the high performing and low performing students were able to
identify the states of matter. Table 7.5 provides supporting data on how all the participants were able to pick the correct answer.

Table 7.5: Supporting statements for states of matter.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR402 (High performance)</td>
<td>“It's just been, like, pounded into our heads. So, I recognize, like, the concept at this point.”</td>
</tr>
<tr>
<td>EW404 (High performance)</td>
<td>“Well, in a solid it's a very...it just has—like I don’t remember what the structure is called—like a very, like, organized structure. Then a liquid, you know, they’re kind of like spread out a little more, they’re, like, moving around a little bit, where these are more, like, static. And then gaseous it is, like, all over the place”.</td>
</tr>
<tr>
<td>KF402 (Low performance)</td>
<td>“Uhm, well, because I know that solids are rigid; liquids tend to, you know, kind of move around; and with gas there's not as much--there's not as many atoms in a space as liquids”.</td>
</tr>
</tbody>
</table>

- **Interview question 4:** In your personal opinion, which of the images below illustrate the process of dissolving best?

Of the participants, six preferred the particulate image because it shows the different molecules and particles inside something, making it easier to visualize the process of them being combined or mixed with each other. Four preferred the macroscopic image because it is a real-life example, which they found more relatable. One student saw value in both images because they cater to different audiences, the particulate image for those who need a more scientific view, and the macroscopic image for those who want a less science view. One
participant was not content with either image, suggesting that multiple photos showing the changing of the molecules would be more helpful in understanding the process of dissolving. The survey results showed that 68% of the high performing students preferred a combination of both and 69% of the low performing students preferred the particulate image. This suggests that there might be room for improvement in the way scientific concepts are illustrated, especially for those who are less familiar with the subject. The results show that some of the low performers are novices to certain concepts on chemistry. According to Biggs & Collis, (1982); DiSessa, (2006) the organization of conceptual structures is one attribute that tells novices apart from experts. Novices have their knowledge fragmented or not connected, and according to Chi et al., (1982) experts' knowledge is structured and organized around central concepts and principles in a way that helps their way of thinking and allows them to use their knowledge in new situations. These findings highlight that there is a need for more effective ways of illustrating scientific concepts to learners who may not be familiar with chemistry. Table 7.6 provides supporting data on the participant's preferences for the different images
Table 7.6: Supporting statements for Dissolving.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subcode: Particulate</strong></td>
<td></td>
</tr>
<tr>
<td>AR402 (high performance)</td>
<td>“Uhm, because you can actually see the atoms separated and surrounded by the water molecules. Versus this, it's just a blue liquid; we don't even know what is in that”.</td>
</tr>
<tr>
<td>KES403 (Low performance)</td>
<td>“So, if you’re just given this picture, it just ... at first glance it kind of just looks like you’re pouring a liquid from a small cup into a bigger cup, and so if you’re looking at the process of something dissolving, just looking at that might not make sense or give enough of, like, a visual aid to show, you know, dissolving is one too things... Something dissolves, or mixes into something else. Like if this had been yellow and this had been blue and you start to see green, like that might have been easier or more helpful, but since they’re both blue... Yeah, I don't think it does anything. But this shows you different molecules and particles inside something, so you can kind of see them starting to be combined or mixed with each other”.</td>
</tr>
<tr>
<td><strong>Subcode: Macroscopic</strong></td>
<td></td>
</tr>
<tr>
<td>LJ402 (Low performance)</td>
<td>“Because it’s a real-life example and I do have a preference for having real-life examples shown to me. But this one is also, like, a very scientific way of showing it, and maybe it’s not as understandable to somebody who's going into a Chem-100 class”.</td>
</tr>
<tr>
<td><strong>Subcode: Both</strong>                                                                ITHER sided with science. So, someone who isn't as familiar with the subject can kind of relate the two. And that one because it is more science-y, and someone who's taking a science class, a chemistry class, needs to know what it looks like. So, it might just make it easier to correlate the two”.</td>
<td></td>
</tr>
<tr>
<td>KF402 (Low performance)</td>
<td>“Well, cause this one, you know, gives a more...not-science-y view. So, someone who isn't as familiar with the subject can kind of relate the two. And that one because it is more science-y, and someone who's taking a science class, a chemistry class, needs to know what it looks like. So, it might just make it easier to correlate the two”.</td>
</tr>
<tr>
<td><strong>Subcode: Neither</strong></td>
<td></td>
</tr>
<tr>
<td>AB404 (High performance)</td>
<td>“If they had, like, multiple photos where it goes into the process.... Like it Shows this, then this, then this, like the changing of the molecules, that's much more helpful. Like, this, this is just blue and blue. And then this is just like, a photo of molecules, like, it's not showing the process”.</td>
</tr>
</tbody>
</table>

- **Interview question 5**: Which image best describes the preparation of an aqueous solution (copper (II) sulfate in water)? Please choose the image that provides you with enough information about the solution preparation.
Of the participants, five preferred Image 1 which gives a step-by-step visual representation of the solution making process. Four preferred Image 2, which includes both images and text to give a better understanding of the process, and three preferred Image 3 which gives a detailed chemical equation along with an image. Having images that show the step-by-step process. (Image 1) was preferred for the visual representation, but the explanation (Image 3) gave a deeper understanding of the process. The same as with the results on dissolving, the low performers are novices to certain chemistry concepts, and the high performers can use their prior knowledge when presented with new material. The preferences of the participants seemed to be related to their individual learning styles and prior knowledge.
of chemistry. Participants who preferred Image 1 often mentioned that it was easy to understand and provided a quick visual overview of the process. On the other hand, participants who preferred Image 2 often mentioned that the combination of text and image helped them understand the process better, especially if they were not familiar with the concept of dissolving. Finally, participants who preferred image 3 mentioned that the chemical equation provided additional detail that helped them understand the process at a deeper level. The survey results showed that most high-performers preferred Image 3 and most low-performers preferred Images 1 or 2. According to Biggs & Collis, (1982); DiSessa, (2006) the organization of conceptual structures is one attribute that tells novices apart from experts. Novices have their knowledge fragmented or not connected, and according to Chi et al., (1982) to experts' knowledge is structured and organized around central concepts and principles in a way that helps their way of thinking and allows them to use their knowledge in new situations. Table 7.7 provides supporting data for the selection of the images.
Table 7.7: Supporting statements for the best image.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subcode: Image 1</strong></td>
<td></td>
</tr>
<tr>
<td>LK404 (High performance)</td>
<td>“Just, like, briefly looking at them, I feel like the one on the left catches my eye the most, just because it’s step-by-step what’s happening, and I don’t have to read a lot. You know what I mean? So, when I look at a big paragraph, it’s kind of intimidating, and I feel like I have a hard time, like, finding what I need actually out of this. And besides that, like, taking the time to actually go through it--cause most of the time when I read, I just, kind of, try to skim as much as I can”.</td>
</tr>
<tr>
<td><strong>Subcode: Image 2</strong></td>
<td></td>
</tr>
<tr>
<td>KES403 (Low performance)</td>
<td>“At the same time, the first picture with only the three textbox and three pictures? I mean, it makes sense to me, because I know what, like, dissolving is, but I don’t think it’s enough information. If somebody has never heard about dissolving anything. But like visually, I do like the three pictures. This text box I like, because it’s saying they pour “copper sulfate from a small beaker into a larger beaker containing water” and you can see that this one is smaller and this is large, so you can put those two together. It’s saying, you know, it forms a mixture of water and copper sulfate. So, I think this one, for me personally. If you had never heard of this, I feel like this would do the trick”.</td>
</tr>
<tr>
<td><strong>Subcode: Image 3</strong></td>
<td></td>
</tr>
<tr>
<td>AMH403 (Low performance)</td>
<td>“Because it gives a deeper, um, meaning and explanation of what's going on, especially the written chemical equation”.</td>
</tr>
<tr>
<td>AR402 (High performance)</td>
<td>“I like this description because it’s more detailed. It actually gives you the chemical formula and everything”.</td>
</tr>
</tbody>
</table>

Research question 2: Engagement

How do students engage with the textbook? Does their engagement with the text lead to correct summaries? To deeply understand how the students engaged with the textbook, four interview questions were developed.

- **Interview question 1**: When you read texts for school now, how do you do it?

  Of the participants, seven (high engagement) reported annotating, highlighting, and taking notes. Five (low engagement) reported reading but not annotating, highlighting, or taking notes. The high-engagement students worked to understand the concepts they were not familiar with, and they appear to be more proactive in seeking out clarification on concepts they did not understand. The low-engagement students mostly skimmed through the reading,
and they seemed to rely on listening to lecture and taking quizzes to understand the material. The low and high performers used different strategies and types of engagements when reading. Both low and high performers were found in the low and high engagement subgroups, the difference was that the low performers mostly worked on taking notes of the concepts they were struggling with or just skimmed without using any strategy due to them being novices, and high performers through the material and looked at specific things for deeper understanding. The survey results showed that most low and high performers engaged with the textbook sometimes. Table 7.8 provides supporting data for the class reading engagement.

Table 7.8: Supporting statements for the class reading engagement.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subcode: high engagement</strong></td>
<td></td>
</tr>
<tr>
<td>KES403 (Low performance)</td>
<td>“Sometimes, it depends. On certain units, if they are concepts that I feel are familiar, or that—when I’m doing the reading—I do understand, I might not take any. But, as of recently, a lot of them are much more new, or things that I struggle with, so I will take notes”.</td>
</tr>
<tr>
<td>KF402 (Low performance)</td>
<td>“Uhm, so I listen...I write down the notes first the day before the lecture and then most of the time I’ll go to the lecture, if I don’t think that I have a super strong grasp on this subject. And then, once that’s done, I will go back over the book and try and cover anything that I still don’t quite understand”.</td>
</tr>
<tr>
<td><strong>Subcode: Low engagement</strong></td>
<td></td>
</tr>
<tr>
<td>WL404 (Low performance)</td>
<td>I’ll be honest, I’m usually just skimming through whatever she does, just do, and then I’ll take the quiz.</td>
</tr>
<tr>
<td>MK403 (High performance)</td>
<td>Typically, what I do is--like, for example with their reading quizzes that we do in the chemistry course—I’ll read through it, or skim through it once to make sure that I understand, “this is what the chapter is about.” And then I will look for the specific questions that don’t make sense to me, or kind of read deeper if I need to on things that don’t make sense.</td>
</tr>
</tbody>
</table>

- **Interview question 2:** Did you read textbooks or reading assignments much in your previous classes?

Of the participants, four of those with high text experience reported reading the textbooks or reading assignments in science classes and using the activities in class. Six of those with low text experience reported very little prior science reading. Two of those with medium
text experience reported reading before but did not do much with the reading. Text experience reflects prior science reading. Participants with high text experience reported reading textbooks or assignments and using the activities in science classes. Those with low text experience reported very little prior science reading. The two participants with medium text experience reported reading but did not use many strategies. The results suggest that prior text experience may be an important factor in student’s academic performance, particularly in science classes.

Students who have prior text experience reading textbooks and completing reading assignments may be better prepared to understand and retain the material presented in class. Students who lack prior text experience may struggle to keep up with the material and may require more support to succeed. The survey results showed that the text experience varied between the high and low performers, just like the interview results. Table 7.9 provides supporting data on text experience.

Table 7.9: Supporting statements for the text experience.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subcode: High experience</strong></td>
<td></td>
</tr>
<tr>
<td>KF402 (Low performance)</td>
<td>“Oh, yeah. I--you know, in college I’d taken biology, astronomy--astronomy, not astrology?--and a couple others, and I was in--I went to ITA down in Kenosha, and I was in their Biotech house which had, like, all AP science classes so we did a lot of reading there too”.</td>
</tr>
<tr>
<td>LJ402 (Low performance)</td>
<td>“Yeah, we had a textbook, we had reading assignments and then, worksheets and things like that as well”.</td>
</tr>
<tr>
<td><strong>Subcode: Medium experience</strong></td>
<td></td>
</tr>
<tr>
<td>MK403 (High performance)</td>
<td>“I would pretty much only refer to the textbook when I needed to. So only if, like I was really, really confused on something or if the teacher had specifically assigned something in the textbook. Beyond that, textbook material didn’t make as much sense to me as, like, a teacher explaining something to me”.</td>
</tr>
<tr>
<td><strong>Subcode: Low experience</strong></td>
<td></td>
</tr>
<tr>
<td>KES403 (Low performance)</td>
<td>“We didn’t... Yeah, no, we didn’t have a textbook in high school. Like, we didn’t have to take one for ourself, our teacher had a textbook that she would just put on the smart board and we kind of take notes from that or PowerPoints, but never a physical copy”.</td>
</tr>
</tbody>
</table>
Interview question 3: Do you have an online or print textbook?

Of the participants, ten reported using an online textbook, and two reported using printed text. Most of the students opted for the online book because it is easy to access and cheaper. Participants that used the online version reported doing this because of convenience and affordability. These results are consistent with the findings in the literature on e-textbooks. In their study, Sun et al., (2012) found that e-textbooks influenced student learning experiences. However, this depended on how they were involved in using the e-textbook during instruction. It is also worth noting that some students may have opted for the physical copy of the textbook, and even the low-performing student who opted for the online version still would prefer the physical copy. This could be just a personal preference for physical material, or they have difficulties with reading on the screen. These results are consistent with the results from the survey used to recruit the students for the interview. Table 7.10 provides supporting data on the text type.

Table 7.10: Supporting statements for the text type.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code: Text type</td>
<td></td>
</tr>
<tr>
<td>Subcode: Online text</td>
<td></td>
</tr>
<tr>
<td>LJ402 (Low performance)</td>
<td>“Uhm, so I ended up opting for the online textbook instead of getting like a physical copy. And I do, like, regret not getting a physical copy. Because it is easier for me to, like, read that way, but obviously it’s more expensive, so.... “</td>
</tr>
<tr>
<td>Subcode: Print text</td>
<td></td>
</tr>
<tr>
<td>KF402 (Low performance)</td>
<td>A physical one</td>
</tr>
</tbody>
</table>

Interview question 4: What does it mean to write a summary? What do you usually include when you summarize?

Of the participants, six summarized the text correctly, and two summarized the text incorrectly. A correct summary would have been a brief, accurate summary of what the text
was about, while including the main ideas and key points of the text. An incorrect summary would be one, irrelevant and unnecessary information about the text. These results show that some students can read and comprehend, while some struggle with summarizing what they are reading. While some students were able to read and comprehend effectively, others may struggle with summarizing. Participant MK403, who is a high performer, highlighted the specific things that were important and left out the other explanations leading to key concepts. Participant LJ402, who is a low performer, stated that a summary is a brief description of what the full text says without providing any specific details or key concepts. Participant AB404, who is a high performer, provided an incorrect summary that did not relate to the original text. Participant AB404 focused on understanding the basic laws and how they relate to each other and “the ideal thing”, which was related to the original text, but the participant did not give much detail. The results highlight the importance of assessing student reading comprehension to ensure that students capture the most important information from a reading. The results also show that it may be necessary to provide low-performing students with feedback, and instruction that can help ensure that the students have the necessary skills to succeed in their courses. Table 7.11 provides supporting data on the summary.
Table 7. 11: Supporting statements for the summary.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant statements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Code: summary</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Subcode: correct summary</strong></td>
<td></td>
</tr>
<tr>
<td>MK403 (High performance)</td>
<td>“So, what I did is I highlighted the specific things that I thought were important, and then in my summary I hit on all those specific things. So, I kind of left out the other explanations leading up to those key concepts and included just the key concepts in the summary”.</td>
</tr>
<tr>
<td>LJ402 (Low performance)</td>
<td>“So, it means a brief, like, description of what the full text says. So, obviously, the first page had a, like a whole paragraph to explain that like there's four factors that can be related to the volume”.</td>
</tr>
<tr>
<td><strong>Subcode: incorrect summary</strong></td>
<td></td>
</tr>
<tr>
<td>AB404 (High performance)</td>
<td>“Yeah, I would say the laws, and how they relate to each other as well”. I don’t know, it’s just what I’m thinking. Which, also...But then we’d also want to know, like... Yeah, I would say both, actually, I know it’s like, not answering, but like, I would say, understanding all of the basic laws, and then understanding as well, like how they relate to each other and then also understanding the ideal thing.</td>
</tr>
</tbody>
</table>

Research question 3: Perception of the reading assignment

How do students perceive the overview and the structure of the reading assignment used during the interview? Do they understand the text and its main point? Two interview questions were developed.

- **Interview question 1:** Did you find the overview helpful in understanding what the reading assignment was about?

Of the participants, nine reported that the overview was helpful in providing an idea of what to expect while reading and what to look for. Participant AR402, who is a high performer, even used the overview to create their summary and found that the overview simplified the text. 3 students did not find the overview helpful. Participant LK404, who is a low performer, found that the information provided in the overview was not useful and did not help in their understanding of the text. These results show that having an overview helps many students understand what to expect in the reading. The results show that providing an overview is helpful for most students, and the low performers seem to find it the most useful. The students
that found the overview helpful reported that it helped them identify the key topics, concepts, and information they needed to focus on while reading. Those that did not find the overview helpful reported that they did not obtain any new information or insights from it, so they preferred to skip it and focus on the text. Table 7.12 provides supporting data on the overview.

Table 7.12: Supporting statements for the overview.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Relevant Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MO403 (Low performance)</td>
<td>“I mean, it kind of gave you, like, what you expect while you were reading it. And just, like, what to look out for. And, generally, things that are in the overview are going to be important to remember”.</td>
</tr>
<tr>
<td>LJ402 (Low performance)</td>
<td>“Yes, I like, knew what to...what we were talking about. So, volume, temperature, pressure, and the amount of gas”.</td>
</tr>
<tr>
<td>AR402 (High performance)</td>
<td>“Yes, that was kind of where I pulled my summary from. Yeah, it makes things a lot more simple than the rest of the text, honestly.”</td>
</tr>
<tr>
<td>LK404 (High performance)</td>
<td>“I personally don't find them super helpful: it's kind of like, “hey, this is what I'm getting into,” but I don't find, like, much information in there that I'll actually use, so…..”</td>
</tr>
</tbody>
</table>

Interview questions 2: What do you think are the main points a student should learn from this reading?

Of the participants, one gave the complete, correct main points in the reading assignment, and 6 gave the incomplete correct main points (Ideal gas laws, properties, and relationships). These results show that most students do not fully comprehend what they are reading. It is possible that the students may not have fully engaged with the reading or did not have the background knowledge to fully comprehend the concepts presented in the reading. It may also be possible that the reading's complexity was challenging, even for the high-performing students. Table 7.13 provides supporting data to the main points.
Table 7. 13: Supporting statements for the main points.

<table>
<thead>
<tr>
<th>Participants Subcode: correct main point</th>
<th>Relevant Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MO403 (Low performance)</td>
<td>“The three, er, 3 rules of like, what gas particles are. And then the types of gas laws. Um, Boyle’s, Charles, and Avro-Avogadro’s. And then what the Ideal gas law actually is”.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Participants Subcode: incomplete correct main point</th>
<th>Relevant Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK403 (High performance)</td>
<td>“The specific variables that that affect the properties of gases; how gases interact with other gases or with itself; um, the specific mathematical relationships of gases; and how those variables interact with those relationships”.</td>
</tr>
</tbody>
</table>

Discussion

This qualitative study's purpose was to collect more detailed data on how the students engaged with science text and to understand student preferences on its delivery and structure. The interview focused on students' preferences about the introductory course textbook and the pre-instruction reading assignments. It was important to get first-hand responses from a selection of introductory chemistry students, since they represented the variety of incoming students, some potentially underprepared for college and college reading.

The findings of Research Question 1 show that multimedia learning is essential for student learning. Mayer (2001) argued that people usually process information in more depth when pictures and words are shown together than when they are shown separately. He described this as the Multimedia Principle. One of the primary purposes of the cognitive theory of multimedia learning (CTML) is to help individuals develop successful multimedia messages drawn from how the brain works and how they process information cognitively (Mayer 2001).

In this study, participants mentioned how having audio narration helped with a deeper understanding of the text. This suggests that having an audio option in the reading assignment
may be a useful strategy for supporting student learning, particularly for students who prefer auditory learning. The participants also valued having descriptive text next to the image. As stated in the multimedia principle, People learn best from words and images than from words alone (Mayer, 2010). However, “just putting in pictures with words does not improve learning; that is, all multimedia presentations are not equally effective” (Mayer 2005. p.31). Words and pictures should be organized; if not, it may create multimedia messages that hinder learning instead of amplifying it, compromising the student's ability to process information (Mayer & Jackson 2005) successfully. They mentioned how prior knowledge helped them recognize the information. According to Mayer 2001, when individuals can pay attention to the essential parts of the material presented to them, organize the information in a coherent mental structure, and combine it with their prior knowledge, they can construct knowledge meaningfully. Exposing students to the material is important because they are able to use their prior knowledge when it comes to learning and understanding scientific concepts. The findings from research question 1 highlight the importance of prior knowledge and experience when designing educational interventions and working with students. Instructors may need to provide additional support and resources to students with lower levels of knowledge to help them develop the necessary skills to engage with scientific texts. It is important to note that text preferences may vary and should be taken into account when designing visuals for different learners.

The findings to research question 2 show the importance of active learning. Active learning strategies help students with attention and increase comprehension and retention of the course material (Freeman et al., 2014). Kosslyn et al., 2017 argued that active learning was
effective in helping students think deeply about the information and improved how students stored, organized, and retrieved information. When people learn without understanding, they tend to forget, making it difficult to use the information in the future. Learning should include skill application and knowledge acquisition. This means instructors must change how they approach teaching. The findings of research question 2 show that it is important for instructors to recognize the impact of engagement on students’ learning and to find ways to encourage engagement in the classroom. In an environment that encourages active learning and critical thinking, instructors may be able to help students develop effective reading strategies and improve their overall academic performance. It is also important for educators to consider the needs and preferences of individual students and provide alternative options when appropriate.

Instructors may need to assign pre-lecture instructions for students with low prior text experience to help them understand the material. Schema theory suggests that knowledge is mostly acquired when new information can be added to existing knowledge networks containing multiple cognitive constructs called schemas (Bartlett, 1932). Bartlett (1932) also found that schemas help in understanding information. A schema organizes new knowledge, giving a framework for future reference and understanding (Anderson & al. 1977). When students receive reading material, they activate the type of schema they think is required, and if they must read a passage and answer questions about the main idea, they stop and ask themselves what they think should be the main points (Resnick, 1985). Students were not able to capture the main points of the interviews passage, even if the embedded questions would have helped them.
The findings of Research Question 3 show that reading comprehension is essential for student success. When students comprehend what they are reading, they can extract important information and construct meaningful interactions with the text. In this qualitative study, one of the goals was to help students form meaningful connections with ideas to help them learn science. Novices have their knowledge fragmented or not connected (Biggs & Collis, 1982; DiSessa, 2006); experts' knowledge is structured and organized around central concepts and principles in a way that helps their way of thinking and allows them to use their knowledge in new situations (Chi et al., 1981/1982). The results suggest that instructors may need to provide additional support to help students develop effective reading strategies to improve their reading comprehension of scientific texts.

**Limitations**

The COVID-19 outbreak was one of the limitations of this study. People were still social distancing, and recruiting students for in-person interviews was challenging. This meant that it was difficult to select a sample that was perfectly balanced in ACT Reading scores and course performance, as all students who volunteered were accepted as participants. Another limitation is that the study was limited to students from the University of Wisconsin Milwaukee introductory to chemistry students, which means the results cannot be generalized to other institutions.

**Implications and conclusions**

In this qualitative study, participants were given a voice to provide an in-depth understanding of how they read and comprehend chemistry in terms of multimedia learning, engagement, and perception of the reading assignments. During the data analysis, three main
research questions were developed. These questions focused on multimedia illustrations, engagement, and perceptions of the reading assignments. This study's results align with students' experiences and perceptions of science textbooks and reading assignments.

In the findings from Research Question 1, participants mentioned how having audio narration helped with a deeper understanding of the text. This shows that adding audio narration to the reading assignments can be beneficial for some students, especially for the students who are audio learners and, or those who struggle with reading comprehension. The participants also valued having descriptive text next to the image. As stated in the Multimedia Principle, people learn best from words and images than from words alone (Mayer, 2010). All the students were able to identify the states of matter, but the high-performing students gave more detailed descriptions than the low-performing students. They mentioned how prior knowledge helped them recognize the information. According to Mayer (2001), when individuals can pay attention to the essential parts of the material presented to them, organize the information in a coherent mental structure, and combine it with their prior knowledge, they can construct knowledge meaningfully. This is also consistent with Mayer’s 2010 cognitive theory of multimedia learning, which is addressed in Chapter 2. The preference of the images, particulate versus macroscopic, depended on the participants’ prior knowledge and learning style. The image that showed a step-by-step process was preferred for the visual representation, but the explanation gave a deeper understanding of the process. Through these findings, instructors may need to consider adding audio narration and descriptive text to reading assignments especially for struggle with reading comprehension and also those that are audio learners. This part of the qualitative study highlights the importance of providing multiple
options for accessing the same content to accommodate students’ different learning preferences and abilities.

In the findings from Research Question 2, participants engaged with the reading assignment and mentioned how they engaged with the science textbook, which is part of the active learning process. The results show that there are differences in reading strategies and engagement between high and low performers in sciences classes. High performers were more proactive in seeking out clarification on concepts they did not understand and worked on unfamiliar concepts, while low performers mostly skimmed through the reading and relied on listening to lectures and taking quizzes to understand the material. They study also found a correlation between prior text experience and academic performance. Students with prior text experience reading textbooks and completing reading assignments may be better prepared to understand and retain the material presented in class. Students who lack prior text experience may struggle to keep up with the material and may require more support to succeed. It was also found in this part of the qualitative study that most students opted for the online textbook because of convenience and affordability. However, some students may prefer physical copies of the textbook for personal reasons or may have difficulties with reading on the screen. It was highlighted in this part as the qualitative study that there is importance in assessing student reading comprehension and providing students with feedback and instruction to help ensure that they have the necessary skills to succeed in their courses.

In the findings from Research Question 3, participants mentioned how having an overview in the reading assignment helped them understand what the reading was about. Those who read and understood the reading could summarize correctly. This suggests that the
overview can be beneficial for students, particularly the low-performing students. The overview can help students understand what to expect from the reading and be able to identify the key topics, concepts, and information they need to focus on while reading. However, some students may not find the overview as helpful as others, and they do not get any new information or insights from it. The results show that many students struggle to fully comprehend what they are reading, as most of them did not give a complete, correct description of the main points in the reading assignment. This could be due to multiple factors, such as not fully engaging with the reading, lacking background knowledge, or struggling with the complexity of the material, even high-performing students may find these tasks challenging. Assigning pre-lecture instruction is also helpful to students with a low level of topic knowledge because these students do not grasp the specific ideas that are significant right away; with pre-lecture instruction, they can be oriented in the right direction toward the ideas that are significant in the scientific text. When students are assigned pre-lecture assignments, they are asked to “summarize or explain; it has been shown that the students will adjust their reading strategies based on the purpose of the reading assigned (Braten & Samuelstuen, 2004).

The findings provided a qualitative perspective on the experience students have with multimedia learning, how they engage with the text, and how they perceive the assigned reading material. This information can help instructors identify areas in which their students deeply engage with the course material. Instructors may need to provide pre-lecture material to help students become familiar with the topic before it’s presented in lecture. Developing appropriate materials to support students' learning can help students with their challenges with science texts and increase student course performance. Instructors may need to also encourage
students to engage with the reading actively, by asking them to take notes, summarize the main points, or discuss the material with their peers.
CHAPTER 8: OVERALL PROJECT IMPLICATIONS AND CONCLUSIONS

In this dissertation, evidence of the importance of implementing reading interventions in introductory chemistry courses and its impact on student exam performance was provided through multiple studies that were backed by literature. The overall conclusions and implications will be summarized in this chapter as well as specific implications for chemistry education research and teaching. The chapter will conclude with a discussion about this study’s limitations.

Conclusions

The main purpose of the research was to investigate the impact of the implementation of accessible pre-instruction reading assignments on student exam performance in introductory chemistry. The research on text accessibility for students of all incoming reading abilities in this study included an adjustment of the text’s Lexile level, and features meant to improve students’ comprehension of images, such as the addition of audio narration and image text placement. This dissertation contains four different but related studies.

The study in Chapter 4 was done to answer the main research question, which was to determine the effect of four different treatments (No reading assignment, reading assignment, reading assignment scaffolded, and reading assignment scaffolded with image and audio) on student exam performance means. In this study, while the analysis of variance did not provide significant results for all the different implementations, the students who received low Lexile level reading assignments performed significantly higher on Final Exam Parts One and Two than the other treatments. This is especially significant since one part of the exam, an ACS standardized exam was not written by the course instructors while the other one was. The
students who received reading assignments at medium and high Lexile levels also performed significantly higher on both final exam parts one and two when reading assignments were implemented versus when they were not (NoRA). While the effect sizes were small, the statistically significant results show that implementing pre-instruction reading is beneficial to student exam performance no matter their incoming reading comprehension level. It is important to note that students were not controlled on how they interact with the reading assignments. If they were, they would have been instructed to use effective reading strategies at all times. For this project, students engaged with the text in ways they felt most comfortable with.

That said, the implementation of pre-lecture reading assignments at a student’s Lexile level is most beneficial to lower-performing students. This helps the students better understand the concepts and retain the information. Implementation of the audio and image redesign was beneficial to the medium and high Lexile students, not the low Lexile students. This may mean that the introduction of audio and addition of text to the images may have been too much for the low Lexile level students.

The second study described in Chapter 5 was done to determine whether the students who received reading assignments performed better on specific exam questions than those who did not (NoRA). Differential item functioning was used to answer this question. The items were evaluated from the Mantel-Haenszel and logistic regression method to determine whether the items functioned differently between groups (Reading assignments scaffolded and no reading assignment). Most of the items in Final Exam Part One did not exhibit DIF; this may mean that responses to these items may not have been influenced by receiving or not receiving
a reading assignment after controlling for the relevant ability level. This also suggests that Final Exam Part One was fair overall, since no group was systematically advantaged or disadvantaged. However, it is important to address the items that showed evidence of DIF in order to ensure fairness for all the students. There were more items in the Final Exam Part Two that exhibited DIF, which indicates that the exam may not have been entirely fair for all the students. Six items exhibited DIF in favor of the students who received and completed reading assignments, which in a 45-item exam makes a difference of more than one grade. The items that showed DIF were related to multiple topics addressed in the reading assignments, which included atomic theory, molecular structures, chemical reactions, and formula calculations. The natural log odds ratio and MH-DIF scales were used, enabling the researcher to classify the DIF for the items that showed DIF in Final Exam Part One and Part Two. The items that showed DIF in favor of the group of students who received scaffolded reading assignments were categorized as negligible DIF, which may mean that even if there was DIF, these items did not favor one group or the other. This information can be useful for instructors in identifying potential bias in exams and ensuring that all students are given a fair and equal opportunity to demonstrate their knowledge and skills. We can conclude that the results of this study suggest that scaffolded reading assignments can be effective in improving student exam performance.

The third study which is outlined in Chapter 6 was done to determine the relationship between the students' self-reported data on the pre-survey and post-survey and the grade obtained in the course. This study was done in connection to the course textbook (pre-survey) and the assigned reading assignments (post-survey). Introductory chemistry students were surveyed on a pre-survey and a post-survey, and a Spearman correlation was done to correlate
their responses to their course grades. The results from the pre-survey and post-survey revealed that students’ predictions are mostly inaccurate. Especially predictions of a passing grade (94.5%, A to C) did not match the number of students who actually received it (76.5%). In agreement with recent findings in reading research, the results from the pre-survey showed that students reported reading compliance was low in introductory chemistry. Even if the percentage decreased from the pre to the post-survey, there may be other underlying factors that may have influenced the decrease in grades. For some students, achieving a higher grade than initially anticipated seems unrelated to their engagement with the textbook or application of effective reading strategies.

The analysis of the pre-survey shows that about 46% of the students, no matter their incoming reading ability, only sometimes engaged with the textbook, about 25% of the students who received the reading assignments at low Lexile levels mostly used effective reading strategies and 45% of the medium and 38% of high Lexile level students never used the strategies. Students in all three of the Lexile levels reported encountering difficulties (approximately 45% of the time) while using the chemistry textbook. Some of the students in the lower Lexile who reported reading most of the time (70%) performed better in the course. When it comes to engagement with the reading assignments, most of the students (80%) read 10-12, and students at all the Lexile levels mentioned that reading assignments supported their learning. Even though it is generally believed that reading a textbook increases student learning, the results from the pre-survey showed that student-reported reading compliance was low. For example, in their study, Podolefsky & Finkelstein, 2006) found that even if 97% of the students from introductory physics courses had access to the course textbook, only 37%
reported using it regularly. In this study, 95% of the students reported having access to the
course textbook; however, only about 10% said reading the textbook regularly. These results
highlight the challenges that students face when using the textbook and how important it is to
consistently promote textbook engagement and active reading strategies.

The study found that there was a significant correlation between the self-reported
grade and the grade obtained for the low Lexile students but not for the medium Lexile level
students. On average, 46% of all the Lexile levels engaged with the textbook, but 42% of the
low Lexile level students did not engage with the textbook by reading about topics before they
are covered in lecture. The study found that 38% of the low Lexile level students mainly used
strategies such as writing questions and comments on the margins of the text, working through
practice problems, and taking notes on the reading on a separate piece of paper, these are
effective reading strategies. Medium (32%) and high (42%) Lexile level students reported never
using these strategies. Approximately 40% of all three groups encountered difficulties using the
textbook, but medium and high Lexile students had a significant correlation between the
difficulty and the grade. The low Lexile level students did not seem to comprehend how to
engage with the textbook, the strategies to use, and even the difficulties they had with the
textbook. The high and medium Lexile level students seemed to know what strategies to use
and the difficulties they had, even though they had low textbook engagement. It could be
suggested that instructors may need to promote student success by helping students engage
with the textbook in a way that is most effective for their learning style.

Overall, the implications of this study suggest that instructors may need to promote
student success by helping students engage with the textbook in a way that is most effective for
their learning style. Instructors may need to encourage students to use effective strategies such as writing questions and comments in the margins of the text, working through practice problems, and taking notes on the reading on a separate piece of paper. The findings also suggest that instructors may need to consider the challenges that their students encounter while using the textbook, especially for medium and high Lexile level students. When students are given a voice through surveys, it may help instructors identify and address the challenges; then instructors may need to help students overcome the difficulties and improve their performance in the course.

The fourth study in Chapter 7 was done to understand how students in introductory chemistry read and comprehend chemistry text. In semi-structured interviews, students were to provide in-depth descriptions of how they read and comprehend chemistry text in the context of multimedia learning, text engagement, and perception of the reading assignments. In terms of multimedia learning, having audio narration added to the images in the reading assignments helped with a deeper understanding of the text because the students who learn better with audio had the option added to the images. The participants valued having descriptive text next (no matter where) to the image because it helped them understand in detail what the image was about. This confirms Mayer’s, (2010) research on the multimedia principle, People learn best from words and images than from words alone. Mayer (2010) mentioned how prior knowledge helped them recognize the information. According to Mayer 2001, when individuals can pay attention to the essential parts of the material presented to them, organize the information in a coherent mental structure, and combine it with their prior
knowledge, they can construct knowledge meaningfully. This is consistent with Mayer’s 2010 cognitive theory of multimedia learning, which is addressed in Chapter 2.

In terms of text engagement, there were multiple ways in which students engaged with the online textbook. 58% of the students reported high text engagement (highlighting and taking notes), while 42% of the students reported low text engagement (skimming through the text and relying more on the quizzes and lectures for understanding the course material). This part of the study demonstrates the importance of students’ text engagement, which is why active reading strategies should be encouraged, and low-performing students should be encouraged and provided with feedback and tools necessary for academic success.

In terms of the perception of the reading assignments, having an overview helped the participants understand what the reading was about, and those who read and understood the reading could summarize correctly. There was a significant number (85%) of students who were not able to extract the main points of the given text; only 15% of the students were able to provide all main points correctly. This suggests that some students are not able to read and comprehend, which can be due to low text engagement, not having background knowledge, or even the text being difficult.

Together the four studies in this dissertation helped in understanding the impact that reading interventions have on student exam mean performances in introductory chemistry. Making text accessible to all students regardless of their background provides students with equal opportunities, which can contribute to their academic success. When text is accessible, students are able to read and comprehend and understand the concepts in the text. Adjusting text to the Lexile level of the students allows for less complex vocabulary and specific concepts
in chemistry. Completing the reading assignments for low Lexile students can bring their exam grade up to about one full grade (~13%). When text is adjusted, students are challenged without being overwhelmed because their cognitive load is reduced. The multiple levels of analysis ranging from quantitative to qualitative, helped expand the scope of chemistry education research by providing an understanding and the effectiveness of the above interventions.

**Implications for teaching**

Based on the four studies in this dissertation, there are multiple implications.

In order to provide equitable learning opportunities in an introductory chemistry classroom, Instructors use available student data to identify students’ levels of college readiness and reading skills and comprehension. This can help create the appropriate materials or provide the proper tools to support student learning. The researcher made reading interventions based on differentiated learning by knowing the student's ACT reading scores. This is not an ideal measure, but it was the only one we had available. Other measures at other institutions might be a better fit. Instructors need to look into the information that is available to them. Assigning pre-lecture instruction is helpful to students with a low level of topic knowledge because these students do not grasp the specific ideas that are significant right away; with pre-lecture instruction, they can be oriented in the right direction toward the ideas that are significant in the scientific text. Instructors may need to be cognizant of the reading ability of their incoming students and the complexity and Lexile level of the reading material. Instructors may need to be cognizant that students have different preferences, such as audio use, image, and text placement. This may be important for students with lower incoming
reading abilities. As suggested in Schema learning theory, when students receive reading material, they activate the type of schema they think is required, and if they must read a passage and answer questions about the main idea, they stop and ask themselves what they think should be the main points Resnick, (1985). Furthermore, when students are assigned pre-lecture assignments, they are asked to “summarize or explain; these have shown that the students will adjust their reading strategies based on the purpose of the reading assigned Braten & Samuelstuen, (2004). Summarizing is an effective reading strategy that allows the reader to form meaningful connections and engage with the text; it also promotes deeper understanding and helps with the retention of knowledge.

Instructors may need to be given opportunities to learn about item attributes that can function differently based on the students’ group. Educators should also be educated on the implications. Reading comprehension must be prioritized for all students; students with strong reading comprehension may be equipped for success in the subject. By ignoring DIF, an assessment can reverse or limit the positive effect of the implementation of accessible reading assignments.

It is essential to examine the relationship between self-reported data on the use of the course textbook and the course grade obtained and the relationship between self-reported data on the student’s thoughts on the reading assignments and if it supports their learning and the course grade obtained. This can help instructors understand how students engage with the course textbook, what strategies they use, and what types of difficulties they encounter. Obtaining valuable information from the students could help instructors understand their students and know how to address their students' challenges while using science textbooks. For
example, students who reported not using the textbook frequently may need additional support or other learning materials to increase their comprehension. The findings on the reading assignments could also help instructors improve when they design pre-lecture material.

The findings provided a qualitative perspective on the experience of introductory chemistry students with multimedia learning, how they engage with the text, and how they perceive the assigned reading material. This information can help instructors identify areas that need support to help students deeply engage with the course material. Instructors may need to provide pre-lecture material to help students get familiar with the topic before it’s presented in lecture. Developing appropriate materials to support students’ learning can help students with their challenges with science texts and increase student course performance.

When instructors understand that not all students learn the same, this helps them provide materials and tools that the students need. And when students are provided with the necessary materials and tools, they better understand the concepts and retain the information. This proportionally minimal change can significantly impact student exam performance and encourage students to continue with STEM education.

**Implications for chemistry education**

Supporting students where they are is an equitable practice in any content area and is a crucial component to student learning and student success. This study has shown an additional way to do so for introductory chemistry students. Reading skills and reading comprehension for STEM learning have not been the focus for science educators in the past, but this study shows that it cannot be overlooked. Chemistry is a subject that involves a significant amount of reading and comprehension. Reading interventions can help students improve their ability to
understand scientific text, which can improve their performance in chemistry. When scientific literacy is promoted through reading intervention, students can read and analyze the text, which helps them make informed decisions about science-related problems. It is essential to increase students' academic performance by providing them with the tools and materials necessary to continue in STEM education. The findings in this study may not be sustainable in higher STEM courses. Students may need instruction on how to work with science text, such as active reading strategies. Chemistry instructors may want to think of including this in their instruction.

Limitations

In 2020 the world health organization declared COVID-19 a global pandemic, leading to universities transferring education to virtual learning (Bevins et al., 2020). People had to social distance to avoid contamination. The data collection was affected by the pandemic. Data collected in the Spring of 2020, the Fall of 2020, the Spring of 2021, and the Fall of 2021 could not be added to the data used for analysis due to online exams and other changes to instruction. This also affected the interview process because the interviews were conducted in the Fall of 2021, and people were still socially distancing, which made recruiting students for an in-person interview challenging.

The data from this study was collected from only the University of Wisconsin-Milwaukee introductory chemistry students, which means the result cannot to generalized for all introductory chemistry students from other institutions. UW-Milwaukee is an R1 university but also an access institution, which means that the student population might not be comparable with other institutions. The chemistry textbook used in this course, from which the reading
assignments were designed, may not be the same one used by other institutions. According to Cromley & Synder-Hogan, 2010, because of the similarities of the scientific texts used in all fields, success in one field of chemistry can result in success in a student’s general chemistry literacy.

The sample size was another limitation of this study. During the investigation in Chapter 4, analysis was done with four groups at different Lexile levels. This resulted in having a smaller sample size in some groups in the high Lexile level because of the limitations in the number of students with a high ACT reading score. ANOVA analysis is robust to normality violations, and a non-parametric method was used when ANOVA assumptions were violated.

The surveys and the interviews were limited to opinions, attitudes, and perceptions of introductory chemistry students on using textbooks and pre-instruction reading assignments. As a researcher, I acknowledge that there might have been some potential for bias.

Nevertheless, the inclusion of the student’s voice was very important for the enhancement of the student academic achievement.
References


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https://doi.org/10.1017/cbo9780511816819.004


middle and high schools. Cambridge, MA: Brookline Books.


APPENDICES

APPENDIX A: IRB

Overall data collection:

IRB #: 14.404

Interview:

IRB #: 21.084
APPENDIX B: SAS code for ANOVA

```sas
proc import OUT=Research_ready datafile= "E:\Research_Ready_for_Analysis_A11.xlsx" dbms=xlsx replace;
sheet = "All";
getnames = YES;
RUN;
/*Rules */
proc contents data = Research_ready;
run;

data Research_ready2;
set Research_ready ;
if 21 <=ACTREAD <= 25 then Lexile_Level = 'Medium' ;
if ACTREAD <=20 then Lexile_Level = 'Low' ;
if ACTREAD >= 26 then Lexile_Level = 'High' ;
run;
proc means data = Research_ready2;
title2 'Descriptive statistics by classes' ;
class Lexile_Level Group;
var Finalexampart1 Finalexampart2 ;
run;

Data Research_ready2_Low ;
set Research_ready2 ;
where Lexile_Level = 'Low' ;
run;

proc univariate data=Research_ready2_Low /*normal plot*/;
title2 'Final exam 1 & 2: check normality distributions' ;
var Finalexampart1 Finalexampart2 ;
   histogram Finalexampart1 Finalexampart2 / normal vscale = percent barlabel = count
        ctext = blue;
        inset Mean = 'Mean' (5.2)
               std = 'Standard Deviation' (6.3)
               min = 'Minimum ' (6.4)
               max= 'Maximum' (6.5)
               median='median' (6.5)
               mode = 'mode'
               N = '# students' / POS =NE;
run;
/* levenes test */
proc glm data=Research_ready2_Low ; ;
title2 'Homogeneity of variance: levenes test ' ;
class Group ;
model Finalexampart1 Finalexampart2 =Group ;
means Group / hovtest=levene(type=abs) hovtest=bf ;
run;
quit;
```
**proc glm** data=Research_ready2_Low  order = internal; 
**title2** 'one way anova testing for differences among group & low lexile level 
on final exam 1 & 2 : ';
**class** Group ;
**model** Finalexampart1 Finalexampart2 = Group / ss3
**effectsize** alpha=0.05;
**lsmeans** Group / pdiff adjust=tukey ; ;
/*OUTPUT out=pred p=ybar r=resid;*/
**run;**
APPENDIX C: SAS code for DIF (Differential Item Functioning)

```sas
proc import out=Items datafile =
"C:\Users\fdiawara\Downloads\Item_04_05_23.xlsx"
dbms=xlsx replace;
sheet="Items";
getnames=YES;
run;

proc format ;
value $RA_NRA '1' = 'RA'
     '0' = 'No-RA' ;
run;

proc format ;
value Question8_1 = 'Correct'
     0 = 'Not correct' ;

DATA AtomictheoryF1_;
SET AtomictheoryF1;
score_Atomictheory = sum(of Question1_-- Question44_) ;
RUN;
PROC RANK DATA=AtomictheoryF1_ OUT=Atomictheory_Subset group=10;
VAR score_Atomictheory;
RANKS stratum;
run;

PROC FREQ DATA=Atomictheory_Subset order = freq;
title2 'Atomic Theory F1 Question8_' ;
TABLES RA_NRA* Question8_ / plots=freqplot(twoway=cluster orient=VERTICAL) cmh ; / *TABLES RA_NRA* Question8_ / plots=freqplot(twoway=stacked orient=VERTICAL) cmh */
format RA_NRA $RA_NRA. ;
format Question8_ Question8_ . ;
RUN;
ods graphics off ;

PROC FREQ DATA=Atomictheory_Subset order = freq;
title2 'Atomic Theory F1 Question8_' ;
TABLES stratum*RA_NRA* Question8_ / CMH nprint;
format RA_NRA $RA_NRA. ;
format Question8_ Question8_ . ;
RUN;
```

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APPENDIX D: Pre-survey and Post-survey

**Pre-survey**

Name__________________________________________________________

UWM email address

- [ ] yourname@uwm.edu __________________________________________

Which section of chemistry 100 are you enrolled in?

- [ ] Chem 100-401
- [ ] Chem 100-402
- [ ] Chem 100-403

Gender

- [ ] Male
- [ ] Female
- [ ] Other______________________________________________________
- [ ] Prefer not to answer.

What grade do you expect to get in this course? (I know it’s hard to tell right now).

- [ ] A
- [ ] B
- [ ] C
- [ ] D
- [ ] F
- [ ] Choose not to answer.
Please indicate which chemistry or science courses you have taken prior to enrolling in Chemistry 100 this semester.

☐ I have NOT taken any chemistry classes before.

☐ A traditional (not AP, IB, honors, or other accelerated) high school chemistry class

☐ A traditional (not AP, IB, honors, or other accelerated) high school non-chemistry science class, such as biology, geology, physics, astronomy, or environmental science.

☐ An AP, IB, honors, or other accelerated high school chemistry class

☐ An AP, IB, honors, or other accelerated non-chemistry science class, such as biology, geology, physics, astronomy, or environmental science

☐ Chemistry 100 or Introductory Chemistry (at UWM or elsewhere)

☐ A college-level chemistry class (other than Chemistry 100)

☐ A college-level non-chemistry science class, such as biology, geology, physics, astronomy, or environmental science.
The following questions ask you about your experience reading the CHEM-100 course textbook. Did you have regular access to the course textbook (print copy or online)?

- Yes, the online version
- Yes, a printed copy
- No

How often do you read the textbook?

- 1-2 times a week
- 3 or more times a week
- 2-5 times a month
- Only for exam preparation
- Never
- Other ________________________________

How do you know when you need to read the textbook?

________________________________________________________________

How often do you use the textbook to do the following?

<table>
<thead>
<tr>
<th>Activity</th>
<th>Always</th>
<th>Most of the time</th>
<th>About half the time</th>
<th>Sometimes</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read about topics before they are covered in lecture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read about topics after they are covered in lecture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refer to the textbook for help in solving homework problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Read more about concepts you are struggling with (4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Find and solve practice problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Look up the definitions to unfamiliar words in the glossary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
When reading the course textbook, how often do you use the following reading strategies?

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Regularly</th>
<th>Most of the time</th>
<th>About half the time</th>
<th>Sometimes</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read the whole chapter all the way through</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-read certain sections of the chapters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highlight important information, like main ideas or definitions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Take notes on the reading on a separate piece of paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write questions and comments in the margins of the text, or on a separate piece of paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write notes and comments explaining pictures, diagrams, and graphs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use the glossary, a dictionary, or other resources to find the definitions of unfamiliar words</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work through practice problems in the text</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Check the answers to practice problems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reading science text is very different than a lot of other reading, even reading course texts for an English or history course. Please indicate how much you agree with the following statements.
Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree

It takes me a long time to read chemistry texts. | o | o | o | o | o

When I read chemistry text, I usually have to look for other explanations to understand what’s going on. | o | o | o | o | o

I recognize all the words in my chemistry textbook from classes or other reading. | o | o | o | o | o

I find it easy to interpret the symbols and math equations in the textbook | o | o | o | o | o

When I read a chemistry textbook, I skim over graphs or images. | o | o | o | o | o

I often get test and quiz questions wrong because I misunderstand what the question is asking. | o | o | o | o | o

There is so much information on one page of a chemistry textbook that I can get overwhelmed | o | o | o | o | o

The chemical formulas and equations in chemistry textbooks are difficult to interpret. | o | o | o | o | o

The sentences in a chemistry textbook are too long | o | o | o | o | o

Chemistry textbooks are written in a way that is easy to understand. | o | o | o | o | o

Did you use the audio option in the e-textbook?

________________________________________________________________

Thank you for your responses on this survey!

The next phase of our research project involves interviewing students. If we interview you, we will ask you about your responses to this survey, then give you some reading tasks to do and discuss.

We will make audio recordings of all our interviews, but we will keep them in a secure file and we will not share them with anyone outside our research group. If we publish any information from your interview, we will use a pseudonym (false name) to identify you.

Each interview should take about 45 minutes. Students who participate will receive an ACS study guide (value $25.00). These study guides apply to material tested in Chem 100, Chem 102, and Chem 104.
Would you like to be interviewed?

- Yes! I would like to participate in the interviews.
- No, I would not like to participate in the interviews.
- I’m not sure whether I would like to participate in the interviews. Can I have more information?
Post-Survey
Q4 Name_____________________________________________________________

Gender

○ Male

○ Female

○ Other _____________________________________________________________

○ Choose not to answer

What grade do you expect to get in this course?

○ A

○ B

○ C

○ D

○ F

○ Choose not to answer

How many reading assignments on Canvas did you complete?

○ 1 - 3

○ 4 - 6

○ 7 - 9

○ 10 - 12

Did you experience any technical difficulties in Canvas accessing or working on the reading assignments?

○ Yes, specify how often and what kind of difficulty

______________________________________________________________________

○ No

Did you have regular access to the course textbook (print copy or online)?
The reading assignments in Canvas are designed to present important concepts in a more condensed format to you. We added questions to the text to increase your engagement with the text aiming to increase your learning.

Please indicate your level of agreement with the following statements.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Strongly agree</th>
<th>Somewhat agree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat disagree</th>
<th>Strongly disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>The condensed format worked for me</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I found the language of the reading assignment more accessible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I preferred reading the textbook chapters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I found the embedded questions helpful, they made me look deeper into the text</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In general, in what way would you say the reading assignments in Canvas helped you?

<table>
<thead>
<tr>
<th></th>
<th>Strongly agree</th>
<th>Somewhat agree</th>
<th>Neither agree nor disagree</th>
<th>Somewhat disagree</th>
<th>Strongly disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helped me prepare for quizzes</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Reading prior to lecture helped me understand the material when it was presented in lecture.</td>
<td>○</td>
<td>○</td>
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<td>○</td>
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<tr>
<td>Helped me prepare for exams</td>
<td>○</td>
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</tr>
<tr>
<td>Helped me understand scientific concepts.</td>
<td>○</td>
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</tr>
<tr>
<td>Helped me become familiar with chemistry specific terminology</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
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</tr>
<tr>
<td>Other</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>
APPENDIX E: SAS code for spearman correlation

```sas
proc import out=presurvey datafile = "C:\Users\fdiawara\Downloads\presurvey.xlsx"
  dbms=xlsx replace;
  sheet="presurvey";
  getnames=YES;
run;
proc print data = presurvey (obs =5) ;
run;
proc contents data = presurvey;
run;
data presurvey2;
  set presurvey ;
  keep Name GRADE Gradeobtained ;
run;
data presurvey3;
  set presurvey2;
  if GRADE = 'A' then GRADE_ = 5 ;
  if GRADE = 'B' then GRADE_ = 4 ;
  if GRADE = 'C' then GRADE_ = 3 ;
  if GRADE = 'D' then GRADE_ = 2 ;
  if GRADE = 'F' then GRADE_ = 1 ;
  if GRADE = 'Choose not to answer' then DELETE ;
  if Gradeobtained = 'A' then Gradeobtained_ = 5 ;
  if Gradeobtained= 'B' then Gradeobtained_ = 4 ;
  if Gradeobtained = 'C' then Gradeobtained_ = 3 ;
  if Gradeobtained= 'D' then Gradeobtained_ = 2 ;
  if Gradeobtained= 'F' then Gradeobtained_ = 1 ;
run;
proc print data =presurvey3;
run;
proc corr data = presurvey3 spearman kendall pearson ;
  var GRADE_ Gradeobtained_ ;
run;
```
Appendix F: The interview protocol

Interview Prompts
Introductions, explanations, and informed consent
• Interviewers introduce themselves.
• “We’re working on a research project about how students read and understand chemistry. To get a sense of how you read, we’re going to give you a piece of text, and ask you to read it and answer some questions about it. We’ll record this session so we can look at it more closely later, but we won’t share it with anyone outside our research group. We’ll also keep any writing you do here, but, again, we won’t share it with anyone. If we publish anything we learn from talking with you, we’ll use a false name so no one will be able to identify you. This interview should last about 45 minutes, and you’re free to say no to any activity we ask you to do. You’re also free to stop the interview at any time.”
• “What questions do you have?”
• “Do you agree to be interviewed?”

Prior Knowledge and Establishing Rapport
• “In the survey we sent you, you mention you took [whatever classes.] Do you feel like they gave you a good idea of what you would need to do in college?”
• “Have the concepts in CHEM-100 been mostly new for you, or mostly review, or something in between?”
• “Did you study the Gas Law at all in the classes you took before? Do you know any equations to find the volume or pressure of a gas?”
• “Did you read textbooks or reading assignments much in your previous classes?”
  o If yes: “What kinds of texts did you read? What activities and assignments did you do with the texts?”
• “When have you read texts for school now, how do you do it?”
  o Do you have an online or print textbook?
  o Where and when do you read?
  o Can give examples of highlighting, using e-book/print book, annotating, etc., but be careful not to lead the participant too much.
• “What do you think might make students more likely to read the textbook in CHEM-100?”
  o Keep probing if they say that it’s difficult to understand—ask what is difficult and what might make it easier.
• Did you use the audio option embedded in the text?
  o Did you find the embedded audio narrative helpful?

Reading Task
• “I’m going to give you a piece of a reading assignment. It is about a topic you have not covered in lecture yet, so don’t worry if it seems unfamiliar. Right now, I’d like you to read this piece of text just like you normally do when you study and write a brief
summary under the reading. We have pens, paper, highlighters, and sticky notes if you want to use them. Is there any other material you usually use?

- Obtain materials student needs.

- “We’re going to step out for a bit to give you time to work on this, so you don’t feel rushed.”

Summary Task

- “What does it mean to write a summary? What do you usually include when you summarize?”

- “What do you think are the main points a student should learn from this reading?”

Question Task

- These are two questions you might see on a quiz or exam about this topic. You do not need to be able to answer them right now, though. However, what kind of information would you look for in the reading to help you answer those questions?

- How do you know this information is useful?

- Questions:
  - What is the mass of 2.24 L of CH4 gas at 1 atm and 25 degrees C?
  - Consider a volume of ideal gas at standard pressure and temperature. If the pressure is doubled and the temperature remains constant, what will happen to the volume? A) Double, B) increase but not double, C) Decrease to ½ the original volume, D) decrease, but not to ½ the original volume

Vocabulary Task

- “I want to ask you about a couple of words that the authors used in this text. The first one is [word], here. [Read sentence word appears in.] What do you think [word] means in this sentence?”

- Words:
  - Properties
  - Particles
  - Absolute temperature
  - Collide
  - Derive

- Did you find the overview helpful in understanding what the reading assignment was about? (Show them the overview)

- Here is an image and some text describing the image. Where would you put the text and labels to make the image easier to understand. Go ahead and move it around.

- What do you think this image shows?
In your personal opinion, which of the images below illustrates the process of dissolving best?

Which image best describes preparation of an aqueous solution (copper (II) sulfate in water).

Please choose the image that provides you with enough information about the solution preparation.

How do you prepare a copper (II) sulfate solution and what particles (atoms, ions, molecules) can be found in the solution?
Appendix G: Reading assignments

Based on the introductory chemistry course curriculum

**Original reading assignments:**

**Atomic Theory:**

The evolution of the atomic theory

**What to expect in this chapter:**

The first part of this chapter introduces John Dalton's atomic theory from 1808, he was an English school teacher and hobby scientist. With his theory, he revived the idea that matter consists of incredibly small particles called atoms, a theory that finds its origins in ancient Greece but had been neglected for over 2000 years.

At the time Dalton published his theory, the existence of subatomic particles was not known. Subatomic particles "live" inside of atoms and are considerably smaller than atoms, they are critical in the sense that they determine the properties of individual elements.

The second part of this chapter will talk about experiments that have been conducted after 1808, these experiments have accidentally or intentionally shown the existence of subatomic particles (cations, anions, or neutrons).

Based on these discoveries, the model of what an atom looks like has been revised a couple of times. Please note that models are often not an accurate mirror of the truth, models change if new information becomes available.

**Dalton’s Atomic Theory**

In 1808 John Dalton, an English school teacher and scientist, published his atomic theory. His postulates can be summarized as follows:

1. All matter is composed of exceedingly small, indivisible particles, called atoms.
2. All atoms of a given element are identical, both in mass and in chemical properties.
   However, atoms of different elements have different masses and different chemical properties.
3. Atoms are not created or destroyed in chemical reactions.
4. Atoms combine in simple, fixed, whole-number ratios to form compounds.

Now let us have a closer look at some important discoveries about the structure of the atom, which happened between 1897 and 1932.

**Question 1:** Please explain in your own words the meaning of Dalton’s second and fourth postulates. Name examples if you can think of some.

Experiments that helped determine the internal structure of the atom

**What are Subatomic Particles?**

Cathode-ray tubes (CRTs) are the fundamental components of older television picture tubes and computer monitors. The screen contains chemical compounds that glow when struck by fast-moving electrons. Different chemicals that glow different colors provide a color picture.

A subatomic particle is a smaller particle found inside an atom. These subatomic particles are the **proton, neutron, and electron**. It was not until the late 1800s that researchers developed
instruments and techniques capable of detecting subatomic particles and revealing their numbers and arrangements in atoms.

**Discovery of the Electron**

The existence of the *electron, a negatively charged subatomic particle*, was demonstrated by J. J. Thomson in 1897. He conducted a series of experiments with cathode-ray tubes (Figure 2.5 next page). In a partially evacuated cathode-ray tube, a voltage is applied by connecting each end of the tube to a battery. Electricity then flows from one end of the tube to the other in the form of a ray. The invisible rays can be observed when they cause certain materials coated on the glass to glow.

Thomson found that, in a magnetic or electric field, the rays bent toward a positively charged plate and were deflected away from a negatively charged plate outside the tube. He knew that electrical charges repel each other, and opposite charges attract each other. The bending of the beam toward the positive plate (and away from the negative plate) showed that the beam was composed of negatively charged particles.

Thomson showed that the rays had a negative electrical charge no matter what material was used for the source of the rays. This result indicated that the rays were composed of identical, negatively charged particles common to all matter. We call these particles electrons. Thomson was also able to determine the charge-to-mass ratio of the electron from such experiments.

**Image A: Cathode ray tube without application of external field**
Image B: Cathode ray tube with application of external field

**FIGURE 2.5 Thomson’s Experiment - Cathode-Ray Tube (Experimental Set-Up)**

**Question 2:** How did the discovery of electrons make it necessary to change one of Dalton's postulates?

**Question 3:** In figure 2.5, what is happening in image B? Please explain.

**The discovery of the Proton**

The discovery of the electron stimulated many more experiments in search of other subatomic particles. Since atoms are electrically neutral, scientists reasoned that atoms must contain positively charged particles to counter the negatively charged electrons. The positively charged particle, called a proton, has a charge equal in magnitude to the electron but opposite in sign, \( +1.6022 \times 10^{-19} \) C. To be electrically neutral, an atom must have equal numbers of protons and electrons. To make it easier to deal with electrical charges in matter, we usually express the charges as a multiple of the charge of an electron or of a proton, instead of in units of coulombs. Expressed in this way, the charge of an electron is \( 1^- \), and the charge of a proton is \( 1^+ \).

**The model of the atomic nucleus (core) in 1904**

How might protons and electrons be arranged in an atom? Thomson's model of the atomic structure, called the "plum pudding" model, assumed that protons and electrons were evenly distributed throughout the atom (*Figure 2.7* below).

![Diagram of the "Plum-Pudding" Model](image)

**FIGURE 2.7 - The "Plum-Pudding" Model**

Thomson’s model suggested that electrons in the atom might be embedded in a sphere of positive charge, like raisins in plum pudding.
Five years later...

**Discovery of the Nucleus - Rutherford's Gold Foil Experiment**

Ernest Rutherford designed an experiment to test the plum-pudding model, and his associate, Hans Geiger, carried it out.

The experiment involved bombarding thin gold foil with alpha particles. Alpha particles were known at the time as positively charged particles thousands of times greater in mass than electrons. (Today we know them as helium atoms that have lost their electrons.) According to the plum pudding model, none of the alpha particles should have been affected by the dispersed bits of positive and negative charge in the gold atoms. They should have zipped right through the gold foil, and most did. However, some were deflected slightly, and a few actually bounced backwards, as shown in Figure 2.8, next page.

*The result was quite unexpected.*

*It was as if you fired a bullet at a sheet of tissue paper and it came back and hit you!* The deflection of these massive alpha particles suggested that most of the mass of the atom had to be concentrated in a positively charged core, which Rutherford called the *nucleus*. The electrons, he reasoned, had to be dispersed in the large volume outside of the nucleus. The large electron space was the area penetrated by most of the alpha particles. Only if an alpha particle came close enough to the incredibly dense nucleus would it be deflected from its original path. The alpha particles that hit the nucleus of a gold atom head-on were deflected backwards.

![Diagram of the gold foil experiment](image_url)
Question 4: Why did the alpha particles swerve? Please explain.

Question 5: Why did Rutherford choose gold for his experiment? Could he have used any other material? Which properties should this material have?

Question 6: What kind of evidence did Rutherford's gold foil experiment provide?

Rutherford's experiment was the basis for the nuclear model of the atom (Figure 2.9), developed in 1907. The model suggested that the nucleus contains the protons and most of the mass of the atom. The electrons exist outside the nucleus in what is often called an "electron cloud."
FIGURE 2.9 – The nuclear model of the atom

In the nuclear model of the atom, protons (blue spheres) and neutrons (red spheres) are located in a tiny nucleus at the center of the atom. The space outside the nucleus is occupied by the electrons.

*The diameter of the nucleus is about $10^{-14}$ m, and the diameter of the atom is about $10^{-10}$ m. These relative sizes are comparable to a flea in the center of a domed stadium. The mass of a proton, $1.6726 \times 10^{-24}$ g, is nearly the same as the mass of a hydrogen atom. The proton is equal in charge (but opposite in sign) to the electron, but 1836 times greater in mass.*

The Neutron

*These experiments helped Rutherford and other scientists understand the structure of the atom better, but they could not account for the entire mass of the atom.*

Most atoms other than the hydrogen atom have masses that are at least twice the sum of the masses of the protons and electrons they contain. For example, calcium contains 20 protons and 20 electrons. Together, their mass is $3.3471 \times 10^{-23}$ g. Yet a calcium atom has a mass that is nearly twice this value ($6.6359 \times 10^{-23}$ g).

**Question 7:** Check the Periodic Table in your textbook (inside front cover). If calcium (Ca) has 20 protons, which element has 16 protons?

**Question 8:** For the atom presented in the following diagram,

A. Determine the number of protons and neutrons
B. Identify the atomic number and the element
C. Determine the mass number for this isotope.

![Color Key:
Bleu: proton (+ charged)
Red: Neutron]
To account for the extra mass, Rutherford hypothesized the neutron. A neutron is an uncharged particle in the nucleus of the atom.

Because of the electrical neutrality of the neutron, it was difficult to find. It was not until 1932 that James Chadwick, a scientist working with Rutherford, did experiments that detected the neutron. The mass of the neutron was determined to be $1.6749 \times 10^{-24}$ g, slightly greater than the mass of a proton. The properties of the electron, proton, and neutron are summarized in Table 2.1. All the subatomic particles in the table are important to the nuclear model of the atom as we understand it today (Figure 2.9).

**Question 9:** Which element is described in figure 2.9?

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Actual Charge</th>
<th>Relative Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$9.1094 \times 10^{-28}$ g</td>
<td>-1.6022$ \times 10^{-19}$ Coulomb</td>
<td>-1</td>
</tr>
<tr>
<td>Proton</td>
<td>$1.6726 \times 10^{-24}$ g</td>
<td>+1.6022$ \times 10^{-19}$ Coulomb</td>
<td>+1</td>
</tr>
<tr>
<td>Neutron</td>
<td>$1.6726 \times 10^{-24}$ g</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A coulomb is a unit of electric charge. It is equal to the amount of electricity carried in one second by a current of one ampere.

**TABLE 2.1 - Subatomic Particles, masses, and charges**

**Question 10:** Looking at the data provided in table 2.1, how much heavier are protons and neutrons compared to electrons?

**Question 11:** Dalton stated that "all atoms of a given element are identical, both in mass and in chemical properties". Can you think of any exceptions to this rule?

**Question 12:** (typical exam questions):

Which subatomic particles make up the mass of an atom?

A. protons and electrons.
B. protons and neutrons.
C. neutrons and electrons.
D. only electrons.

**Question 13:** Describe what you have learned about the proton in this reading assignment.
2. Modern Model of the Atom

What to expect in this chapter:

You just learned that electrons are located outside the nucleus and protons and neutrons are located inside the nucleus.

The phrase “outside the nucleus” is not very specific and therefore scientists tried to determine and describe models to better describe the location of the electrons. One of the models is the Bohr model, named after the Danish physicist Niels Bohr (1885–1962) who received the Nobel Prize in Physics in 1922 for his contributions to correctly describe the structure of the atom.

Bohr’s model, also called the orbital model, described different energy levels in a hydrogen atom well but is more complicated when applied to atoms with more than one electron. This describes a path where electrons in the atom can be found. Even though newer models more accurately describe where electrons can be found, the Bohr model is still very much in use.

In this chapter, you will be introduced to the most recent “modern model of the atom”. It identifies not only 3-dimensional spaces in which electrons can be found, it also associates distinct energy levels with these locations.

The Modern Model of the Atom

By the 1920s, scientists started to work on a new model of the atom that could account for the line spectra of other elements. (Line spectra are colored lines of light emitted elements. Each element has a distinct line spectrum that can be used to identify the element. See also Chapter 7 pg. 260). Erwin Schrödinger, from Austria, developed a mathematical model that seemed to work for all atoms. Schrödinger’s model of the atom was similar to Bohr’s model in that the energies of electrons were quantized, meaning they could have only certain energies.

The new model, however, describes electrons as occupying orbitals, not orbits (as in Bohr’s model). An orbital is a three-dimensional region in space where the electron is likely to be found, not a circular pathway (shown in Figure 7.12). The mathematical model was based on the probability of finding an electron in a region outside the nucleus. From it, chemists created a probability map to show where an electron is likely to be found (Figure 7.11).
Figure 7.11A is the probability map for a hydrogen electron in its lowest-energy state. The darker regions represent areas where the electron is most likely to be found. Because the likelihood of finding an electron in the outer regions of the probability map is small, it is customary to show an enclosed region in space where the electron is likely to be found 95% of the time (Figure 7.11B). We will use orbital representations without dots for the rest of this chapter.

In the modern model of the atom, orbitals of similar size are considered to be in the same principal energy level. The first six principal energy levels for the electron in a hydrogen atom are shown in Figure 7.12 below.

Maximum occupancy of each energy level:
- n = 1 (2 electrons)
- n = 2 (8 electrons)
- n = 3 (18 electrons)
- n = 4 (32 electrons)
- n = 5 (50 electrons)
- n = 6 (72 electrons)

Figure 7.12:

The allowed energies for the electron are the same as the energies of the Bohr orbits.

Question 1: Why are there multiple possible energy levels in a hydrogen atom? Hydrogen just has one electron!

Orbitals come in different shapes and sizes. There are four types of occupied orbitals in atoms in their lowest energy states, which we label with the letters s, p, d, and f. The general shapes of these orbitals are shown in Figure 7.13. These orbitals are distributed into the principal energy levels (n=1, 2, 3...).
Figure 7.13: The s, p, d, and f orbitals differ in shapes and number of lobes.

The grey planes in Figure 7.13 depict the 3 axes in a Cartesian coordinate system.

Question 2: Transferring the images in Figure 7.13 on an actual atom, what is the probability to find electrons in the origin where the three axes intersect?

Orbitals at lower-energy levels are smaller. Orbitals at the higher-energy levels are larger and extend farther from the nucleus.

Example:

The first principal energy level (n = 1) consists of a single s orbital. We call this s orbital a 1s orbital because it is in the n = 1 principal energy level and it has the s orbital shape:

The second principal energy level (n = 2) consists of s and p orbitals called the 2s and 2p orbitals. The 2s orbital is like the 1s orbital, but it is larger (Figure 7.14).

Figure 7.14: The size of the orbitals increases as the principal energy level increases.

A single p orbital, as depicted in Figure 7.13, has a figure-eight or dumbbell shape. In their respective energy levels, p orbitals always come in sets of three (Figure 7.15). The three 2p orbitals lie with their centers overlapping at the nucleus and perpendicular to one another. We can think of each two-lobed orbital as directed along one of the x, y, or z axes that are each perpendicular to one another. We label these orbitals accordingly as px, py, and pz orbitals.
**Figure 7.15:** (A) Three $p$ orbitals compose a $p$ sublevel. They have the same shape, but they point in different directions in space. They lie perpendicular to one another, so we can imagine them lying along perpendicular lines that we call $x$, $y$, and $z$ axes. The $pz$ orbital lies along the $z$ axis, the $px$ orbital lies along the $x$ axis, and the $py$ orbital lies along the $y$ axis. (B) The three $p$ orbitals coexist with their centers at the nucleus.

Because there are **two types of orbitals in the second principal energy level**, we say that there are two sublevels: the $2s$ sublevel and the $2p$ sublevel. A sublevel consists of just one type of orbital at a specific principal energy level. The $2s$ sublevel consists of a single $2s$ orbital, and the $2p$ sublevel consists of three $2p$ orbitals.

**At the third principal energy level** ($n = 3$), **three sublevels are available:** the $3s$, $3p$, and $3d$ sublevels. The $3s$ sublevel consists of a single $3s$ orbital, and the $3p$ sublevel consists of a set of three $3p$ orbitals. The $3d$ sublevel consists of five $d$ orbitals (Figure 7.16).

**The fourth principal energy level** ($n = 4$) consists of **four sublevels**: the $4s$, $4p$, $4d$, and $4f$ sublevels. The $4f$ sublevel consists of seven $4f$ orbitals (image of $f$ orbitals not given).

**Figure 7.16:** There are five $d$ orbitals in a $d$ sublevel. Most have four lobes that lie along a specific plane in space. One looks like a $p$ orbital with a donut shape around its center.

In the modern model of the hydrogen atom, the energy levels have the same energies as the orbits described in the Bohr model. The hydrogen line spectrum is produced by the movement of electrons in an atom from orbitals in higher principal energy levels to orbitals in lower
principal energy levels (transition from an “excited state” to a lower energy state, such as the “ground state”, pg. 261 in textbook).

The hydrogen atom line spectrum is simple to explain because the orbitals in the same principal energy level have the same energy. This is not the case for atoms with more than one electron.

**Orbital Diagrams for Multi Electron Atoms** (*"multi" here means more than one!*)

A convenient way to show the distribution of sublevels and orbitals in an atom is with an orbital diagram. The one shown in *Figure 7.17* (next page) is specifically for the hydrogen atom. The boxes represent orbitals, and the groups of boxes represent sublevels.

![Orbital Diagram for Hydrogen Atom](image)

*Figure 7.17*: The orbital diagram for the hydrogen atom shows the sublevels and orbitals that can exist at each principal energy level. Each box represents an orbital, and groups of boxes represent sublevels. For the hydrogen atom, only the sublevels within a principal energy level all have the same energy. Here we show only the first three principal energy levels for hydrogen.

The orbital diagram for a multi-electron atom looks different. It shows the same energy levels and sublevels, but the energies of some sublevels differ.
Sublevels in the same principal energy level have the same energy only in atoms with one electron (hydrogen). In atoms with more than one electron, the interaction among electrons causes the sublevels within the same principal energy level to have different energies. The result is an orbital diagram like that shown in Figure 7.18. Notice that, within a given principal energy level, the p orbitals are higher in energy than the s orbitals, and the d orbitals are higher in energy than the p orbitals. The 3d orbitals are so high that they are slightly higher in energy than the 4s orbitals.

Question 3: What kind of interaction between electrons could it be that causes the sublevels within the same principal energy level to have different energies?

Now we have to look at how electrons are being arranged into these principal energy levels, sublevels, and orbitals.

Consider the orbital diagram that represents how electrons are arranged in a carbon atom in its ground state:

Carbon has an atomic number of 6 (6 electrons). The 1s orbital will get 2 electrons, the 2s will get 2 electrons and the remaining 2 electrons will go into the first 2p orbitals.

The boxes represent orbitals, and the arrows represent electrons.
Question 4: Please summarize in your own words, why the location of the electrons in an atom is important?

When we create an orbital diagram for a particular atom, we fill in electrons starting with a bare nucleus and add one electron at a time. (This is not how atoms are created in nature.) You may have noticed that the lowest-energy orbitals have two electrons in them, and some of the higher-energy orbitals have only one or none.

This is a result of the Aufbau principle (from the German Aufbauen, "to build up"), which states that electrons fill orbitals starting with the lowest-energy orbitals. For the hydrogen atom in its ground state, its electron is in the 1s orbital. You may have also noted that no more than two electrons occupy each orbital.

This is the basis for the Pauli Exclusion Principle, which states that a maximum of two electrons can occupy each orbital, and they must have opposite spins.

Electrons in the same orbital are represented by arrows that point in opposite directions. An electron can spin in one of two directions. We represent these spins with an up arrow and a down arrow.

For example, helium’s ground-state orbital diagram consists of two electrons in the 1s orbital:

For lithium, with three electrons, two electrons go in the 1s orbital. The first principal energy level is filled. We can now proceed to the second principal energy level. Because the 2s sublevel is lower in energy than the 2p sublevel, the third electron goes into the 2s orbital.
Boron, with five electrons, has an orbital diagram with two electrons in the 1s orbital, two electrons in the 2s orbital, and one electron in one of the 2p orbitals. It makes no difference which p orbital we place the electron in because they are equal in energy. The orbital diagram for boron is:

What happens when there is more than one electron in a sublevel that contains more than one orbital, such as a p sublevel? Are electrons paired up right away, or are they kept in separate orbitals until pairing is required? Did you notice in carbon’s orbital diagram that the electrons in the p sublevel are unpaired in separate p orbitals?

This brings us to the third rule:

**Hund’s rule:** Electrons are distributed into orbitals of identical energy (same sublevel) in such a way as to give the maximum number of unpaired electrons.

**Hund’s rule is a consequence of the fact that negatively charged electrons repel each other.** It follows that electrons should be found in separate orbitals if no energy is required to get there.

It is common to show a simpler orbital diagram, where all the orbitals are represented on one line, with sublevels labeled. We must remember that the energy of the sublevels increases from left to right. For example, we can represent the orbital diagram for carbon as

Following Hund’s rule, the arrows (electrons) in the 1s orbital should face opposite directions, same goes for the 2s orbital. The p sublevel has 3 orbitals, but we only have 2 electrons left. The remaining 2 electrons should be distributed evenly.

**Question 5:** In your own words can you summarize the meaning of Hund’s rule.
Question 6: (possible exam question)
Which element in its ground state has exactly one unpaired electron?

(A) Al  (B) Mg  (C) P  (D) Si

Question 7: (possible exam question)
Which picture shows a $p$ orbital?

A.  
B.  
C.  
D.  

Question 8: Please briefly describe the differences and similarities between an energy level diagram, a Bohr model, and an orbital diagram (as shown in the text above). You most likely will encounter some of these in exams and quizzes.
3. Molecular Shapes:

3-Dimensional Shapes of Molecules

What to expect in this chapter:

This chapter discusses the relationship between the 3-dimensional shape of a molecule and its properties. While the chemical make-up of a molecule is given by the chemical formula, only a few predictions about properties can be made based only on this information.

However, the 3-dimensional shape of a molecule and the position of its atoms within the molecule determine how molecules not only interact with other molecules of the same kind, but also with other substances.

This chapter will guide you through a couple of steps that will allow you to determine molecular shape. You will see that the arrangement of atoms and the location of electrons within the molecule play an important role.

Let us look at an interesting real-world example first – the senses of smell and taste!

The 2004 Nobel Prize in Physiology or Medicine was given to Richard Axel of Columbia University and Linda Buck of the Fred Hutchinson Cancer Center in Seattle for their studies of the sense of smell.

Although senses have a chemical basis, determining how they operate has not been simple. It has become clear that there are receptor sites in the nose and tongue where molecules can fit. The receptors are built from proteins that make up the membranes of cells. The proteins are interlinked in various ways, creating pockets in the structure of the cell membrane. The pockets act as receptors from other molecules if two conditions meet.

First, the molecules must be the right size and shape to fit in them. Second, the molecules must interact in a certain way with atoms in the membrane protein, causing a change that can trigger a nerve impulse.

The importance of molecular shape – an example:

Recognizable tastes fall into several categories. One is sweet, and it is highly attractive to humans for good reasons. Lactose is a sweet substance found in mothers’ milk. The sweet taste encourages babies to consume more. Other sweet substances include glucose and sucrose (two different forms of sugar), which occur naturally in plants. While it has been difficult to relate the structures of molecules to their tastes, a common feature of sweet molecules is the size of a particular portion of the molecule. This part of a sweet molecule presumably fits into the receptor site. Sweet molecules commonly have a —H (or —OH) separated from a —O— atom by about 300 pm, as illustrated in Figure 8.23:
Figure 8.23 Glucose is sweet because it contains —H and —OH groups that fit into a taste receptor site on the tongue.

Although humans can distinguish thousands of odors, one theory proposes that there are only seven primary odors, each associated with a different type of receptor in the nose. When a gaseous molecule enters the nose and interacts with a particular receptor, a nerve impulse is generated and sent to the brain. A molecule that can fit into more than one type of receptor triggers multiple signals, generating a composite odor.

How does science explain molecular shape?

The Valence-Shell Electron-Pair Repulsion Theory

As the senses of taste and smell demonstrate, the observable properties of substances derive from the three-dimensional shapes of their molecules. Shape, in turn, is a function of the arrangement of atoms in a molecule. The relative locations of electron pairs around a central atom play a large role in determining a molecule's three-dimensional shape. Negatively charged electrons repel one another, so electron pairs in different orbitals stay as far apart as possible.

Definition: The tendency of electron pairs to adjust the orientation of their orbitals to maximize the distance between them is the basis of the valence-shell electron-pair repulsion (VSEPR) theory. (Valence shell is another name for valence level.)

Question 1: Based on your knowledge about Lewis structured, what is the center atom in sulfur dioxide, SO₂, and what number and type (bonding pairs or lone pairs) of electron pairs are located around it? Explain!
A Lewis formula does not show the shape of a molecule, but it does help us to determine molecular shape.

Since it is hard to see how atoms are arranged in a two-dimensional line drawing, chemists often use a system of solid lines, dashed lines, and wedges to depict the three-dimensional structure of molecules. Solid lines indicate bonds in the plane of the paper. Dashed lines are bonds that point back from the plane of the paper. Wedges depict bonds that come forward from the plane of the paper (this way of drawing bonds becomes especially important in Organic Chemistry!):

![Diagram showing molecular structure with in-plane and out-of-plane bonds](image)

To predict the geometric shape of a molecule or ion using VSEPR theory, we first need to know how electrons are arranged in a molecule. In particular we need to know how many unshared electron pairs and atoms surround the central atom.

We can get this information by examining the Lewis formula. For example, CH₄ has four atoms and no unshared electron pairs surrounding the carbon atom. In the CO₂ molecule, carbon has only two atoms bonded to it, as shown in the Lewis formula, and it has no unshared pairs of electrons. The NH₃ molecule has three bonded atoms and one unshared electron pair (see figures below).

![Lewis formulas for CH₄, CO₂, and NH₃](image)
The bonded atoms and unshared electron pairs are arranged around the central atom as far apart as possible. The result is a shape characterized by the bond angle between the central atom and the atoms bonded to it.

What shapes and angles would you predict for molecules having two, three, and four pairs of unshared electrons or atoms around a central atom? How would you make these predictions based on repulsions of electron pairs?

Example: To see what angles to predict, let’s examine the shape commonly found in hydrocarbons and many other molecules that arise from four electron pairs or atoms. The Lewis formulas look flat, as in CH₄:

```
H
H—C—H
H
```

This structure looks as if it would have bond angles of 90°:

```
H
H—C<H
H
```

However, this does not accurately represent the three-dimensional structure of the CH₄ molecule, which is not flat. If we move atoms to correct the flatness, we change the bond angles. The larger the angles, the farther away from one another the atoms are. If we move only the carbon atom, the angles actually get smaller. The only way to make the angles larger is to move two hydrogen atoms up and two down:

```
Before

After
```

How large can the angles get if we move two up and two down? When the angles all become equal, they have values of 109.5°, giving a tetrahedral shape. This structure is usually shown in a rotated form:

```
H
H—C<H
H
```

Table 8.5 shows the geometries that achieve the maximum distance between combinations of two, three, or four atoms, or unshared electron pairs. The geometries shown in the table are adopted by any set of objects that are attached at a common point and that stay as far apart as possible. For example, the balloons shown in Figure 8.25 adopt the same geometries as atoms (or unshared pairs of electrons) around a central atom. These structures, called parent structures, partly predict a molecule's shape.
Table 8.5

<table>
<thead>
<tr>
<th>Number of Atoms or Electron Pairs</th>
<th>Parent Structure</th>
<th>Geometric Arrangement of Atoms or Electron Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Trigonal planar</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Tetrahedral</td>
<td></td>
</tr>
</tbody>
</table>

Macroscopically this looks like this (-with a little help of balloons):

![Linear](image1.png) ![Trigonal Planar](image2.png) ![Tetrahedral](image3.png)

**Figure 8.25:** Macroscopic objects that are fastened to a common center adopt the same structures as molecules because, like electron pairs, they stay as far apart as possible.

The shape we assign a molecule includes only the groups of bonding electrons within the parent structure, and not the unshared pairs of electrons; the shape is a description of the locations of the atoms in the molecule.

Consider, as an example, the water molecule, which has two atoms and two unshared pairs of electrons around the central atom. The four electron pairs in H₂O arrange themselves tetrahedrally around the oxygen atom.

![Water Molecule](image4.png)

But because we consider only the two bonding pairs when we describe the molecular shape, we do not say that the water molecule is tetrahedral. Rather, we describe it as bent.
Consider the Lewis formulas for several molecules and ions (Figure 8.26) having the same general composition \( AX_3 \), \( A \) being the central atom, \( X \) being the terminal atoms.

![Lewis formulas for molecules and ions](image)

**Figure 8.26** Some molecules and ions with the formula \( AX_3 \) have a trigonal planar shape, while others have a trigonal pyramidal shape.

All possible shapes for molecules that have two to four electron pairs are summarized in Table 8.6. The bond angles for these structures are approximately those of the parent structures.

<table>
<thead>
<tr>
<th>General Formula</th>
<th>Number of Bonded Atoms</th>
<th>Number of Unshared Pairs</th>
<th>Molecular Shape</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parent Structure: Linear</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( AX_2 )</td>
<td>2</td>
<td>0</td>
<td>Linear</td>
<td>( BeCl_2, CO_2, HCN )</td>
</tr>
<tr>
<td><strong>Parent Structure: Trigonal Planar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( AX_3 )</td>
<td>3</td>
<td>0</td>
<td>Trigonal planar</td>
<td>( BF_3, BH_3, SO_3, NO_3^- )</td>
</tr>
<tr>
<td>( AX_2 )</td>
<td>2</td>
<td>1</td>
<td>Bent</td>
<td>( SO_2, NO_3^- )</td>
</tr>
<tr>
<td><strong>Parent Structure: Tetrahedral</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( AX_4 )</td>
<td>4</td>
<td>0</td>
<td>Tetrahedral</td>
<td>( CH_4, CH_2Cl_2, SiCl_4, POCl_3, BrO_3^- )</td>
</tr>
<tr>
<td>( AX_3 )</td>
<td>3</td>
<td>1</td>
<td>Trigonal pyramidal</td>
<td>( NH_3, PF_3, NH_2Cl )</td>
</tr>
<tr>
<td>( AX_2 )</td>
<td>2</td>
<td>2</td>
<td>Bent</td>
<td>( H_2O, OF_2, BrO_2^- , SCl_2 )</td>
</tr>
</tbody>
</table>
Table 8.6 Arrangement of Electron Pairs and Molecular Shapes (textbook pg. 322)

Question 2: Consider the carbonate ion, do you expect this molecule to have unshared electron pairs on the center atom? What shape will it be?

Questions 3: Please check table 8.6: Which molecular shapes result from unshared electron pairs on the center atom?

Notice in Table 8.6 that CO₂ is linear, but SO₂ with the same number of atoms is bent.

We can understand this difference using VSEPR theory. Examine the Lewis formulas of these molecules:

What is different about them? The carbon in CO₂ has two bonded atoms and no unshared electron pairs, so it has a linear structure. In contrast, sulfur in SO₂ has two bonded atoms and one unshared electron pair. The unshared pair causes the molecule to be bent. Models of these molecules are shown below.

\[ O=C=O \quad \text{and} \quad O=S=O \]

Figure 8.28 Carbon dioxide is linear, whereas sulfur dioxide is bent, because there is an unshared electron pair on the sulfur atom.

Question 4: Explain in your own words and with as much detail as you can how non-bonding electron pairs influence molecular shape. You may use terms such as "attraction" or "repulsion" in your explanation.

Now, let's take a look at what we need to do to predict the shape of a molecule according to VSEPR theory; you can use the following four steps.

The bond angles in real molecules often differ a little from the values predicted by the VSEPR theory. Differences occur because unshared pairs of electrons occupy more space than bonded pairs. The bonded pairs are forced together somewhat, resulting in slightly smaller bond angles.
than predicted. For example, ammonia, which has one unshared pair of electrons, has a bond angle of 107° rather than the predicted 109.5°. Water has two unshared pairs of electrons and a bond angle of about 105°. A similar effect is caused by a double bond, which occupies more space than a single bond.

Steps for Predicting the Shape of a Molecule

1. Draw a Lewis formula.
2. Count the number of atoms bonded to the central atom and count unshared electron pairs on the central atom.
3. Add the numbers of atoms and the number of unshared electron pairs around the central atom. The total indicates the parent structure.
4. The molecular shape is derived from the parent structure by considering only the positions in the structure occupied by bonded atoms.

Question 5: Is it really important to start by drawing the Lewis structure when predicting the molecular shape? What piece of information that a Lewis structure can provide is so crucial?

What do I do if a molecule has more than one central atom?

For molecules with more than one central atom, we can repeat the procedure for each central atom, a process that allows us to predict the structures of molecules as large and complex as proteins. Let's consider one amino acid, glycine, which might be found in a protein. It has a sweet taste and is found in gelatin and other animal products. Its formula is $\text{H}_2\text{NCH}_2\text{CO}_2\text{H}$. How do we predict its structure?

![Glycine structure]

**Glycine color Key:**
White: Hydrogen
Red: Oxygen
Blue: Nitrogen
Black: Carbon

We start, as before, by writing a Lewis formula for the molecule:

Please take a piece of paper and try it yourself. You can see the molecular structure in the figure below. Just add the remaining valence electrons. You can also follow along the description written underneath the figure to complete the structure.
The molecule contains four atoms acting as central atoms: the nitrogen atom (blue), both carbon atoms (black), and one of the oxygen atoms (red).

The **nitrogen atom** has three atoms bonded to it and one unshared electron pair. Thus, the structure around this nitrogen atom is based on a tetrahedral parent structure with one unshared pair of electrons. The shape around the nitrogen atom is trigonal pyramidal, with bond angles of about 109.5°.

The **first carbon atom (left)** is bonded to four other atoms (N, two H, and C) and has no unshared electron pairs, so the shape around it is tetrahedral, with bond angles of about 109.5°.

The **second carbon atom (right)** is bonded to three other atoms (C and two O) and has no unshared electron pairs, so the shape around it is trigonal planar, with bond angles of around 120°.

Finally, **one of the oxygen atoms** has two atoms (C and H) bonded to it and has two unshared electron pairs. The structure around it is based on a tetrahedral parent structure, but with two unshared pairs, the shape is bent. The bond angles will be around 109.5°. Verify each of these predictions by examining the molecular model of glycine in **Figure 8.29** below.

**Figure 8.29**: VSEPR Theory predicts the structure of glycine.
Question 6: In this chapter, the molecular shape has been related to the observable property of odor/smell. Can you think of other observable molecular properties that are directly related to molecular geometry?

Question 7: (possible exam question): Which molecule is linear?

A. $SO_2$  
B. $NH_3$  
C. $OF_2$  
D. $CS_2$

Question 8: (possible exam question): What is the bond angle in Freon, $CF_2Cl_2$, ([shown in figure]?)

A. 45°  
B. 90°  
C. 109.5°  
D. 120°

Question 9: Explain in your own words what is the molecular shape.
4. Covalent Bonding:

**Chemical Bonding: Covalent Bonding**

The formation and properties of ionic compounds have been discussed in the previous reading assignment; this chapter now looks more closely into covalent bonding which has been described by Gilbert N. Lewis in 1916 as “sharing of electron pairs”. Gilbert Lewis also introduced dot structures (Lewis Dot Structures) which are still used today to represent valence electrons and covalent bonding.

**What to expect in this chapter:**

In this chapter, you will learn how electrons are shared in pairs, forming covalent compounds, called molecules. The chapter also discusses the nature of the attractive forces that hold atoms together in covalent bonds (single, double, or triple bonds) and introduces intermolecular forces, which are forces that are present between two or more molecules. These forces determine a variety of molecular properties, such as the melting, and boiling point.

**When chemists discuss molecular shapes and Lewis structures, they refer to covalent compounds. Covalent compounds form through the attractions of two or more nonmetal atoms, leading to the formation of a molecule.**

**From the text (Chapter 8.2):** When two nonmetals form a compound, the bonds within the molecule are covalent.

**Review:** The ionic bond between sodium and chlorine results in the ionic compound, sodium chloride. The image below depicts the process of the electron transfers.

\[ \text{Na} + \cdot \text{Cl} \rightarrow [\text{Na}]^+ + [\cdot \text{Cl}]^- \]

A sodium atom has 1 valence electron, Chlorine has 7 valence electrons. When the atoms collide, the chlorine atom will remove the electron from the sodium. The sodium atom loses its only electron and becomes a positively charged sodium ion. This extra electron completes the stable octet for chlorine. Which becomes a negatively charged chloride ion.

It is important to note that no electrons are being transferred in a covalent molecule. Lewis structure of covalent compounds show shared electrons (bonds) as can be seen in the image showing the H₂ molecule below, and also non-bonding, free electrons as shown in the HCl molecule.
Question 1: What type of electrons (valence or core) do participate in chemical bonding and are therefore shown in Lewis structures?

From the text (Chapter 8.3): Covalent bonds involve localized attractive forces between atoms that are held together tightly in molecules. A covalent bond is strong because each shared electron interacts simultaneously with two nuclei. Electrons and nuclei attract one another because of their opposite charges. At the same time, electrons repel one another, and nuclei repel each other because of their like charges. When the electrons are located primarily between the two nuclei, the attractions are maximized, and the repulsions are minimized, resulting in a covalent bond, as shown in Figure 8.12.

When atoms are bonded, attractive and repulsive forces exist between them.

The arrows show attractive forces between subatomic particles of opposite charge and repulsive forces between particles of the same charge. Bonding still occurs because the attractive forces are stronger than the repulsive forces.

**FIGURE 8.12:** A covalent bond results when attractive forces between opposite charges are greater than repulsive forces between like charges.

The stability and bond strength of covalent bonds are due to the attractive forces acting on the individual atoms involved. Let’s consider two nonmetal atoms, A and B: When they are close to one another, there is an attraction between atom A’s electron (a negative charge) and atom B’s nucleus (a positive charge), as well as between atom A’s electron and atom A’s nucleus. At the same time though, atom A’s electron is repelled by atom B’s electron, and atom B’s nucleus is repelled by atom A’s nucleus. When the attractive forces between nuclei and electrons are
stronger than the repulsive forces between electron-electron and nucleus-nucleus interactions, a covalent bond can form!

The concept of electrostatic potential energy can be applied to explain why two neutral atoms (compared to ions of opposite charge) may come together to form a stable molecule. In the case of two hydrogen atoms (figure below), the potential energy in respect to each other is zero when they are sufficiently far apart so they have no interaction.

As they approach each other, the proton in the nucleus of one H atom is attracted to the electron of the other, and vice versa. This mutual attraction produces negative potential energy. As the distance between the atoms decreases, the potential energy decreases as well, eventually reaching a minimum when the two nuclei are 74 pm apart (bond length in H₂ molecule).

At 74 pm bond length, the atoms experience maximum attraction.

If the atoms came any closer together, the repulsion between their two positive nuclei more than offsets the mutual attraction, the potential energy rises, and the atoms will move further apart.

Question 2: Would you expect the bond length in Cl₂ to be longer or shorter than that of H₂? Explain your reasoning!

From the text (Chapter 8.3): Although the attractions (bonds) between atoms within the molecule are strong, the molecules are not bonded to other molecules. Consequently, covalent compounds have low melting and boiling points, and they often exist as gases or liquids. As solids, they are brittle or soft, because their molecules are not held together strongly. For example, in solid carbon dioxide (dry ice), the individual molecules remain intact and are identifiable in the molecular model (Figure 8.13).

Attractions between molecules are called intermolecular forces (IMF). You will need to understand these forces to completely understand the properties of covalent compounds.

Nevertheless, here are some important characteristics of covalent bonds. Please compare them with what you will learn about ionic bonds.
Substances with covalent bonds often exist as gases and liquids.

Covalent bonds have relatively low melting and boiling points.

Covalent solids are brittle or soft.

**Figure 8.13:** In solid carbon dioxide, CO₂, molecules pack together in a regular array, but they retain their identity and can be removed from the crystal easily.

**Modeling bonding in molecular compounds**

You have already discussed Lewis structures and ionic bonding and have very briefly looked at them in covalent bonding. We will now take a more in-depth look at covalent Lewis structures as well as other models for this type of bonding.

It is important to remember that **Lewis structures** only **MODEL** bonding and is method to keep track of the valence electrons of the molecule. A Lewis structure does not depict the true 3-dimensional shape of a molecule.

When writing Lewis structures, it is practical to follow certain rules, one of which is the **Octet Rule (review)**

**Text Definition:** the tendency of an atom to achieve an electron configuration having eight valence electrons

Note that there are exceptions to this definition, especially going further down the periods of the periodic table.

**Question 3:** Why do you think the models employ the idea of elements preferring the electron octet? Do you see parallels to the Bohr model or the orbital model (electron configuration)?

A closer look at single, double, and triple bonds

The number of bonds an element can form depends on its number of filled valences. In the described Lewis model, elements achieve a configuration with an octet of eight valence electrons by sharing electrons. In the oxygen molecule (O₂) for example, the number of filled valences for
each atom is 6. This means there are still 2 valences to fill. When the atoms come close enough to attract, overlap happens, and electrons can be shared. Now each oxygen atom will share 2 of its electrons with the other atom (in total, 4 electrons are shared between them).

![Diagram of oxygen atoms sharing electrons]

The 2 oxygen atoms are in close distance and their electron clouds can overlap and share electrons. Each oxygen atom has 6 valence electrons, the atoms share 2 of their electrons with each other, and that's why we see 4 electrons shared between them. Sharing electrons leads to each oxygen atom having a completed electron octet.

**Question 4:** Summarize what you have learned from the paragraph above about bonding.

**Question 5:** Review the electron configuration of the elements carbon through fluorine. How many bonds do you think each atom will make? Do your predictions result in an electron configuration containing an octet of valence electrons?

**Single Covalent Bonds**

A covalent bond that consists of a pair (2 electrons) of electrons shared by two atoms is a single bond. Each atom has a half-filled orbital in the valence level, and the orbitals overlap to allow the electron pair to be a part of both atoms. For example, in the formation of the diatomic hydrogen molecule, each hydrogen atom has an electron in the 1s orbital. When the atoms come together, as shown in Figure 8.15, the orbitals overlap, and the atoms share an electron pair:

\[ \text{H} + \text{H} \rightarrow \text{H-H} \]

The representation above of a hydrogen molecule is a Lewis formula (or electron dot formula), in which the atoms are shown separately, and the valence electrons are represented by dots. Lewis formulas are sometimes simplified by showing each bond not as a pair of dots, but as a line. For H\(_2\), the Lewis formula could be either H:H or H-H.

The important thing to remember here is that covalent bonds SHARE electrons, no atoms in the molecule "own" the valence electrons that are shared because they are partially their own, and partially the other atom's. This is what is meant by a "half-filled orbital". In the case of a hydrogen atom, 2 electrons are needed to fill its 1s orbital. When another hydrogen atom comes in close enough proximity, the two are able to share a space when they can keep the electrons, they both need to share. Because these electrons are shared, they appear as 2 dots between the 2 hydrogen atoms.
Covalent bonding cannot happen unless the atoms are close enough for attractions to take effect!

From the text (Ch 8.3): The halogens, each with seven valence electrons, also share one pair of electrons in diatomic molecules. Lewis formulas that show the distribution of electrons in the halogen molecules are given in Figure 8.16. Each atom in these structures has an octet, provided that the shared electrons are counted for each atom. Each of the covalent bonds in these molecules is a single bond since it arises from the sharing of a single electron pair.

![Figure 8.16: All the halogen elements exist as diatomic molecules. Each atom has an octet of electrons, as shown by the circles, because they share one electron pair between the bonded atoms. The shared electron pair is a single covalent bond, shown here in the overlapping circles.]

**One electron pair (2 electrons shared within the molecule) = Single Bond**

Double and Triple Covalent Bonds

Question 6: Which diatomic compounds (not elements!) form multiple bonds (double or triple) in order to achieve the electron octet
From the text (Chapter 8.3): The sum of the two points of intersection is a double bond. The
sum of the four points of intersection is a triple bond. In Lewis formulas, two points of a bond or two
parallel lines represent a double bond. Three points of a bond or three parallel lines represent a
triple bond.

<table>
<thead>
<tr>
<th>Example</th>
<th>Number of shared electrons</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>:\cdot\cdot:</td>
<td>2</td>
<td>Single Bond</td>
</tr>
<tr>
<td>:\cdot\cdot\cdot:</td>
<td>4</td>
<td>Double Bond</td>
</tr>
<tr>
<td>:\cdot\cdot\cdot\cdot:</td>
<td>6</td>
<td>Triple Bond</td>
</tr>
</tbody>
</table>
5. Ionic Bonding:

**What to expect in this chapter:**

This chapter is the first of two chapters about chemical bonding. It discusses the major differences between ionic and covalent bonding and what these differences are based on. You will also learn how an element’s electron configuration can help explain how ionic compounds are being formed and how this process can be expressed in chemical equations.

Lastly, you will look into the particle-level structure and properties of different ionic compounds.

**Ionic and covalent bonding – what is the difference?**

Ionic bonding primarily differs from covalent bonding in 2 ways:

1. Ionic bonding occurs between a metal and a nonmetal (or polyatomic ions in the place of the cation or anion); covalent bonding is between a nonmetal and another nonmetal.
2. In ionic bonding electrons are being transferred; in covalent bonding, electrons are being shared.

Two concepts that are important in this context... In order to understand why some elements bond together to form covalent bonds and others result in ionic bonds, we need to look into two important concepts:

1. **Bond Polarity**
   - Definition: The degree of transfer of electrons between two atoms. Basically, which atom in the bonded pair is pulling the bonding electrons (two electrons form a single bond) to itself. Non-polar covalent bonds, in which both atoms equally share the bonding electrons, lie at one end of the continuum shown in Figure 8.3, ionic bonds, in which one atom pulls much stronger than the other, lie at the other. Some ionic compounds, e.g., sodium chloride (NaCl) are already familiar to you. Sodium chloride is also commonly called table salt.

2. **Electronegativity**
   - Definition: The ability of an atom to attract bonding electrons. The electronegativity of two bonded atoms determines the nature of a bond: equal sharing of electrons between atoms of the same electronegativity (e.g., in O₂ or N₂) results in nonpolar covalent bonds, while unequal sharing between atoms of different electronegativity (e.g., HCl or CO) creates a polar covalent bond (Higher electron density around one of the bonded atoms).

   If the difference in electronegativity between the bonded atoms is even greater, the result is an ionic bond.

   The table below provides more detailed information about atom’s electronegativity difference and the resulting bonding type (approximation).
In Figure 8.3, it can be seen that the polar covalent bond falls between the nonpolar covalent bond and the ionic bond.

In Figure 8.3
Let’s dive a bit deeper into ionic bonding

Ionic bonding happens between a metal and a non-metal (or polyatomic ions in place of either). Electrons are being transferred from the less electronegative metal to the more electronegative non-metal which will result in the formation of a metal cation (an ion with a positive charge) and a non-metal anion (an ion with a negative charge) held together by electrostatic forces.

With this review in mind, we can take a look at the bonding itself:
From the book (Chapter 8.2): The formation of ions and ionic bonds relates to the electron configurations of the elements. We can see this relationship in the Periodic Table. Each element immediately following a noble gas (in the Periodic Table) is a metal, which has a strong tendency to lose electrons and thereby achieve a stable noble-gas electron configuration. When giving up electrons to gain a noble-gas configuration, the metal develops a positive electrical charge, forming a cation. Each element immediately preceding a noble gas in the Periodic Table is a nonmetal, which has a strong tendency to gain electrons to achieve a noble-gas configuration. In so doing, it develops a negative electrical charge, forming an anion.

Questions 1: Please summarize the main idea expressed in the paragraph above (2 sentences, and in your own words).

Lewis Symbols (Not the same as Lewis structures)

So now that we know what ionic bonding is, it’s helpful to have a method of showing the valence electrons (the electrons involved in bonding) and how they are transferred between the cations and anions.

A quick review from Chapter 7.3: For the main-group elements, the valence electrons are located in ns and np orbitals, where n designates the principal energy level.

From the text (Chapter 8.2): The electrons involved in bonding are the valence electrons. A convenient way to show the valence electrons is with a Lewis symbol or an electron dot-symbol, in which dots placed around an element’s symbol represent valence electrons. The dots are placed singly on the four sides of the elemental symbol, in any order, and then paired as necessary. An element with a noble-gas configuration is surrounded by four pairs of dots representing eight electrons, an octet.

Example: Lewis symbol for chlorine

Chlorine has 7 valence electrons which is why its Lewis dot structure is written with 7 dots.

The Lewis symbols for the period 2 elements show a progression starting with one valence electron for Li and ending with eight for Ne. You can also draw the Lewis symbols for the period 3 elements, Na through Ar. What pattern develops? It should look the same, starting with one valence electron for the group IA (1) elements and ending with eight in group VIIA (18). All the noble-gas elements have eight valence electrons occurring in four pairs, except for helium, which only has two.

Lewis symbols give a quick yet efficient look at how many valence electrons an atom has, and they can also show how those valence electrons will be distributed during bonding. To understand how they work, take a look at Table 8.3 below. Notice how the number of valence electrons (the number of dots placed around the element) comes directly from the number of
electrons in the 2s and 2p orbitals. In other words, the number of dots around the element directly corresponds to the Main Group numbers IA through VIIIA, (NOT the group number because this would include the Transition elements).

<table>
<thead>
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<th>1</th>
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<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Configuration</td>
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<td>[He]2s²2p⁰</td>
<td>[He]2s²2p⁰</td>
<td>[He]2s²2p⁰</td>
<td>[He]2s²2p⁰</td>
<td>[He]2s²2p⁰</td>
<td>[He]2s²2p⁰</td>
<td>[He]2s²2p⁰</td>
</tr>
<tr>
<td>Lewis Dot Symbol</td>
<td>Li⁺</td>
<td>Be⁺</td>
<td>B⁺</td>
<td>C⁺</td>
<td>N⁺</td>
<td>O⁺</td>
<td>F⁻</td>
<td>Ne²⁻</td>
</tr>
</tbody>
</table>

**Table 8.3**

**Question 2:** How can you describe the location of valence electrons in an atom compared to its core electrons.

**Question 3:** How many electrons should be shown in the Lewis symbol of Aluminum? You can use the Bohr model of aluminum below to answer the question.

Aluminum has an atomic number of 13, (13 electrons). The 1st energy level takes 2 electrons, the 2nd takes 8 electrons. The remaining 3 will be placed on the 3rd energy level and all this adds up to 13.

The formation of ionic compounds

The loss of electrons from a metal and the gain of electrons by a nonmetal create the simplest kind of ionic bond. The transfer must happen at the same time. A neutral metal can lose electrons to form a cation only when a nonmetal is available to gain them. The nonmetal then forms an anion with a stable octet of valence electrons. Therefore, the net charge on an ionic compound remains the same as in neutral atoms, which is zero. We can’t lose electrons and have them go nowhere!
The following equations use Lewis symbols to illustrate this process in the formation of sodium chloride:

Example A: NaCl

\[
\begin{align*}
\text{Na}^+ & \rightarrow \text{Na}^+ + \text{e}^- \\
:\overset{\cdot}{\text{Cl}}^- + \text{e}^- & \rightarrow :\overset{\cdot}{\text{Cl}}^- \\
\text{Na}^+ + :\overset{\cdot}{\text{Cl}}^- & \rightarrow (\text{Na}^+)(:\overset{\cdot}{\text{Cl}}^-) \text{ or NaCl}
\end{align*}
\]

The sodium atom loses one electron to form a sodium ion. The ion then has 10 electrons, it has noble-gas configuration (same number of electrons as neon). The electron is transferred to a chlorine atom, which becomes a chloride ion; this ion also has a noble-gas configuration. The ions associate to form sodium chloride, a compound held together by attractions between the opposite charges of the ions (electrostatic attractions).

Because sodium loses one electron and chlorine gains one, the atoms combine in a 1:1 ratio, which leads to electrical neutrality.

Remember, the metal (Na) loses its electron which is transferred to the nonmetal (Cl). When this happens, Na has lost one negatively charged electron, so now it is positive. Because Cl has gained the electron, it is now negative.

Other ions may combine in different ratios. Consider, for example, the formation of aluminum chloride:

Example B: AlCl₃

\[
\begin{align*}
\text{Al}^+ & \rightarrow \text{Al}^{3+} + 3\text{e}^- \\
3:\overset{\cdot}{\text{Cl}}^- + 3\text{e}^- & \rightarrow 3:\overset{\cdot}{\text{Cl}}^- \\
\text{Al}^{3+} + 3:\overset{\cdot}{\text{Cl}}^- & \rightarrow (\text{Al}^{3+})(:\overset{\cdot}{\text{Cl}}^-)_3 \text{ or AlCl}_3
\end{align*}
\]

Aluminum loses three electrons to achieve a noble-gas electron configuration. Since it takes only one electron to complete the chlorine atoms octet, three chlorine atoms are required to take the three electrons given up by the aluminum atom. We now have an aluminum ion and three chloride ions, which associate in an electrically neutral 1:3 ratio to form ionic aluminum chloride, AlCl₃. This ratio is maintained by an array of aluminum cations and chloride anions arranged in a regular pattern.

Important note! In the previous two examples, a series of equations was given to visualize the process of ionic bonding. It is important to remember that while they are displayed in stepwise equations, these processes are happening simultaneously, NOT in a series of steps.

Question 4: What is the ratio of Al and S if those elements combine to form an ionic compound? Explain how you determined the ratio.
Structure and Properties of Ionic Crystals

Now let's take a look at the actual structure of ionic compounds.

When an ionic compound forms from its elements, billions of cations and billions of anions form and bond to give a single ionic crystal. (Mono-atomic ions on average have a radius of 150 pm (10^{-12} m)).

From the text (Chapter 8.2): The bonds that hold ions together in ionic compounds result from attractions between oppositely charged ions. If like-charged ions are close to one another, their repulsions partially offset these attractive forces, as shown in Figure 8.7. How do the ions fit together to make a stable ionic compound? An ion, which may be represented as a charged sphere, exerts a force equally in all directions, so ions of opposite charge surround it. The pattern is a crystal lattice, and the result is an ionic crystal, in which the ions are arranged in a regular geometric pattern that maximizes the attractive forces and minimizes the repulsive forces.

Question 5: Summarize in one sentence, why atoms bond to other atoms?

Figure 8.7

We know that ions are formed by atoms losing or gaining electrons. An electrostatic attraction happens, and a bond is formed. When there is a larger charge, there will be a larger attraction between atoms. A small ion and a large charge also result in a stronger interaction.

It is the opposite charges on ions in ionic compounds that hold them together so tightly and accounts for many of their characteristics, for example, high melting point.

The charges and sizes of the ions largely determine the characteristic patterns of ionic crystals.
For example, many ionic solids with 3:1 ratio of ions have the same structure as sodium chloride. With each ion surrounded by six ions of opposite charge (Figure 8.8).

![Diagram of sodium chloride structure]

Figure 8.8: The sodium chloride structure is represented as the molecular level in two ways. A. shows the bonds between the ions in the crystal lattice. B. shows the arrangement of the ions in the crystal lattice.

A and B are two different models of a crystal lattice, both are useful to help visualize the overall bonding of sodium chlorides in the crystal lattice. For a crystal lattice to form, charges on ions must cancel to form negative and positive ions. If the force of attraction between ions is too strong, the crystal lattice will not form.

CCl4 (carbon tetrachloride) is an example of a substance that has a different structure to crystals. CCl4 exists as a gas at room temperature and is nonpolar. The C-Cl bonds are nonpolar, and the molecule is symmetrical. The molecule is nonpolar, and the molecule is symmetrical. The C-Cl bonds are nonpolar, and the molecule is symmetrical. The C-Cl bonds are nonpolar, and the molecule is symmetrical. The C-Cl bonds are nonpolar, and the molecule is symmetrical.
**FIGURE 8.10:** Ionic compounds that have twice as many of one ion as the other often adopt the same structure as CaF$_2$, found in the mineral fluorite.

Ionic bonds are very strong because of the large number of interactions between oppositely charged ions. It takes a lot of energy to separate an ion from the solid structure. The structure directly affects the compounds properties.

Because melting and boiling require the separation of ions, ionic compounds have high melting and boiling points.

The strong attractive forces also make ionic crystals hard and brittle. If struck forcefully, ionic crystals shatter. They break because the force shifts the alignment of ions from the stable interaction of opposite charges to an unstable alignment of like charges (Figure 8.11). Along a shifted layer, strong repulsive forces replace strong attractive forces and the crystal cracks.

**FIGURE 8.11:** When a crystal such as NaCl is struck with sufficient force, layers of ions shift. The attractive forces between ions of opposite charge move out of alignment. Layers of like charge align, and they are pushed apart by repulsive forces. The crystal splits along these lines.

The crystalline structure of ionic compounds also explains why solid ionic salts are poor conductors of electricity. The ions are not mobile but are held in place in the crystal lattice. However, melting greatly increases the electrical conductivity of ionic salts, because the ions in the liquid are free to move around.

Other properties of ionic molecules include:
• Dissociation in water: compounds “break apart into separate ions” when dissolved in water
• Good electrical conductivity
• Strong electrolytes
• High melting point
• Solid at room temp. (this refers right back to the high melting point)
• Brittle
• High density

Question 6: What exactly determines if a substance is conductive?

Question 7: (possible MC exam question)
Which element has the exact same number of valence electrons as carbon?
A. Boron  B. Nitrogen  C. Silicon  D. Sulfur

Question 8: (possible MC exam question)
An ionic compound is formed between a metal (M) and nitrogen with the formula M₃N₂. What is M?
A. Potassium  B. Oxygen  C. Magnesium  D. Aluminum
6. Periodic Trends:

**Periodic Trends**

**What to expect in this chapter:**

Over the course of history, many scientists attempted to compare, and group chemical elements based on their properties. The development of the modern periodic table is the work of the Russian chemist Dmitri Mendeleev who presented his version of the Periodic Table in 1869 to the world. He arranged chemical elements by their atomic mass and properties and was even able to predict the existence of elements that had not yet been discovered.

This chapter will discuss patterns in regard to the properties of chemical elements on the periodic table. These reoccurring patterns (period trends) allow us to make predictions about the properties of elements based on their location in the periodic table. The electron configuration of elements plays a very important role.

Therefore, we’ll talk about how electron arrangements relate to other properties of elements, such as reactivity, ionization energy and atomic size.

**Chemical Reactivity and Electron Configurations:**

The activity series predicts the relative reactivity of metals (and Hydrogen) relative to one another. Notice the elements that are at the top of the activity series, as shown in Figure 7.24. Can you see the pattern? Most are alkali metals, group IA (1), and alkaline earth metals, group IIA (2). They are the most reactive metals.

The alkali metals, in the first group in the periodic table, are commonly found in nature as oxides. Their stable compounds with oxygen have the general formula $M_2O$, where $M$ represents an alkali metal:

$$Li_2O, Na_2O, K_2O, Rb_2O, Cs_2O,$$

**Question 1:** What would be the general formula of compounds formed between group IIA elements and oxygen?
Figure 7.24 In this chemical activity series, the most active elements appear at the top.

Ionization Energy:

When metal elements react, they lose valence electrons and form cations. The more easily metal atoms give up their valence electrons, the more reactive they are. One important factor is ionization energy (IE), which is a measure of the energy required to remove a valence electron from a gaseous atom to form a gaseous ion. It is usually expressed as the energy required to remove an electron from each atom in exactly 1 mol (6.022 × 10^23) of atoms. For example, consider the ionization process for lithium, which can be represented with the following equation:

\[ \text{Li}(g) \rightarrow \text{Li}^+(g) + e^- \quad \text{IE} = 520 \text{ KJ/mol} \]

In other words, 520 KJ of energy would be required to remove the outermost electron from each atom in 1 mol of lithium. Ionization energy is related to electron arrangement and helps explain differences in the reactivities of metals. In general, atoms with low ionization energies do not bind their valence electrons very tightly, so they are very reactive.

Trends in Ionization Energies:

The ionization energies of the main-group elements are given in Figure 7.26. Notice that the ionization energies of the alkali and alkaline earth metals are relatively low. If we look specifically at elements in the same group, we can see that their ionization energies decrease as we move down a group. This happens because the valence electron that’s removed upon ionization is farther from the nucleus as we move down a group. Electrons farther from the nucleus are easier to remove. They are not as strongly attracted to the positive charge of the nucleus (Figure 7.27). Effective nuclear charge \( Z_{\text{eff}} \) is the net positive charge experienced by an electron in an atom that contains more than one atom. It is a measure of how strongly an electron is held. In addition, valence electrons are shielded from the attraction of protons by
core electrons closer to the nucleus. As the number of core sublevels increases, so does the effect of shielding. This explains why elements such as cesium are so reactive.

FIGURE 7.26 Ionization energies for the main group elements are given in units of kJ/mol. They are the amount of energy needed to remove one electron from each atom in 1 mol of atoms of the element when in the gaseous state.

In smaller atoms, electrons are closer to the nucleus, and therefore more strongly attracted by the positive nuclear charge.

FIGURE 7.27 A valence electron in a lower principal energy level is closer to the nucleus than a valence electron in a higher principal energy level. The attraction between the nucleus and the valence electron is greater for smaller atoms, resulting in a greater ionization energy.

Question 2: Which element, carbon or fluorine, should have the greater first ionization energy? Why? Please give your reasoning.

Question 3: Which element, strontium or magnesium, should have the greater first ionization energy? Why? Please give your reasoning.

You may have observed another pattern in ionization energies from Figure 7.26. They increase from left to right on the periodic table. What is different about atoms in the same period that makes ionization energy increase? The increase in the number of electrons does not explain this trend. As we move across a period from left to right, electrons are added to the same principal energy level. This has a negligible effect on ionization energy. However, an increase in the number of protons in the nucleus as we move across the periodic table causes ionization energy to increase because of the additional positive charge. This increase in nuclear charge
pulls the electrons in the valence level closer to the nucleus and makes the removal of a valence electron more difficult. The general tendency is for ionization energy to increase from bottom to top and from left to right across the periodic table (Figure 7.28).

Question 4: Please summarize in one sentence and in your own words, the main idea in the paragraph above.

![Figure 7.28](image) Ionization energy tends to increase going up the periodic table and from left to right.

Atomic Size:

Another trend that shows a pattern throughout the periodic table is the size of atoms. The size of an atom is often described in terms of its atomic radius, the distance from the center of the nucleus to the outer edge of the atom. The radius of an atom is often reported in units of picometers (1 pm = 10^{-12} m). Because the outer edge of an atom is not sharply defined, scientists measure the distance between the centers of two identical bonded atoms to determine atomic radii. The radius is one-half this distance (Figure 7.29).

![Figure 7.29](image) To determine the size of an atom, scientists measure the distance between the centers of two bonded atoms. For identical atoms, the atomic radius is one-half this distance.

Atomic radii for the main-group elements are shown in Figure 7.30. Do you observe any patterns? Notice that the atomic radius generally increases as we move down a group. How might you explain this trend? The electron configurations for the elements in a group provide the answer.
For example, recall the electron configurations for the alkali metals, group IA (1):

Li \quad [\text{He}]2s^1 \quad \text{Rb} \quad [\text{Kr}]5s^1
Na \quad [\text{Ne}]3s^1 \quad \text{Cs} \quad [\text{Xe}]6s^1
K \quad [\text{Ar}]4s^1

Lithium’s valence electron is in the 2s orbital; the valence level is \( n = 2 \), very close to the nucleus. At the bottom of the group is cesium. Its valence level is \( n = 6 \), much farther from the nucleus. As we go from top to bottom in a group, the atomic radius increases because the valence electrons are in larger orbitals farther away from the nucleus.

**Question 5:** What can you say about the nuclear attraction on one of the electrons in the principle energy level with \( n = 6 \) (in comparison to electrons in lower energy levels)?

As we move from left to right across a period, atomic size generally decreases. You might think that size should increase because the number of electrons increases, but the electrons are added to the same principal energy level while the positive charge in the nucleus increases. As we move from left to right across a period, the increased positive charge in the nucleus becomes more effective at drawing the valence electrons closer to the center of the atom, causing atoms to the right on the periodic table to be smaller in size. Trends in atomic size are shown in Figure 7.31.

As you go from left to right, the atomic size decreases because even though the number of electrons increases, the number of protons for each element increases which as well strengthens the attraction of the electrons to the nucleus. A stronger attraction results in a decrease of size...

This image shows us that the atomic size increases from right to left and from top to bottom. Please refer to the audio on Figure 7.29 to understand this trend.
FIGURE 7.30 This periodic table shows the relative atomic size of the main-group elements, along with their atomic radii in units of picometers. (Except for the noble gases, the atomic radius is determined as half the distance between two bonded atoms.)

FIGURE 7.31 Atomic size increases down a group and from right to left in a period.

Question 6: Which atom is larger, carbon or fluorine? Explain.

Question 7: Which atom is smaller, strontium or magnesium? Explain.

Sizes of Ions:
When ions form from neutral atoms, the radii of the atoms change. Consider what happens when lithium ionizes (Figure 7.32A). A neutral atom of lithium has 3 electrons and 3 protons. The ion has 2 electrons and 3 protons. The nuclear charge remains the same, while the number of electrons decreases. In the ion, the protons draw the remaining electrons closer to the nucleus. Consequently, the Li⁺ ion is smaller than the neutral atom.

When an atom loses one or more electrons, it becomes a positively charged ion, called a cation. In Figure 7.32, the metal Lithium loses an electron to form a single positive lithium ion. On the other hand, the image shows that if neutral atoms gain electrons, an anion is formed. As an example, here, Florine gains one electron to form a negatively charged fluoride ion.

FIGURE 7.32 (A) A cation is smaller than the neutral atom from which it forms. The nucleus holds the cation’s fewer electrons more tightly. (B) An anion is larger than the neutral atom from which it forms. The nucleus holds the anion’s greater number of electrons less tightly.
The opposite happens with anions. For example, consider the formation of the fluoride ion (Figure 7.32B). The neutral atom has 9 electrons and 9 protons. The F⁻ ion has 10 electrons and 9 protons. Because there are more electrons, the protons cannot hold the electrons as close to the nucleus. Thus, the ion is larger than the neutral atom. A summary of the sizes of many main-group ions is given in Figure 7.33.

There are so many factors involved in determining the sizes of ions that no single trend spans the entire periodic table. However, for a series of ions with the same number of electrons—an isoelectronic series—consider the following ions:

<table>
<thead>
<tr>
<th>Ion</th>
<th>Radius (pm)</th>
<th>Electron Configuration</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>S²⁻</td>
<td>184</td>
<td>1s²2s²2p⁶3s²3p⁶</td>
<td>16</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>181</td>
<td>1s²2s²2p⁶3s²3p⁶</td>
<td>17</td>
</tr>
<tr>
<td>K⁺</td>
<td>133</td>
<td>1s²2s²2p⁶3s²3p⁶</td>
<td>19</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>99</td>
<td>1s²2s²2p⁶3s²3p⁶</td>
<td>20</td>
</tr>
<tr>
<td>Sc⁵⁺</td>
<td>81</td>
<td>1s²2s²2p⁶3s²3p⁶</td>
<td>21</td>
</tr>
</tbody>
</table>

All of the ions in this series have the same number of electrons and the same electron configuration. However, they have different numbers of protons (atomic numbers). For any isoelectronic series, as the number of protons increases, the ion size decreases.
FIGURE 7.33 Shown here are the ionic radii for ions of the main-group elements. Note the trends down a group and for ions that are isoelectronic.

Question 8: How does this all relate to electronegativity?
7. Properties and Changes:

Properties and Changes

What to expect in this chapter:

Science depends on observations and accurate descriptions of, for example, phenomena and experimental results. Each substance can be described by its physical and chemical properties and its behavior. In this chapter, you will discuss the various categories of properties that are used to describe and also changes that substances can undergo. In addition, you will learn about two properties, density, and temperature, in more detail.

Changes in matter are part of the properties of matter. Their observations could be either qualitative, based on some quality of the matter; or quantitative, based on a numerical value. When making qualitative observations, color, shape, texture, shininess, and physical state are described.

In this chapter, you will be introduced to some important physical changes, temperature, and density.

Properties:

When reporting qualitative data, we can classify properties as either physical or chemical.

When you observe the color, shape, texture, shininess, and physical state of things around you, you are noting their physical properties.

A physical property is a characteristic that we can observe or measure without changing the composition of a substance.

Other examples of physical properties are odor, taste, hardness, mass, volume, density, magnetism, conductivity, and the temperatures at which a substance changes from one physical state to another (e.g., freezing, or boiling point).

As you can see above, there are many physical properties, some of which depend on the size of a sample, like mass and volume, some of which are independent of the sample size, meaning they do not change whether you investigate a large or a small sample size. Examples for this are odor, hardness, density, conductivity, and color.

Physical properties that are dependent on sample size are called extensive physical properties; properties that do not depend on the sample size are called intensive physical properties.

Chemical properties are different. A chemical property of a substance is defined by what it is composed of and what chemical changes it can undergo.

It is, for example, a chemical property of iron that it can rust when exposed to the environment. A substance’s reactivity with water is another example – some elements or compounds react vigorously; some do not react at all.
Question 1: Can you name/describe other chemical properties?

Important examples of physical properties: density and temperature

Let's take a close look at density and temperature. These properties are quantitative; they involve numerical values - like also e.g., mass and volume.

Density:

The density of an object is the ratio of its mass to its volume.

This ratio can be expressed using an equation: \[ \text{Density} = \frac{\text{mass}}{\text{volume}} \]

While mass and volume both depend on the size of the object or sample, density does not. Density is an unvarying property of a substance no matter how much of it is present, as long as temperature and pressure are constant. The densities of a few substances are listed in Table 1.6.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Physical State</th>
<th>Density in g/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>gas</td>
<td>0.000178</td>
</tr>
<tr>
<td>Oxygen</td>
<td>gas</td>
<td>0.00143</td>
</tr>
<tr>
<td>Cooking Oil</td>
<td>liquid</td>
<td>0.92</td>
</tr>
<tr>
<td>Water</td>
<td>liquid</td>
<td>1</td>
</tr>
<tr>
<td>Mercury</td>
<td>liquid</td>
<td>13.6</td>
</tr>
<tr>
<td>Gold</td>
<td>solid</td>
<td>19.3</td>
</tr>
<tr>
<td>Copper</td>
<td>solid</td>
<td>8.92</td>
</tr>
<tr>
<td>Zinc</td>
<td>solid</td>
<td>7.14</td>
</tr>
<tr>
<td>Ice</td>
<td>solid</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table 1.6: Densities of some common Substances

The graduated cylinder below contains several liquids with different densities. The densities of antifreeze, corn oil, dish detergent, maple syrup, shampoo, and water in g/mL are 1.13, 0.93, 1.03, 1.32, 1.01, and 1.00, respectively.

Question 2: What is the pink liquid and what is its density?

If we compare equal volumes of two different substances, such as aluminum and gold, as shown in Figure 1.19, the substance with the greater mass has the greater density.

How, though, can we compare densities if we do not have equal volumes? The mathematical relationship of mass, volume, and density reveals the answer.
density = \frac{mass}{volume}

The graduated cylinder above contains several liquids with different densities. From top to bottom the density of the liquids increases. We have Corn oil (0.93), water (1.00), shampoo (1.01), dish detergent (1.03), antifreeze (1.13) and maple syrup (1.32).

**Question 3:** What is the unit for density? Does the unit depend on the state of matter of the substance?

![Image](image1.png)

**Figure 1.19:**

Atoms in metals are tightly packed together in a defined volume, some metals pack more closely than others. The atoms in gold are tightly packed than those in aluminum, which is why gold is denser than aluminum.

![Image](image2.png)

**Figure 1.20**

Gold (Au) has a greater density than aluminum (Al) because gold has a greater mass per unit volume.

**Question 4:** Why do different solids have different densities?

Water is unique among liquids because its solid form (ice) floats on its liquid form. This results from the relatively open structure adopted by water molecules in the solid state. What would happen to fish during the winter if ice were like other solids that sink in their liquid form? Why do substances have different densities? Gases, in general, have very low densities because gas particles spread out and occupy large volumes. Metals tend to have high densities because their atoms pack together efficiently. Because ice floats on water, we can infer that water in its solid form must have a lesser density than water in its liquid form. Example 1.8 shows how to use molecular pictures to predict relative densities.

**Question 5:** How do the molecular diagrams of ice and water (see below) help explain why ice is less dense than water? And - what fills the space between water molecules?
Here is something to think about:

**Question 6:** Does one water molecule have the same density as a drop of water? Explain!

**Temperature (another physical intensive property)**

Some days you might not be happy with your lunch; the pizza is cold, and the soda is warm. When we make such comparisons, we are observing relative temperatures. Temperature is a measure of how hot or cold something is relative to some standard. We measure temperature with a thermometer. In the United States, we often use the Fahrenheit scale to measure body temperature and air temperature. Fahrenheit is rarely used in science. Two other temperature scales are standard: the Celsius scale and the Kelvin scale. The relationships between the three temperature scales, Fahrenheit (°F), Celsius (°C), and Kelvin (K), are shown in Figure 1.22.

This image compares the different temperature scales. The Celsius temperature scale is the most used scale in the world; however, the US uses the Fahrenheit scale. You can see that ice melts/liquid water freezes at 32°F, which corresponds to 0 Celsius and 273.15 on the Kelvin scale.
Figure 1.22: Comparison of the Fahrenheit, Celsius, and Kelvin temperature scales

Temperatures are written differently for the different scales. While Celsius and Fahrenheit use the superscript ° to indicate degrees, the Kelvin scale does not. The unit is written as K (the capital letter), but temperatures are measured in kelvins (lowercase).

Another property of matter that is independent of sample size is the temperature at which the substance changes from one physical state to another. The boiling point is the temperature at which the liquid form of a substance changes to the gaseous form. At the melting point, the substance changes from a solid to a liquid. Between these two temperatures, the substance is normally in its liquid state. For example, on the Celsius scale, the boiling point of water is 100°C. Water melts (or freezes, depending on its original state) at 0°C. On the Kelvin scale, these values are 373.15 K and 273.15 K, respectively. On the Fahrenheit scale, they are 212°F and 32°F, respectively.

**Question 7:** Please summarize in your own words the main idea described in the paragraph above.

There are no negative values on the Kelvin scale. It is an absolute temperature scale because its zero point is the lowest possible temperature observable in the universe. This value is absolute zero, which is equivalent to −273.15°C. The temperature increments on the Kelvin scale are the same as those on the Celsius scale. The difference in temperature between the boiling point of water and the freezing point of water is 100 in both the Celsius (100°C – 0°C) and kelvin (373.15 K – 273.15 K) scales, while the difference is 180 on the Fahrenheit scale (212°F – 32°F). Because the temperature in Kelvins is always 273.15 greater than the temperature in degrees Celsius, we can easily convert between them.

**Question 8:** Why do we have different temperature scales? How could you set up a new temperature scale?

**Physical and Chemical Changes:**

As you have just seen, when water changes its state of matter, it does not change the overall composition of the substance (H₂O molecules stay intact). Any change like this is called a physical change.

On the other hand, changes in which substances change their composition, and these changes result in the formation of one or more new substances, is called a chemical change or chemical reaction.
Summary of new terms:
A physical property is a characteristic that we can observe or measure without changing the composition of a substance.

Accordingly, a physical change is a process that changes the physical properties of a substance without changing its composition.

In contrast, a chemical change (or chemical reaction) is a process in which one or more substances are converted into one or more new substances.

A substance is a particular kind of matter with the same properties.

Question 9: According to these definitions, what is the correct answer to the question below?

What is shown in the representation?
A. A compound undergoing a chemical change.
B. A compound undergoing a physical change.
C. An element undergoing a chemical change.
D. An element undergoing a physical change.
8. Formula Calculations:

Formula Calculations

What to expect in this chapter:
This chapter will introduce you to the way chemists describe and calculate with large amounts of particles that are too small to see. You will be introduced to a unit called “the mole”, which has a value of $6.022 \times 10^{23}$ (Avogadro’s Number). The mole allows chemists to translate masses (measured in grams) into the amount of particles a sample contains. In this context, it is very helpful to work with molar masses (mass of one mole of particles) for different elements. The molar mass of each element and compound is very different due to the fact that atoms of different elements have different masses. In addition to mass – particle calculations, this chapter will also explain how Avogadro’s number and molar masses can be used to determine empirical and molecular formulas.

Formula calculations:
Formula calculations are calculations that are based on the ratios of elements given in the chemical formula. Therefore, let’s look at some examples first:

What information does the formula $\text{Na}_2\text{SO}_4$ provide?

1. It provides information about the type of compound, in the case of sodium sulfate, the compound is ionic (review).
2. The formula also gives the total number of atoms in one formula unit, for sodium sulfate, the total number is 7.
3. The formula provides the element ratios: one formula unit of sodium sulfate for example contains four times as many oxygen atoms as it contains sulfur atoms, twice as many oxygen atoms as sodium atoms, and double the amount of sodium atoms as there are sulfur atoms.

Question 1: Describe the atomic ratios in the molecular compound ethanol, $\text{CH}_3\text{CH}_2\text{OH}$.

The Mole: Describing larger quantities:
Chemical formulas are helpful more than the ways described above, they also let us calculate larger quantities of those components, quantities that we can work with in a laboratory environment. For the previous example of sodium sulfate, we describe the atom ratios in one formula unit. In a laboratory setting though, chemists are not working with single molecules, as the sheer number of molecules involved in a given reaction would be completely impractical. Unfortunately, we cannot see atoms and molecules because they are too small. Although we can use a scanning tunneling microscope to “see” atoms and molecules on the surface of a solid, as shown in Figure 4.7, this technique reveals only atoms on a surface, not those beneath.

Atoms and molecules cannot be seen with bare eyes, because they are too small, which is why a scanning tunneling microscope was used to see atoms and molecules on the surface of this solid.
Figure 4.7: The "bumps" in this image are atoms on the surface of a mica crystal. Mica is a mineral containing potassium and aluminum cations and silicate and hydroxide anions.

Did you know...

... a dust-sized piece of a solid contains over $10^{16}$ of each type of atom. We certainly wouldn't want to count that many atoms individually, even if we could. Fortunately, we don't have to see atoms to count them. Instead, we can find the relative masses of the elements in a compound.

Units of Quantity:

From the text (Chap. 4.2): In Chapter 2, we saw that the average masses of the elements can be expressed as their relative atomic masses. For the elements in hydrogen sulfide, the relative atomic masses are 1.008 amu for hydrogen and 32.07 amu for sulfur.

While relative atomic masses are very useful for comparing the masses of elements, atomic mass units are not useful to chemists weighing substances to use in chemical reactions like those for processing copper oxides.

Common laboratory balances measure masses in grams, not atomic mass units. We cannot weigh one or even a few atoms, molecules, or formula units of a substance, since the masses of most atoms and common molecules are less than $10^{-21}$ g. To work with a mass of about 1 g, we have to measure a number of formula units greater than $10^{21}$. For example, to get 1.0 g of H$_2$S, we would need almost $2 \times 10^{22}$ molecules. To get an idea of how large this number is, consider a teaspoon of water.

There are as many molecules of water in this teaspoon (about $1.7 \times 10^{23}$) as there are teaspoons full of water in all the oceans on Earth. Similarly, there are about as many SiO$_2$ formula units in one grain of quartz sand as there are sand grains on all the beaches on Earth.

Because numbers this large are too unwieldy to work with easily, we need some way to measure the amount of a substance without counting the number of atoms, formula units, or molecules.

This unit that bridges this gap is called the mole, or mol, and represents the amount of substance that contains as many atoms, molecules, formula units, etc. as there are atoms in exactly 12g of Carbon. (Definition!!)

The number of atoms in 12g of C has been experimentally determined as $6.022 \times 10^{23}$ atoms and is commonly referred to as Avogadro's Number ($N_A$).

$$\text{Avogadro's Number } = N_A = 6.022 \times 10^{23} \text{ atoms } \text{ mole}$$

Although 1 mol contains different volumes and different masses of different materials, it is always the same number of formula units (atoms, molecules, or ionic compound formula units).

→important Note! We use the abbreviation mol for mole, but molecule should not be abbreviated.
Calculations Involving Moles:

We can now discuss various ways in which moles can be used to quantize and calculate chemical components.

1. The mole as the number of particles.

From the text (Chap. 4.2): *We can convert between moles and formula units using the following pathway:*

![Diagram showing the conversion process from moles to number of atoms, molecules, or ions using Avogadro's number (N_a).]

If 1 mol can be 1 mol of atoms, molecules, formula units (referring to ionic compounds), or ions, then we can easily calculate the number of copper atoms in 2 moles of copper.

The mathematical set-up is as follows; the unwanted units cancel out.

\[
2 \text{ mol Cu} = \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol Cu}} = 1.204 \times 10^{24} \text{ Cu atoms}
\]

**Questions 2: How many copper atoms are in 0.3 mol of copper?**

2. The mole used to calculate the number of atoms in a compound

*We can also calculate the number of atoms or ions in a formula unit. To determine the number of atoms or ions in a given number of moles of a substance, we extend the pathway further to include analysis of the chemical formula:*

![Diagram showing the conversion process from moles to number of atoms or ions in a compound involving Avogadro's number, chemical formula, and number of formula units.]

Consider another example, copper(I) oxide. How many ions does 1 mol of Cu_2O contain? Analysis of the chemical formula indicates that a formula unit of Cu_2O contains two Cu^+ ions and one O^{2-} ion, as shown in Figure 4.9.
This gives us the following:

\[
\frac{1 \text{ mol Cu}_2\text{O}}{1 \text{ mol Cu}_2\text{O}} \times \frac{6.022 \times 10^{23} \text{ formula units Cu}_2\text{O}^-}{1 \text{ mol Cu}_2\text{O}} \times \frac{2 \text{ Cu}^+ \text{ ions}}{1 \text{ formula unit Cu}_2\text{O}^-} = 1.204 \times 10^{24} \text{ Cu}^+ \text{ ions}
\]

\[
\frac{1 \text{ mol Cu}_2\text{O}}{1 \text{ mol Cu}_2\text{O}} \times \frac{6.022 \times 10^{23} \text{ formula units Cu}_2\text{O}^-}{1 \text{ mol Cu}_2\text{O}} \times \frac{1 \text{ O}^2^- \text{ ion}}{1 \text{ formula unit Cu}_2\text{O}^-} = 6.022 \times 10^{23} \text{ O}^2^- \text{ ions}
\]

If those numbers are added up, the total number of ions in 1 mol Cu\textsubscript{2}O is $1.807 \times 10^{24}$ ions ($3 \times 6.022 \times 10^{23}$).

This image highlights ONE formula unit of Cu\textsubscript{2}O as part of a larger ionic lattice.

Figure 4.9: One formula unit of Cu\textsubscript{2}O, shown highlighted, contains two Cu\textsuperscript{+} ions and one O\textsuperscript{2–} ion.

Molar Mass – (of elements and compounds)

From the text (Chap. 4.2): The relative atomic mass is the average mass of atoms of an element in atomic mass units. This definition describes the average mass of one atom, but we can extend it to larger quantities of matter as well. Recall that the basis of the definition is that one atom of 12-C has a mass of exactly 12amu.

Avogadro's number has been defined so that the mass of 1 mol of 12-C (that is, $6.022 \times 10^{23}$ atoms of 12-C) is exactly 12g.

Consequently, the mass of a basic particle of any substance in atomic mass units and the mass of 1 mol of the substance in grams have exactly the same numerical value.

Question 3: Rephrase what is said in the sentence above. Use your own words.

The definition of a mole can be restated, then, in terms of the mass of our reference, 12-C: A mole is the amount of substance that contains as many basic particles (atoms, molecules, or formula units)
as there are atoms in exactly 12 g of 12C. The term that describes the mass of 1 mol of a substance is molar mass. (Definition!!)

Since the molar mass value for any atom, in units of grams per mole (g/mol), is numerically the same as the relative atomic mass value (in units of amu per atom), we can use the periodic table to determine the molar mass of any element or compound.

For example, the average mass of 1 hydrogen atom is 1.008 amu, and the mass of 1 mol of hydrogen atoms is 1.008g.

The molar mass of a molecular or ionic substance has the same value as the sum of the relative atomic masses of its component elements.

For example, the average mass of a molecule of H₂S is 34.07amu, and its molar mass is 34.07g/mol. Molar masses of molecules (or formula units) are obtained by adding the molar masses of the component elements, each weighted by the number of that atom in the molecule (or formula unit). For simplicity, we will abbreviate molar mass as MM.

Molar Masses of Compounds:

Example question: When copper sulfide ores are roasted in a furnace, sulfur dioxide gas, SO₂, forms. What is the molar mass of SO₂?

Solution: The molar mass of a compound is the sum of the molar masses of its component elements—in this case, sulfur, and oxygen.

A molecule of sulfur dioxide contains one sulfur atom and two oxygen atoms, so we must multiply the molar mass of oxygen by a factor of 2. We can find the molar masses of sulfur and oxygen on a periodic table, multiply the molar mass of oxygen by 2, and find the sum:

\[
\begin{align*}
\text{Mass of 1 mol of S} &= 1 \text{ mol} \times 32.07 \text{ g/mol} = 32.07 \text{ g} \\
\text{Mass of 2 mol of O} &= 2 \text{ mol} \times 16.00 \text{ g/mol} = 32.00 \text{ g} \\
\text{Mass of 1 mol of SO}_2 &= = 64.07 \text{ g}
\end{align*}
\]

The molar mass of SO₂ is 64.07g/mol. The unit for molar is g/mol.

Question 4 (possible exam question): What is the molar mass of aluminum hydroxide, Al(OH)₃?

Percent Composition by mass:

Another way of thinking about the composition of elements is to express it through the “percent composition by mass”. It is an expression of the portion of the total mass contributed by each element. The percent composition of a substance is constant, no matter what the size of the sample.
The percent composition by mass can be calculated using the molar mass of a compound and the mass of each element that contributes to the total mass of one mole of the compound.

Let’s take the example of sulfur dioxide from above. Each of the elements contributed almost equally to the molar mass of the compound (32.07 g sulfur and 32.0 g oxygen). We can use the number to determine the exact percent composition of the compound $SO_2$.

$$\% \text{ S} = \frac{32.07 \text{ g sulfur}}{64.07 \text{ g SO}_2 \text{ sample}} \times 100\% = 50.05\%$$

$$\% \text{ O} = \frac{32.00 \text{ g oxygen}}{64.07 \text{ g SO}_2 \text{ sample}} \times 100\% = 49.95\%$$

Note that the percentages of all elements add up to the total of 100%.

**Empirical and molecular formulas:**

You have seen now how to express the composition of a substance in terms of masses, percent composition, moles, and atoms or molecules of the component elements.

There are two types of chemical formulas that are related to the composition of a substance.

An empirical formula expresses the simplest ratios of atoms in a compound. It is written with the smallest possible whole number subscripts. The empirical formula is not always the same as the molecular formula (for covalent compounds), but it is the same for ionic formulas (remember, ionic formulas give the smallest whole numbered ratio of ions).

*Question 5: Please summarize in your own words and in one sentence the paragraph above.*
### Table 4.1: Some empirical and molecular formulas

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecular formula</th>
<th>Empirical formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyclopentane</td>
<td>C₅H₁₀</td>
<td>CH₂</td>
</tr>
<tr>
<td>cyclohexane</td>
<td>C₆H₁₂</td>
<td>CH₂</td>
</tr>
<tr>
<td>ethylene</td>
<td>C₂H₄</td>
<td>CH₂</td>
</tr>
<tr>
<td>hydrogen sulfide</td>
<td>H₂S</td>
<td>H₂S</td>
</tr>
<tr>
<td>calcium chloride</td>
<td>CaCl₂ (there is no molecular formula for an ionic compound)</td>
<td>CaCl₂</td>
</tr>
</tbody>
</table>

Question 6: The empirical formulas of three compounds in the table are the same. What information about the molecular formula would you need to determine the correct molecular formula from the empirical formula?
SOLUTIONS

What to expect in this chapter:
Now that we know about the mole and how it can be used in calculating the quantities of reactants and products in chemical reactions, we may discuss the methods by which those reactions occur. As seen previously, the mole can be used to convert between units of particles and masses (e.g., moles to grams). When considering grams, or the weight of the compound in question, we often think of solid reactants and products. However, many reactions happen in aqueous solutions. When dissolved, reactant particles can move faster, and reactions occur much quicker and often more efficiently.

An aqueous solution is a homogeneous mixture of a solvent (in this case water) and a solute, which is often a compound. By definition, the solvent is the substance present in a larger amount, the solute is always the substance that is present in a lesser amount. In this chapter, you will be shown how to make an aqueous solution which is a very important skill when you are conducting experiments in the laboratory. Solutions are also called homogenous mixtures because the solute particles are evenly distributed among the solvent particles. The dissolved particles are so small that they cannot be separated from the water molecules by using a filter. You will see that the concentration of a substance depends on the solute/solvent ratio; the more solute is dissolved, the higher the concentration of a defined volume of solution is.

The amount of reactants and products in solutions can be expressed in terms of concentration (given in mol/L), which will be used in stoichiometric to calculate the moles of a substance.

Question 1: Why do you think reactions in solution are often faster?

From the text (Chapter 4.4): Recall from Chapter 1: A solution is any mixture that is homogeneous at the molecular or ionic scale. In a solution, the substance that is dissolved is called the solute (usually present in a lesser amount), and the substance doing the dissolving is called the solvent (usually present in a greater amount). (Definitions!!)

Question 2: Please describe the main idea expressed in the paragraph above in your own words.
Figure 4.17 shows a solution of copper (II) sulfate (the solute) dissolved in water (the solvent).

FIGURE 4.17 In this system, dissolved copper (II) sulfate is present in a lesser quantity than water, so copper (II) sulfate is the solute and water is the solvent.

Solute = substance being dissolved, present in lesser amount

Solvent = substance doing the dissolving; present in greater amount

Note: If water is the solvent, we talk about an aqueous solution.

Solutions described on the molecular level

Example Question: From this picture of a solution containing CuSO₄ and water, identify the solute and the solvent.

Answer: In this image, the dark red spheres represent copper ions. The yellow/red groups of spheres represent sulfate ions (sulfate molecules). The pale red and white groups represent H₂O molecules. The number of copper and sulfate ions is equal and is less than the number of H₂O molecules. Thus, the solute is CuSO₄, which yields Cu²⁺ and SO₄²⁻ ions in solution. The solvent is H₂O since it is present in the greater amount.

Now you try!
Question/task 3: In the following image of a solution containing hydrogen sulfide and water, identify the solute and the solvent.

The particle representations above show the difference between an ionic compound dissolving in water in which we can observe dissociation of ions, and the dissolving process of molecular compounds in which the molecular unit stays intact.

Question 4 (possible exam question): Assuming now that the following compounds are all soluble in water, which compounds will dissociate into ions when in aqueous solution?

   a) NaCl   b) CH₃OH   c) C₆H₁₂O₆   d) LiOH   e) K₃PO₄

Concentration of Solutions:

From the text [Chapter 4.4]: Solutions are homogeneous mixtures, but different solutions can contain varying amounts of solute and solvent. So, how do we express the composition of a solution? One way is to describe its concentration, is by the relative amounts of solute and solvent in it.

When comparing solutions, we can describe them as either dilute or concentrated. A dilute solution contains a relatively small amount of solute, whereas a concentrated solution contains a comparatively large amount of solute. These terms are helpful when we compare two solutions of different concentrations, indicating that one contains more or less solute than the other. We see these differences in concentration in everyday solutions. For example, when we brew a pot of tea, the color is more intense if the tea is "strong" (concentrated) than if it is "weak" (dilute).

Important concepts to remember:

- Concentration: how much solute per solvent is in the solution
- Dilute: there is more solvent than solute in the solution
- Concentrated: there is more solute than solvent in the solution

Question 5: What are some other solutions that you see in your environment where color gives you an indication of the concentration?
What other ways can you compare concentrations of solutions?

The concentrations of sugar solutions, for example, could be compared by how slowly they pour. If you compared a teaspoonful of sugar dissolved in a cup of water to molasses or syrup (also sugar solutions), which would pour more slowly?

Question 6: Can the different behavior be explained by different densities as well?

Comparing Concentrations of Solutions:

A variety of experimental methods allows us to determine the concentrations of solutions. For example, if the solute is colored and the solvent is colorless, then the intensity of color in the solution is a measure of its concentration. Consider the aqueous solutions of copper (II) sulfate shown in Figure 4.18. The more copper (II) sulfate dissolved in the water, the more intense is the blue color due to the Cu²⁺ ions.

![Image of copper (II) sulfate solutions]

Remember: the concentration is directly proportional to the number of solute particles in solution!!

FIGURE 4.18 The color intensity of a colored solution decreases as the concentration of the solute decreases. Compare the concentrations of ions in the solution for these copper (II) sulfate solutions. Which has more copper (II) ions? More sulfate ions? Which solution has the greatest concentration?

Question 7: Assuming that the solutions in Figure 4.18 contain 8, 5, or 3 moles of sulfate molecules (going from left to right, one sulfate molecule representing one mole), how many grams SO₄²⁻ (sulfate) are in each solution?

Figure 4.18 also shows, at a molecular level, how the relative amounts of solute and solvent vary with the concentration. If you count the solute particles [copper (II) ions and sulfate ions] and compare them to the number of water molecules, you can see that as the solution becomes more dilute, the number of ions in a measured amount decreases and the number of water molecules in that same measured amount increases. Because the concentration of copper (II) ions decreases relative to the number of water molecules, the color of the blue solution fades.
Molarity—a measure of concentration:

The concentration of a solution can be expressed in a variety of ways. One of the most common ways is molarity (M). The molarity of a solution is the number of moles of solute dissolved in 1 L of solution. The molarity of any solution can be calculated by dividing the moles of solute by the liters of solution:

\[
\text{molarity} = \frac{\text{moles of solute}}{\text{Liters of solution}}
\]

For example: if 0.291 mol of NaCl are added to 150 mL of solution, the molarity (M) would be represented as...

\[
\text{molarity} = \frac{0.291 \text{ mol NaCl}}{0.1500 \text{ L solution}} = 1.94 \frac{\text{mol NaCl}}{\text{L solution}} = 1.94 \text{M}
\]

*Molarity is calculated from liters of solution, NOT liters of solvent.* How large the difference is, depends on the concentration of the solution. Dilute solutions contain only a small amount of solute. The volume of such solutions is very nearly the same as the volume of solvent. However, the difference can be significant for solutions in which the volume of the solvent is significantly less than the volume of the solution.

To ensure accuracy, solutions of the desired molarity are usually prepared in volumetric flasks, as shown in the pictures below.

![Volumetric flask](image)

**Figure 4.19:** In the laboratory, solutions of known molarity are usually prepared in volumetric flasks, which are calibrated to contain a specific volume. (A) To prepare 250 mL of a 0.100 M solution of CuSO₄ · 5H₂O, weigh 6.24 g (which is 0.0250 mol) of the solute. (B) Transfer it to the flask and add some solvent, water. Dissolve the solute by swirling. (C) Solvent is added with swirling until the bottom of the liquid surface just matches the marked line on the neck of the flask. (D) Then a stopper is inserted into the flask and the flask is inverted several times to thoroughly mix the contents. Convince yourself that this procedure will indeed result in a solution whose concentration is 0.100 M.
If we know the mass of the solute and the volume of the solution, we can calculate the molarity of the solution. To begin, calculate the number of moles of solute contained in the solution. Then divide by the volume (in liters), of the solution.

Step-by-step example: You dissolve 5.5 g NaCl in 250 mL of water. The molar mass of NaCl is 58.44 $g/mol$.

Therefore: \[ 5.5g \text{ NaCl} \times \frac{1\text{ mol}}{58.44g} = 0.0941 \text{ mol (moles of solute)} \]
\[ \frac{0.0941 \text{ mol}}{0.250L} = 0.38 \text{ mol/L} = 0.38 \text{ M} \]

Ion Concentration in Solution—which can differ from the overall concentration of the solution

We commonly express the concentration of a solution as a molarity of the solute compound. For example, a solution might contain 0.100 M CuCl₂. If we are interested in the concentrations of ions in a solution of this ionic compound, we must account for the fact that the solution contains twice as many chloride ions as copper (II) ions (Figure 4.20).

For each formula unit of CuCl₂ in the solution, we have one Cu²⁺ ion and two Cl⁻ ions. For each mole of CuCl₂ in the solution, we have 1 mol of Cu²⁺ ions and 2 mol of Cl⁻ ions. Thus, the 0.100 M CuCl₂ solution contains 0.100 M Cu²⁺ and 0.200 M Cl⁻ ions.

Calculations:
\[ 0.100 \text{ M CuCl}_2 = \left( \frac{0.100 \text{ mol}}{L} \right) \times \left( \frac{1 \text{ mol Cu}^{2+}}{1 \text{ mol CuCl}_2} \right) = 0.100 \text{ M Cu}^{2+} \]
\[ 0.100 \text{ M CuCl}_2 = \left( \frac{0.100 \text{ mol}}{L} \right) \times \left( \frac{2 \text{ mol Cl}^-}{1 \text{ mol CuCl}_2} \right) = 0.200 \text{ M Cl}^- \]
Process of Dilution:

Pipette  Volumetric flask  Water  Stopper

**FIGURE 4.21** (A) A pipette is used to accurately measure 25.00 mL of 1.000 M CuSO₄ solution and (B) deliver it into a 250.0-mL volumetric flask. (C and D) Water is added with swirling until the diluted solution fills the flask to the marked level. (E) As water is added, the amount of water increases, leading to a lesser concentration of solute. A stopper is placed in the flask, and the flask is inverted several times to completely mix the solution. The number of Cu²⁺ ions and SO₄²⁻ ions in a given volume of solution decreases, but the total number of Cu²⁺ ions and SO₄²⁻ ions in the flask is constant. The new solution has a concentration of 0.1000 M.

**Question 9:** In performing dilutions, what part(s) of the solution (solute, solvent, concentration, components) is NOT changed?

**Calculations Involving Dilutions:**

The number of moles of solute contained in the volume of the more concentrated solution \((V_{\text{conc}})\) is found by multiplying the molarity \((M_{\text{conc}})\) of this solution by its volume in liters:

\[
\text{moles}_{\text{conc}} = M_{\text{conc}} \times V_{\text{conc}}
\]

Since we are adding only solvent, the moles of solute do not change upon dilution, so the moles of solute before and after dilution are equal:

\[
\text{moles}_{\text{conc}} = \text{moles}_{\text{dil}}
\]

The moles of solute in the diluted solution also equal the product of molarity \((M_{\text{dil}})\) and volume \((V_{\text{dil}})\) in liters, where the volume is the total volume after dilution:

\[
M_{\text{dil}} \times V_{\text{dil}} = M_{\text{conc}} \times V_{\text{conc}}
\]
We can rearrange this equation to solve for the molarity of the diluted solution:

\[ M_{\text{dil}} = \frac{M_{\text{conc}} \times V_{\text{conc}}}{V_{\text{dil}}} \]

**Example Question (possible exam questions):** You are given 0.1000M NaCl solution. Initially, this solution has a volume of 25mL. Upon dilution, the new volume is found to be 250mL. Find the molarity of the diluted solution.

\[ M_{\text{dil}} = \frac{0.1000M \times 0.02500L}{0.2500L} = 0.01000M \]

(Note: The final volume is given here correctly as 0.2500 L or 250.00 mL. What would the final volume be if the questions stated that 250.00 mL of water had been added to the initial volume? How would this change the new concentration? - Please always read the questions very carefully!)

**Question 10 (Possible exam questions):** If the volume of a solution stays the same but you double the amount of solute, how does the concentration of the solution change?
Chemical Reactions:

Chemical reactions

What to expect in this chapter:
A chemical reaction is the change of one substance or a set of substances into another. The starting material(s) is called reactant(s), the newly formed substances are called products. Products are different from reactants in the arrangement of their component atoms and therefore also their properties. It is important to mention at this time that chemical reactions neither destroy atoms nor create new atoms, atoms are just rearranged to form new products. This rearrangement happens because the bonds that hold atoms together on the reactant side will be broken and new bonds are formed to form new products. This chapter discuss common, observable signs that chemical reactions happen and talk about how chemical reactions are represented through chemical equation using chemical symbols, and particle representations. This chapter also introduces different categories of chemical reactions and how these can be used to predict reaction products.

Consider the reaction of hydrogen gas with oxygen gas, as shown in Figure 5.5. Hydrogen and oxygen both occur naturally as diatomic molecules. If they mix, they react slowly; but if ignited, the reaction is vigorous, even explosive. In either case, the reactants form the same product: gaseous water molecules, each containing two hydrogen atoms and one oxygen atom.

A reaction of hydrogen gas and oxygen set on fire.
Symbolic Representation: \(2\text{H}_2(g) + \text{O}_2 \rightarrow 2\text{H}_2\text{O}(g)\)

Now consider the arrangement of atoms in Figure 5.6. What are oxygen atoms attached to in the reactants? In the products? How many hydrogen atoms? In the reactants, each hydrogen atom is attached to another hydrogen atom and each oxygen atom is attached to another oxygen atom. In the products, two hydrogen atoms are attached to one oxygen atom. The number of atoms is the same, but their arrangement is different.
Figure 5.6 The hydrogen atoms from hydrogen molecules combine with the oxygen atoms from oxygen molecules to form gaseous water molecules.

*Signs of Chemical Reactions*

*How do we know a chemical reaction occurs:*

Just as artists use paint and stone to create works of art, chemists use elements and compounds to create new substances. Both the artist and the chemist are constrained by the materials available to them. Both must work within the rules of nature regarding the properties and behaviors of their materials.

The clues most often used by chemists are the following:

- Change in color
- Production of light
- Formation of a solid (such as a precipitate in solution, smoke in air, or a metal coating)
- Formation of a gas (bubbles in solution or fumes in the gaseous state)
- Absorption or release of heat (sometimes appearing as a flame)

Did you come up with any clues that do not fit one of these categories?

*Question 1: Describe in your own words how a chemical reaction is different from a physical reaction.*

*Figure 5.8 illustrates some of these chemical reactions.*
Figure 5.8 Do any of these photos give you visible clues that a chemical reaction occurs? All reactants are listed below.

(A) $I_2(aq) + NaI(aq) + starch(aq)$
(B) $Mg(s) + O_2(g)$
(C) $Ba(OH)_2 \cdot 8H_2O(s) + NH_4Cl(s)$
(D) $Cu(s) + HNO_3(aq)$
(E) $BaCl_2(aq) + Na_2SO_4(aq)$
(F) $CH_4(g) + O_2(g)$
(G) $AgNO_3(aq) + glucose(aq)$
(H) $CaCO_3(s) + HCl(aq)$

Question 2: Xenon gas reacts with fluorine gas to form Xenon tetrafluoride gas. Identify which image represents reactants and then which image represents products.
Writing chemical equations:

Describing chemical reactions in words is awkward and time consuming. For this reason, chemists use a chemical equation to show what reactants are involved and what products are formed. A chemical equation is a symbolic representation of a chemical reaction. The equation must be balanced. In a balanced equation, the number of atoms of each element is the same in the products as in the reactants.

Question 3: Please summarize the main idea expressed in the paragraph above.

Let’s work through writing and balancing the thermite reaction. In words, it looks like this:
Aluminum + Iron (III) oxide → Aluminum oxide + Iron

\[ Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + Fe(l) \]

This equation is not yet complete because it is not balanced. The same number of atoms of each element must appear on both sides of the arrow. In its present form, it has the following numbers of atoms:

<table>
<thead>
<tr>
<th># of atoms (reactants)</th>
<th># of atoms (products)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Al</td>
<td>2 Al</td>
</tr>
<tr>
<td>2 Fe</td>
<td>1 Fe</td>
</tr>
<tr>
<td>3 O</td>
<td>3 O</td>
</tr>
</tbody>
</table>

Therefore, we need to balance the equation with coefficients:

\[ 2 Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + 2 Fe(s) \]

Question 4: Write complete, balanced equations for each of the following reactions.

(a) Sodium metal reacts with oxygen gas to form solid sodium oxide.

(b) Solid copper (II) nitrate is heated to produce solid copper (II) oxide, gaseous nitrogen dioxide, and oxygen.
To see how and why equations balance, use a model kit or gumdrops and toothpicks to build models of reactant molecules. Take them apart and rearrange them into product molecules. Use the smallest number of atoms possible to achieve conservation of mass. Reactions do not actually occur this way, but we want to emphasize the conservation of atoms in reactions as a means of balancing equations.

General approach to balancing equations:

1. Write correct formulas for reactants on the left side and products on the right side of the arrow.
2. Look for elements that appear only once on each side of the equation.
3. Do not change the subscripts! Changing subscripts in a formula would change the identity of the substance
4. The atoms to be balanced should be those in elemental substances.
5. Make a final check by counting the atoms of each element on both sides of the equation.

**Question 5: Balance the following chemical reactions**

(A) \( \text{Ba}(s) + HCl(aq) \rightarrow \text{BaCl}_2(aq) + H_2(g) \)

(B) \( \text{Na}_2\text{CrO}_4(aq) + \text{Pb(NO}_3)_2(aq) \rightarrow \text{PbCrO}_4(s) + \text{NaNO}_3(aq) \)

**Predicting chemical reactions:**
In all the chemical reactions we have considered so far, the identities of the reactant and products are known. Identity of the reactants is easy enough, since we usually know what we have mixed. But how do we know what products will result? The answer could be from an experiment.
Classes of Chemical reactions:

<table>
<thead>
<tr>
<th>Class</th>
<th>Reactants</th>
<th>Products</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition</td>
<td>1 compound</td>
<td>2 elements (or smaller compounds)</td>
<td>CD → C + D</td>
</tr>
<tr>
<td>Combination</td>
<td>2 elements or compounds</td>
<td>1 compound</td>
<td>A + B → AB</td>
</tr>
<tr>
<td>Single displacement</td>
<td>1 element and 1 compound</td>
<td>1 element and 1 compound</td>
<td>A + CD → C +AD</td>
</tr>
<tr>
<td>Double displacement</td>
<td>2 compounds</td>
<td>2 compounds</td>
<td>CD +EF → CF + ED</td>
</tr>
</tbody>
</table>

Decomposition:

When a compound undergoes a decomposition reaction, it breaks down into the elements of which it is composed or into simpler compounds.

\[
\text{2HgO(s)} \xrightarrow{\Delta} \text{2Hg(l)} + \text{O}_2(g)
\]

Figure 5.13 when solid mercury (II) oxide, HgO, is heated, it decomposes into liquid mercury metal and oxygen gas.
The oxide ions lose their negative charge as they are converted to oxygen atoms. The mercury (II) ions lose their positive charge to form mercury atoms.

**Question 6:** Complete and balance the following decomposition reactions

(a) \( \text{CaCO}_3(s) \rightarrow \) \\
(b) \( \text{CuSO}_4\cdot5\text{H}_2\text{O} \rightarrow \)

**Combination reactions:**

In a combination reaction (also called synthesis), two substances react to produce a single compound.

\[
2\text{Al}(s) + 3\text{Br}_2(l) \rightarrow 2\text{AlBr}_3(s)
\]

**Figure 5.16** Aluminum reacts with bromine to form aluminum bromide.

**Figure 5.19:** The combination reaction of carbon monoxide and oxygen shown on a molecular level.

\[
2\text{CO}(s) + \text{O}_2(g) \rightarrow 2\text{CO}_2
\]
Question 7: Complete and balance the following combination reactions

(a) \(Ca(s) + N_2(g) \rightarrow\)

(b) \(Al(s) + O_2(g) \rightarrow\)

Single displacement reaction:

In a single displacement reaction, a free element displaces another element from a compound to produce a different compound and a different element.

\[2Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + 2Fe(l)\]

Figure 5.20 calcium reacts with water to form aqueous calcium hydroxide and gaseous hydrogen.

\[Cu(s) + 2AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2Ag(s)\]

Copper atoms are converted to copper (II) ions, and silver ions are converted to silver atoms. Nitrate ions remain unchanged in solution.

Question 8: Complete and balance the following single displacement reactions

(a) \(Zn(s) + AgNO_3(aq) \rightarrow\)

(b) \(Na(s) + FeCl_2(s) \rightarrow\)

Double displacement:

In all double displacement reactions, two compounds exchange ions or elements to form new
compounds.

Figure 5.26 When solutions of barium chloride and sodium sulfate mix, a precipitate of barium sulfate forms, leaving sodium chloride in the solution.

\[ \text{BaCl}_2(aq) + \text{Na}_2\text{SO}_4(aq) \rightarrow \text{BaSO}_4(s) + \text{NaCl}(aq) \]

Question 9: Complete and balance the following double displacement reactions.
(a) \( \text{BaCO}_3(s) + \text{H}_2\text{SO}_4(aq) \rightarrow \)
(b) \( \text{CuCl}_2(aq) + \text{AgNO}_3(aq) \rightarrow \)
10. Limiting Reactants:

Limiting Reactant

What to expect in this chapter:

Balanced chemical equations give the exact ratios in which reactants react with one another to form products, and you have already learned to calculate the amounts. But what actually needs to happen to one or more reactants in a reaction? They need to react and therefore need to be close to one another. Therefore, scientists often do not use reactants in the exact ratios (also called "stoichiometric amounts"); instead, they start with one reactant in excess to ensure all of the other reactants will be used up completely.

In this chapter, you will look at a few reactions on the macroscopic and on the particle level, which will help you understand how to identify the "limiting reactant" (aka limiting reagent). You will additionally learn how to use this information to calculate how much product can be formed.

Limiting Reactants (or also called Limiting “Reagents”)

Using exact stoichiometric amounts of reactants is often not the most practical thing to do when conducting an experiment in the lab. Why is this?

Think about what has to happen on a particle level during a chemical reaction to actually form products. Think about the reaction of hydrogen molecules (H₂) and oxygen molecules (O₂) to form water (H₂O).

Question/task 1: Describe what has to happen in a reaction vessel which contains oxygen and hydrogen molecules in order to form water! Is interaction between the gaseous molecules necessary?

What exactly is a” limiting reactant”?

Definition: The limiting reactant in a chemical reaction is the reactant that determines the maximum amount of product that can be formed. The limiting reactant usually reacts completely in a chemical reaction.

To gain a better understanding of limiting reactants, let’s look at a system that is not a chemical reaction.

Suppose someone wants to build a model solar-powered car.

He needs 1 frame, 1 solar cell, 1 electric motor, and 4 wheels (Figure below).

We can write an equation (like chemical equation) to represent the numbers of parts required to make one car:
1 frame + 1 solar cell + 1 electric motor + 4 wheels \rightarrow 1 model solar car

or in terms of “particles”

reactants \rightarrow \text{product}

The equations show the amount and type of parts that are needed to build exactly one solar car. This is comparable to a chemical reaction with reactants and product(s) that show the ratios of reactants needed to form the product(s). These ratios/amounts indicated through the stoichiometric coefficients are called stoichiometric amounts.

Question 2: Summarize in your own words the main idea expressed in the paragraph above.

What if you are given a certain amount of parts different from the “stoichiometric” amounts? How do you figure out what the limiting reactant is and how much product can you obtain?

Solution:

You need to compare the needed amounts of reactants with the available amounts of reactants and then determine the maximum amount of product possible.

Needed amounts for one car:

1 frame, 1 solar cell, 1 electric motor, and 4 wheels

Given amounts of reactants:
Chemical example:

Silver bromide used in photographic films is prepared by the reaction of magnesium bromide and silver nitrate solutions.

\[ \text{MgBr}_2 + 2\text{AgNO}_3 \rightarrow 2\text{AgBr} + \text{Mg(NO}_3)_2 \] (the reaction is conducted in an aqueous solution)

As this equation suggests, using twice the molar amounts of silver nitrate compared to magnesium bromide will ensure that both reactants completely react, and the maximum amount of product can be obtained.

This is the ideal, theoretical scenario but is often not realized under laboratory conditions.

So- what can be done?

Magnesium bromide is usually used in excess to ensure that all of the more expensive silver nitrate is used completely.
Question 3: If magnesium bromide is used in excess in the reaction, which substances will be in the mixture when the reaction is completed?

More practical information about reactants in excess:

When gas burns in a car engine, we rely on oxygen in the air to support the combustion. We do not worry about running out of oxygen. A chemist would say that oxygen is in excess for the reaction.

When the space shuttle is in space, however, there is no air to provide oxygen. The shuttle must take the right amounts of hydrogen and oxygen with it. If too much of one reactant were transported, the extra reactant would have nothing to react with. It would simply add extra mass to the shuttle. Mass-mass calculations are important in such situations.

When a space shuttle takes off, it leaves with measured amounts of hydrogen and oxygen so that no extra mass is added. Many reactions, however, occur with an excess of one reactant.

Consider a single-displacement reaction between magnesium metal and aqueous hydrochloric acid:

\[ \text{Mg(s)} + 2\text{HCl (aq)} \rightarrow \text{MgCl}_2(\text{aq}) + \text{H}_2(\text{g}) \]

How do we know if all of each reactant is used up in the reaction?

If one of the reactants does not react completely, there will be some of it left over at the end of the reaction. The leftover amount will be present mixed with the product, as shown in Figure 6.7.

![Figure 6.7](image)

**Figure 6.7:** When reactants are not mixed in relative amounts as described by the balanced equation, one reactant does not react completely. (A) Here magnesium metal reacts with hydrochloric acid to form magnesium chloride in solution and hydrogen gas.

Question 4: When the reaction is complete (see Figure 6.7), one reactant remains in excess. What is the excess reactant in beaker B? And in beaker C?
If we do not want any unreacted magnesium or hydrochloric acid left over, we should mix the reactants in the proper (stoichiometric) quantities so that their mole ratio (NOT mass ratio!!) is the same as that shown by the coefficients in the balanced equation.

*If the reactants mixed together are not present in the exact mole ratio, then we will have too much of one reactant and not enough of another. One reactant reacts completely, and some of the other is left unreacted.*

Limiting Reactant - On the molecular level

Now let's look at what occurs at the molecular level in a reaction that has a limiting reactant.

Let's review the combustion of hydrogen to form water. The molecular-level diagram and balanced equation in *Figure 6.9* show that the molecule ratio of \( \text{H}_2 \) to \( \text{O}_2 \) is 2:1. The molecule ratio is the same as the mole ratio because both are related to the coefficients in the balanced equation.

\[
2\text{H}_2 (g) + \text{O}_2 (g) \rightarrow 2\text{H}_2\text{O} (g)
\]

*Figure 6.9*: For every 2 \( \text{H}_2 \) molecules that react, 1 \( \text{O}_2 \) molecule reacts with it to form 2 \( \text{H}_2\text{O} \) molecules.

In this chemical reaction, the reactant molecules are the “parts” that combine in a specific ratio to make the product \( \text{H}_2\text{O} \) molecules.

If the number of \( \text{H}_2 \) molecules mixed is exactly two times the number of \( \text{O}_2 \) molecules, then all the \( \text{H}_2 \) and \( \text{O}_2 \) molecules will react, and no reactants will be left over.

OR

If the ratio of \( \text{H}_2 \) to \( \text{O}_2 \) molecules mixed together is not exactly, then one reactant is the limiting reactant, and the other is in excess.
For example, suppose 8 molecules of \( \text{H}_2 \) are mixed with 5 molecules of \( \text{O}_2 \), as shown in Figure 6.10. The reactant ratio is not the same as in the balanced chemical reaction, so only one of the reactants is completely consumed. The other is in excess.

After the reactants combine in this 2 to 1 ratio, 8 \( \text{H}_2\text{O} \) molecules form.

The \( \text{H}_2 \) reactant is the limiting reactant because it was completely used up. It limited the number of \( \text{H}_2\text{O} \) molecules that could form. The \( \text{O}_2 \) reactant is left over. It was in excess.

When the reaction is complete, the 1 leftover \( \text{O}_2 \) molecule that did not react will also be present in the reaction mixture along with the 8 \( \text{H}_2\text{O} \) molecules that formed.

\[
2\text{H}_2 (g) + \text{O}_2 (g) \rightarrow 2\text{H}_2\text{O} (g)
\]

**Figure 6.10:** Reaction of \( \text{H}_2 \) and \( \text{O}_2 \) in non-stoichiometric amounts.

**Identifying the Limiting Reactant:**

Iron metal is added to an aqueous solution of copper(II) chloride. The solution is blue because copper(II) ions in solution produce a blue color. When the reaction is complete, the solution is colorless. The piece of iron is coated with a granular, brownish-black metal.
Question/task 5: Which compound is the limiting reactant in this reaction? You do not have enough information to determine the limiting reactant through calculation? Do you have visual signs that gives you a clue? Explain!

Question 6: How can you increase the amount of product (H₂O) in Figure 6.10 that is being formed? Do you add more oxygen or more hydrogen to the reaction mixture?

Mathematical investigation of limiting reactants:
How can you determine the limiting reactant mathematically?
You need to compare the molar amounts of two (or more) reactants!
Here is what you have to do:

Step 1: Calculate the molar amount for each reactant. If you have the masses of the reactants given, divide by the molar mass.

Example (using the reaction between molecular hydrogen and molecular oxygen above):
Assuming the reaction mixture will contain 4.0 grams of hydrogen and 5.0 grams of oxygen.

For hydrogen: \[ 4.0 \text{ g H}_2 \times \frac{1 \text{ mol}}{2.016 \text{ g}} = 1.98 \text{ mol H}_2 \]

For oxygen: \[ 5.0 \text{ g O}_2 \times \frac{1 \text{ mol}}{32.0 \text{ g}} = 0.16 \text{ mol O}_2 \]

So far you calculated the available molar amounts of reactants.
Step 2: Using the stoichiometric coefficients from the balanced equation calculate the molar amount of one reactant needed to react completely with the other reactant.

Let’s start with 1.98 mol of hydrogen and using the stoichiometric coefficients from the balanced chemical equation, calculate the exact amount of oxygen needed to react completely with 1.98 mol hydrogen. (Note: You could also start with the molar amount of oxygen, 0.16 mol.)

$$1.98 \text{ mol H}_2 \times \frac{1 \text{ mol O}_2}{2 \text{ mol H}_2} = 0.99 \text{ mol O}_2$$

Your result shows that you need 0.99 mol of oxygen to react completely with 1.98 mol H₂, but you just have 0.16 mol available (see result of Step 1).

What does that mean?

You have less oxygen available (0.16 mol) than you would need to completely react with 1.98 mol of hydrogen, therefore oxygen is the limiting reactant since it limits the amount of water (product) that can be produced.

Question 7: (possible exam question, relating to reaction above) Which reactant would be the limiting reactant if you had 1.16 mol of oxygen available? Explain!

Question 8: (Possible exam question)

Given the reaction vessel and the balanced chemical reaction, what is the limiting reactant?

Each symbol represents 1 mol of molecules of the substance.

$$2\text{C}_2\text{H}_2(\text{g}) + 5\text{O}_2(\text{g}) \rightarrow 4\text{CO}_2(\text{g}) + 2\text{H}_2\text{O(l)}$$

A. C₂H₂  B. O₂  C. CO₂  D. H₂O
12. Ideal Gases:

THE IDEAL GAS LAW

What to expect in this chapter:
The properties and behavior of gases are often not easy to observe. Some properties of gases are easy to see, e.g., when an air-filled balloon decreases in size when cooled down in the refrigerator (gas volume decreases!), but it is much more difficult to imagine what happens to gas particles in these situations. The properties of gas particles—whether we talk about gaseous atoms (e.g., Ne, He, Ar) or gaseous molecules (O₂, N₂, CH₄, H₂O) depend on a couple of variables, such as the volume (V), temperature (T), pressure (P), the amount of gas (n), and sometimes also the identity of the gas (what type of gas). All these variables explain why we observe macroscopic properties of gases but to really understand them, we need to look at gases at the particle level as well.
In this chapter, you will be introduced to gas laws that explain the relationships between the properties (V, T, P, n) and how you can use them to calculate and predict gases’ behavior.

Some of these particle properties are:

- **Gases consist of particles that are relatively far apart.**
The large spaces between particles explain why gases have much lower densities than liquids and solids. Because gases have so much empty space, it is easy to compress them into smaller volumes by applying external pressure.

- **Gas particles move rapidly.**
  For example, the average velocity of oxygen gas molecules (O₂) at 20°C and normal atmospheric pressure is 0.44 km/s (980 mi/h).
• Gas particles have little effect on one another unless they collide.
  Gas particles have only a small amount of attraction for one another at normal
temperatures and pressures, so they move about freely in all directions. When they collide,
gas particles simply bounce off of each other.

• Gases expand to fill their containers.
  Gases take the volume and shape of their containers as a consequence of their random
motion.

Now you’ve heard a lot about gases and some descriptions include phrases such as “at 20°C and
normal atmospheric pressure” or “at normal temperatures and pressures”.

This indicates, that the properties depend greatly on certain variables. The main relationship
between the four important variables that determine the properties of gases are:

From the text (Chapter 9.3): The properties of gases can be described by the four variables
pressure (P), volume (V), absolute temperature (T), and number of moles (n). Suppose we want to
describe a gas under a specific set of static conditions. The relationships among the individual gas
laws can be manipulated to give us a general equation that relates volume, pressure, temperature,
and amount of gas.

Important relationships (or interdependencies) between these variables that are being discussed in this
course are:

1) Boyle’s Law: \( V \propto \frac{1}{P} \), therefore two sets of conditions \( P_1 \cdot V_1 = P_2 \cdot V_2 \) (at constant n and T)
   Principle: Volume and pressure are inversely related (when pressure increases, volume decreases
   and vice versa).

2) Charles’ Law: \( V \propto T \), therefore two sets of conditions \( \frac{V_1}{T_1} = \frac{V_2}{T_2} \)
   Principle: Volume and temperature are directly related (when volume increases, temperature
   increases and vice versa). (at constant n and P)

3) Avogadro’s Hypothesis: \( V \propto n \), therefore two sets of conditions \( \frac{V_1}{n_1} = \frac{V_2}{n_2} \) (at constant V and P)
   Principle: Volume and moles are directly related (when the amount of gas particles increases,
   volume increases and vice versa).

The combined gas law derives from these relations (Avogadro not included!)
Combined Gas Law: \[ \frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2} \] (at constant n)

When including Avogadro’s law, an equation derives that is very useful to describe a gas under a single set of conditions. This combination of laws produces a single equation called the ideal gas law, which we will discuss here.

Since volume is proportional to each of the three factors, it must be simultaneously proportional to all of them:

\[ V \propto \frac{n \cdot T}{P} \]

Since these variables are proportionally related, we can use a constant to express an equivalent relationship (note: whenever a mathematical proportionality is converted into an equation, you need to introduce a constant)

\[ V = \text{constant} \times \frac{n \cdot T}{P} \]

Because it relates all the terms from the individual gas laws, we have a special name for the constant in this expression, the ideal gas constant, and we use R to represent it. Substituting the ideal gas constant R into the expression, we obtain the following equation:

\[ V = \frac{R \cdot n \cdot T}{P} \]

Rearranging the variables results in the equation known as the ideal gas law:

\[ P \cdot V = R \cdot n \cdot T \]

Question 1: In which container in the image below will the gas pressure be higher? Please explain your answer?

Same amount of gas molecules in both containers.
Volume 1: larger container with more space.
Volume 2: smaller container with less space.
The ideal gas constant, $R$

An ideal gas is a gas that follows behavior predicted by the ideal gas law. Using the observation that 1 mol of an ideal gas at STP occupies 22.414 L, we can calculate the value of $R$ as follows:

$R = \frac{P \cdot V}{n \cdot T} = \frac{(1.000\text{ atm}) \cdot (22.414\text{ L})}{(1.000\text{ mol}) \cdot (273\text{ K})} = 0.08206 \frac{\text{L} \cdot \text{ atm}}{\text{mol} \cdot \text{K}}$

This numerical constant is valid only if we measure volume in liters and pressure in atmospheres, absolute temperature in Kelvin and the amount of substance in moles. Measurements in other units must be converted to use this constant.

Review: an ideal gas is a gas that at 1 mol, a temperature of 273.15K, and 1 atm of pressure will occupy a volume of 22.414L.

From the text (Chapter 9.3): The ideal gas law includes all the information summarized by Boyle's law, Charles's law, and Avogadro's hypothesis. Like them, the ideal gas law is valid only for an ideal gas. It indicates that the volume occupied by an ideal gas is directly proportional to the absolute temperature and to the number of moles of gas molecules. It is inversely proportional to pressure. A single equation that relates all the variables is a useful tool, because given any three values and the value of $R$, we can calculate the unknown quantity.

Question 2: Please summarize the paragraph above, in your own words and in one sentence.

Question 3: What kind of assumptions are we making to call a gas "ideal"? Can you comment on the distance between gas particles, the interactions between them, and the volume of the particle itself? Are any of these aspects accommodated for in the ideal gas law?

Calculations with the Ideal Gas Law

From the text (Ch. 9.3): To solve a gas law problem, we must first determine what is going on in the gas system and then select the appropriate mathematical relationship. For changes in volume, pressure, and temperature, we generally use the combined gas law (same as ideal gas law, but n is constant).

In contrast, the ideal gas law allows us to determine any one of the quantities volume, pressure, temperature, or moles of the gas given the other three. The law can also be used to determine the densities of gases and if the identity of the gas is known, we can also calculate its mass using its molar mass.
Calculating density:

In order to calculate the density of a gas \( d = \frac{m}{V} \), the amount of gas \( n \) has to be expressed differently.

Using \( n = \frac{m}{MM} \), the ideal gas law reads as \( P \cdot V = \frac{m}{MM} \cdot R \cdot T \).

Now solving for density \( \frac{m}{V} \) results in \( \frac{m}{V} = \frac{P \cdot MM}{R \cdot T} \) = density.

Calculating masses or molar masses

You can use the same expression above to solve for mass or molar mass of a gas:

For mass: \( m = \frac{P \cdot MM \cdot V}{R \cdot T} \)

For molar mass: \( MM = \frac{m \cdot R \cdot T}{P \cdot V} \) or, if the density is known, \( MM = \frac{m \cdot R \cdot T}{P} \) (with \( \frac{m}{V} = d \))

Question 4: What is the density of neon at STP?

Calculating the amount (moles) of gas

From the text (Ch. 9.3): If we are given the \( P \), \( V \), and \( T \) conditions for a sample of a gas, we can calculate the number of moles of the gas, using the ideal gas law. We need to only rearrange the equation \( P \cdot V = n \cdot R \cdot T \) to solve for the number of moles. Remember that all the other quantities must be in units that match the value used for the ideal gas constant.

Example: The volume of a propane cylinder is 0.960 L. When filled, the cylinder contains liquid propane stored under pressure. When the cylinder is "empty," it contains propane gas molecules at atmospheric pressure and temperature. How many moles of propane gas remain in a cylinder when it is empty if the surrounding atmospheric conditions are 25.0°C and 745 torr?

Solution:

1. Convert to the desired units of \( T \) and \( P \):
   \[
   T = 25.0\, ^\circ\text{C} + 273.15 = 298.2\, \text{K}
   \]
   \[
   P = 745\, \text{torr} \cdot \frac{1\, \text{atm}}{760\, \text{torr}} = 0.980\, \text{atm}
   \]

2. Rearrange the ideal gas law and substitute the appropriate values to calculate the number of moles:
\[ P \cdot V = n \cdot R \cdot T \]
\[ n = \frac{P \cdot V}{R \cdot T} = \frac{(0.980 \text{ atm}) \cdot (0.960 \text{ L})}{(0.08206 \frac{\text{L \cdot atm}}{\text{mol \cdot K}}) \cdot (298.2 \text{ K})} = 0.0384 \text{ mol} \]

Ask yourself - does this answer seem reasonable? (This is a very important question to ask!!)

At standard temperature (273.15 K) and pressure (1.00 atm), 1 mol of an ideal gas occupies 22.414 L, the molar volume. In this case the temperature is 25° higher than standard, the pressure is close to standard pressure, and the volume is significantly less than the molar volume of a gas. We would expect significantly fewer moles of gas present in the cylinder under these conditions, and that’s what our calculation shows.

Calculating the mass of a gas (equation has been discussed above)

Once the number of moles of gas is determined from the ideal gas law, we can calculate the mass of the gas if we know its identity. Knowing the number of moles, we can use the molar mass of the gas to convert moles to grams.

Now knowing the number of moles of propane and the identity of the gas, we can determine the mass of propane (you have done this type of calculation often before)

Answering the questions: What mass of propane, \( \text{C}_3\text{H}_8 \), is left in the cylinder of Example 1?

Solution:

Recall that molar mass provides a relationship between moles of a substance and grams of that substance. The molar mass of propane is 44.10g/mol. The mass of 0.0384 mol of propane can be determined by multiplying moles by molar mass:

If we know the mass and volume of a gas, we can now also determine its density.

Solution:

Question 5: What is the mass of 15.0 L of methane at 10°C and 1.2 atm?
Low Lexile reading assignments:

1. Atomic Theory 980L

The evolution of the atomic theory

What to expect in this chapter:

The first part of this chapter introduces John Dalton's atomic theory from 1808. John Dalton was an English schoolteacher and hobby scientist. With his theory, he revived the idea that matter consists of incredibly small particles called atoms, a theory that finds its origin in ancient Greece but had been neglected for over 2000 years.

At the time Dalton published his theory, the existence of subatomic particles was not known. Subatomic particles “live” inside of atoms and are considerably smaller than atoms. They are critical in the sense that they determine the properties of individual elements.

The second part of this chapter will talk about experiments that have been conducted after 1808. These experiments have accidentally or intentionally shown the existence of subatomic particles (cations, anions, or neutrons).

Based on these discoveries, the model of what an atom looks like has been revised a couple of times. Please note that models are often not an accurate mirror of the truth. Models change if new information becomes available.

Dalton's Atomic Theory

In 1808 John Dalton, an English school teacher and scientist, published his atomic theory. He suggested that:

1. All matter is made up of very small, indivisible particles, called atoms.
2. All atoms of a given element are identical, both in mass and in chemical properties. However, atoms of different elements have different masses and different chemical properties.
3. Atoms are not created or destroyed in chemical reactions.
4. Atoms combine in simple, fixed, whole-number ratios to form compounds.

Between 1897 and 1932, important discoveries about the structure of the atom were made.

Now let’s have a look at some of the important discoveries.

The Structure of the Atom

Subatomic Particles

Older television picture tubes and computer monitors have important components called Cathode-ray tubes (CRTs). A cathode-ray tube is a high vacuum tube where cathode rays make glowing images on a screen. When hit by fast-moving electrons the chemical compounds on the screen glow. Different chemicals that glow different colors provide a color picture.

An atom is made up of a smaller particle called a subatomic particle. The subatomic particles are Proton, neutron and electron. In the late 1800s researchers developed instruments and techniques capable of detecting subatomic particles. The instruments and techniques could also show their numbers and arrangements in atoms.
Atomic Structure

Discovery of the Electron

The existence of the electron, a negatively charged subatomic particle, was shown by J. J. Thomson in 1897. He conducted a list of experiments in partly evacuated cathode-ray tubes (Figure 2.5 next page). A voltage is applied by connecting each end of the tube to a battery. The tube is partially evacuated. Electricity then moves from one end of the tube to the other in the form of a ray. The invisible rays can be seen when they cause certain materials coated on the glass to glow.

Although it was believed that cathode rays only traveled in straight lines. A cathode is a negatively charged electrode. Thomson found that, in a magnetic or electric field, the rays bent toward a positively charged plate. They also changed direction from a negatively charged plate outside the tube. He knew that the same electrical charges repel each other, and opposite charges attract each other. The bending of the beam toward the positive plate (and away from the negative plate) showed that the beam was composed of negatively charged particles.

Image A: Cathode ray tube

![Image A: Cathode ray tube]

Image B: Cathode ray tube

![Image B: Cathode ray tube]
Thomson showed that the rays had a negative electrical charge no matter what material was used for the source of the rays. This result indicated that the rays were composed of identical, negatively charged particles common to all matter. We call these particles electrons. Thomson was also able to determine the charge-to-mass ratio of the electron from such experiments.

**Question 1:** How did the discovery of electrons make it necessary to change one of Dalton’s postulates?

**Question 2:** In figure 2.5, what’s happening in image B? Please explain.

**Question 3:** Why did the alpha particles swerve? Please explain.

The Proton

The discovery of the electron stimulated many more experiments in search of other subatomic particles. Atoms are electrically neutral. Scientists concluded that atoms must contain positively charged particles. They counter the negatively charged electrons. The positively charged particle is called a proton. It has a charge equal in magnitude to the electron but opposite in sign, $+1.6022 \times 10^{-19}$ C. To be electrically neutral, an atom must have equal numbers of protons and electrons. An atom should be able to deal with electrical charges in matter easily. The charges are usually expressed as a multiple of the charge of an electron or of a proton. Instead of in units of coulombs. Expressed in this way, the charge of an electron is 1-, and the charge of a proton is 1+.

The Nuclear Atom

How might protons and electrons be arranged in an atom? Thomson’s model of atomic structure was called the “plum pudding” model. It assumed that protons and electrons were distributed the same way throughout the atom (Figure 2.7 below).
Thomson’s model suggested that electrons in the atom might be embedded in a sphere of positive charge, like raisins in plum pudding.

**Discovery of the Nucleus - Rutherford’s Gold Foil Experiment**

Ernest Rutherford designed an experiment to test the plum-pudding model. His associate, Hans Geiger, carried it out.

The experiment involved blasting thin gold foil with alpha particles. Alpha particles were known at the time as positively charged particles. They were thousands of times greater in mass than electrons. (Today we know them as helium atoms that have lost their electrons.) According to the plum pudding model, none of the alpha particles should have been affected by the dispersed bits of positive and negative charge in the gold atoms. They should have zipped right through the gold foil, and most did. However, some swerved a bit, and a few actually bounced backwards, as shown in Figure 2.8, next page.

*The result was quite unexpected.*

It was as if you fired a bullet at a sheet of tissue paper and it came back and hit you! The swerving of these massive alpha particles suggested that most of the mass of the atom had to be concentrated in a positively charged core. Rutherford called the core, the nucleus. The electrons, he reasoned, had to be scattered in the large volume outside of the nucleus. Most of the alpha particles passed through the large electron space. Only if an alpha particle came close enough to the incredibly thick nucleus would it be swerved from its original path. The alpha particles that hit the nucleus of a gold atom head-on were swerved backwards.
(internet.savannah.chatham.k12.ga.us/.../gradelevels/.../8th%20Grade%20Science/Deve...)

FIGURE 2.8 – Gold Foil Experiment (Experimental Set-Up, Hypothesis and Actual Result)

Question 4: Why did Rutherford choose gold for his experiment?
Could he have used any other material?
Which properties should this material have?

Question 5: what kind of evidence did Rutherford’s gold foil experiment provide?

Rutherford’s experiment was the basis for the nuclear model of the atom (Figure 2.9), developed in 1907. The model suggested that the nucleus contains the protons and most of the mass of the atom. The electrons exist outside the nucleus in what is often called an “electron cloud.”
FIGURE 2.9 – The nuclear model of the atom (new model of the plum pudding).

In the nuclear model of the atom, protons (blue spheres) and neutrons (red spheres) are located in a tiny nucleus at the center of the atom. The space outside the nucleus is occupied by the electrons.

The diameter of the nucleus is about $10^{-14}$ m, and the diameter of the atom is about $10^{-10}$ m. These relative sizes are comparable to a flea in the center of a domed stadium. The mass of a proton, $1.6726 \times 10^{-24}$ g, is nearly the same as the mass of a hydrogen atom. The proton is equal in charge (but opposite in sign) to the electron, but 1836 times greater in mass.

The Neutron

These experiments helped Rutherford and other scientists understand the structure of the atom better. They could not however account for the entire mass of the atom.

Most atoms other than the hydrogen atom have masses that are at least twice the sum of the masses of the protons and electrons they contain. For example, calcium contains 20 protons and 20 electrons. Together, their mass is $3.3471 \times 10^{-23}$ g. Yet a calcium atom has a mass that is nearly twice this value ($6.6359 \times 10^{-23}$ g).

Question 6: Check the Periodic Table in your textbook (inside front cover). If calcium (Ca) has 20 protons, which element has 16 protons?

Question 7: For the atom presented in the following diagram,

A. Determine the number of protons and neutrons
B. Identify the atomic number and the element
C. Determine the mass number for this isotope.
To account for the extra mass, Rutherford hypothesized the neutron. A neutron is an uncharged particle in the nucleus of the atom.

Because of the electrical neutrality of the neutron, it was difficult to find. It was not until 1932 that James Chadwick, a scientist working with Rutherford, did experiments that detected the neutron. The mass of the neutron was determined to be $1.6749 \times 10^{-24}$ g. The mass of a neutron is a little greater than the mass of a proton. The properties of the electron, proton, and neutron are summarized in Table 2.1. All of the subatomic particles in the table are important to the nuclear model of the atom as we understand it today (Figure 2.9).

Question 8: Which element is described in Figure 2.9?

Question 9: Which scientist suggested that all matter is made up of small subatomic particles called atoms?

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Actual Charge</th>
<th>Relative Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$9.1094 \times 10^{-28}$ g</td>
<td>-1.6022x10^{-19} Coulomb</td>
<td>-1</td>
</tr>
<tr>
<td>Proton</td>
<td>$1.6726 \times 10^{-24}$ g</td>
<td>+1.6022x10^{-19} Coulomb</td>
<td>+1</td>
</tr>
<tr>
<td>Neutron</td>
<td>$1.6726 \times 10^{-24}$ g</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A coulomb is a unit of electric charge. It's equal to the amount of electricity carried in one second by a current of one ampere.

TABLE 2.1 - Subatomic Particles, masses and charges

Question 10: Dalton stated that "all atoms of a given element are identical, both in mass and in chemical properties".

Can you think of any exceptions to this rule?

Question 11 (typical exam questions):

Which subatomic particles make up the mass of an atom?

A. protons and electrons.
B. protons and neutrons.
C. neutrons and electrons.
D. only electrons.
2. Modern model of the atom

What to expect in this chapter:

You just learned that electrons are located outside the nucleus, and protons and neutrons are located inside the nucleus.

The phrase “outside the nucleus” is not very specific, and therefore scientists tried to determine and describe models to describe the location of the electrons better. One of the models is the Bohr model, named after the Danish physicist Niels Bohr (1885-1962), who received the Nobel Prize in Physics in 1922 for his contributions to correctly describing the atom’s structure.

Bohr’s model, also called the orbital model, described different energy levels in a hydrogen atom well but is more complicated when applied to atoms with more than one electron. The chapter describes a path where electrons in the atom can be found. Even though newer models more accurately describe where electrons can be found, the Bohr model is still very much in use.

In this chapter, you will be introduced to the most recent “modern model of the atom.” It identifies not only 3-dimensional spaces in which electrons can be found, but it also associates distinct energy levels with these locations.

The Modern Model of the Atom

By the 1920s, scientists started to work on a new model of the atom that explains the line spectra of other elements. (Line spectra are colored lines of light emitted by elements. Each element has a distinct line spectrum that can be used to identify the element. See also Chapter 7 pg. 260). Erwin Schrödinger, from Austria, developed a mathematical model that seemed to work for all atoms. Schrödinger’s model of the atom was the same as Bohr’s model. The similarities were that the energies of electrons were quantized. This meant that they could have only certain energies.

However, the new model describes electrons as occupying orbitals, not orbits (as in Bohr’s model). An orbital is a three-dimensional region in space where the electron is likely to be found, not a circular pathway as Bohr initially proposed (shown in Figure 7.12). The mathematical model was based on the probability of finding an electron in a region outside the nucleus. From it, chemists created a probability map to show where an electron is likely to be found (Figure 7.11).
Figure 7.11A is the probability map for a hydrogen electron in its lowest-energy state. The darker regions represent areas where the electron is most likely to be found. However, the likelihood of finding an electron in the outer regions of the probability map is small. It is customary to show a confined region in space where the electron is likely to be found 95% of the time (Figure 7.11B). We will use orbital representations without dots for the rest of this chapter.

In the modern model of the atom, orbitals that have the same size (not necessarily the same shape, though) are considered to be in the same principal energy level. The first six principal energy levels for the electron in a hydrogen atom are shown in Figure 7.12 below. The figure also relates two different ways of representation to one another, vertical energy-level diagrams and the planetary Bohr model.

### Maximum occupancy of each energy level:
- n = 1 (2 electrons)
- n = 2 (8 electrons)
- n = 3 (18 electrons)
- n = 4 (32 electrons)
- n = 5 (50 electrons)
- n = 6 (72 electrons)

![Energy-level diagram](image)

**Figure 7.12:**

The allowed energies for the electron are the same as the energies of the Bohr orbits.

**Question 1:** Why are there many possible energy levels in a hydrogen atom? Hydrogen just has one electron!
Orbitals come in different shapes and sizes. There are four types of occupied orbitals in atoms in their lowest energy states, which we label with the letters $s$, $p$, $d$, and $f$. The general shapes of these orbitals are shown in Figure 7.13. These orbitals are distributed into the principal energy levels ($n=1, 2, 3,...$).

<table>
<thead>
<tr>
<th>Orbital</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$ orbital</td>
<td>centered around the nucleus and can only take up to 2 electrons.</td>
</tr>
<tr>
<td>$p$ orbital</td>
<td>three $p$ orbitals, and they are oriented perpendicular to each other and can only take up to 6 electrons.</td>
</tr>
<tr>
<td>$d$ orbital</td>
<td>five $d$ orbitals, and they can take up to 10 electrons.</td>
</tr>
<tr>
<td>$f$ orbital</td>
<td>seven $f$ orbitals, and they can take up to 14 electrons.</td>
</tr>
</tbody>
</table>

**Figure 7.13:** The $s$, $p$, $d$, and $f$ orbitals differ in shapes and number of lobes.

Transferring the images in Figure 7.13 on an actual atom, what is the probability to find electrons in the origin where the three axes intersect? Please explain.

Orbitals at lower-energy levels are smaller. Orbitals at the higher-energy levels are larger and extend farther from the nucleus.

**Example:**

The first principal energy level ($n = 1$) consists of a single $s$ orbital. We call this $s$ orbital a $1s$ orbital because it is in the $n = 1$ principal energy level, and it has the $s$ orbital shape:

The second principal energy level ($n = 2$) consists of $s$ and $p$ orbitals called the $2s$ and $2p$ orbitals. The $2s$ orbital is like the $1s$ orbital, but it is larger (Figure 7.14).
Figure 7.14: The size of the orbitals increases as the principal energy level increases.

A single $p$ orbital, as shown in Figure 7.13, has a figure-eight or dumbbell shape. In their respective energy levels, $p$ orbitals always come in sets of three (Figure 7.15). The three $2p$ orbitals lie with their centers on top of each other at the nucleus. They are also perpendicular to one another. We can think of each two-lobed orbital as directed along one of the $x$, $y$, or $z$ axes that are each perpendicular to one another. We label these orbitals accordingly as $px$, $py$, and $pz$ orbitals.

Figure 7.15: (A) Three $p$ orbitals consist of a $p$ sublevel. They have the same shape, but they point in different directions in space. They lie perpendicular to one another. We can imagine them lying along perpendicular lines that we call $x$, $y$, and $z$ axes. The $Pz$ orbital lies along the $z$-axis. The $px$ orbital lies along the $x$-axis, and the $py$ orbital lies along the $y$-axis. (B) The three $p$ orbitals coexist with their centers at the nucleus.

Because there are two types of orbitals in the second principal energy level, we say that there are two sublevels: the $2s$ sublevel and the $2p$ sublevel. A sublevel consists of just one type of orbital at a specific principal energy level. The $2s$ sublevel consists of a single $2s$ orbital. The $2p$ sublevel consists of three $2p$ orbitals.

At the third principal energy level ($n = 3$), three sublevels are available: the $3s$, $3p$, and $3d$ sublevels. The $3s$ sublevel consists of a single $3s$ orbital. The $3p$ sublevel consists of a set of three $3p$ orbitals. The $3d$ sublevel consists of five $d$ orbitals (Figure 7.16).

The fourth principal energy level ($n = 4$) consists of four sublevels: the $4s$, $4p$, $4d$, and $4f$ sublevels. The $4f$ sublevel consists of seven $4f$ orbitals (image of $f$ orbitals not given).
Figure 7.16: There are five d orbitals in a d sublevel. Most have four lobes that lie along a specific plane in space. One looks like a p orbital with a donut shape around its center.

In the modern model of the hydrogen atom, the energy levels have the same energies as the orbits described in the Bohr model. The hydrogen line spectrum is produced by the movement of electrons in an atom from orbitals in higher principal energy levels to orbitals in lower principal energy levels (transition from an "excited state" to a lower energy state, such as the "ground state," pg. 261 in the textbook).

The hydrogen atom line spectrum is simple to explain because the orbitals in the same principal energy level have the same energy. This is not the case for atoms with more than one electron.

Orbital Diagrams for Multi-Electron Atoms ("multi" in this context means more than one electron!)

An orbital diagram is a good way to show the distribution of sublevels and orbitals in an atom. The one shown in Figure 7.17 (next page) is specifically for the hydrogen atom. The boxes represent orbitals, and the groups of boxes represent sublevels.

Figure 7.17: The orbital diagram for the hydrogen atom shows the sublevels and orbitals that can exist at each principal energy level. Each box represents an orbital. The groups of boxes represent sublevels. For the hydrogen atom only, the sublevels within a principal energy level all have the same energy. Here we show only the first three principal energy levels for hydrogen.

The orbital diagram for a multi-electron atom looks different. It shows the same energy levels and sublevels, but the energies of some sublevels differ.
Figure 7.18: The orbital diagram for a multi-electron atom shows the same sublevels and orbitals as for the hydrogen atom. However, in atoms that contain more than one electron, the sublevels within a principal energy level have different energies. Note that the energy of the 3d sublevel is higher than the energy of the 4s sublevel.

Sublevels in the same principal energy level have the same energy only in atoms with one electron (hydrogen). In atoms with more than one electron, the interaction among electrons causes the sublevels within the same principal energy level to have different energies. The result is an orbital diagram like that shown in Figure 7.18. Notice that the p orbitals are higher in energy than the s orbitals within a given principal energy level. The d orbitals are higher in energy than the p orbitals. The 3d orbitals are so high that they are slightly higher in energy than the 4s orbitals.

Question 3: What kind of interaction between electrons could it be that causes the sublevels within the same principal energy level to have different energies?

Now we have to look at how electrons are being arranged into these principal energy levels, sublevels, and orbitals.

Consider the orbital diagram that represents how electrons are arranged in a carbon atom in its ground state:

Carbon has an atomic number of 6 (6 electrons). The 1s orbital will get 2 electrons, the 2s will get 2 electrons and the remaining 2 electrons will go into the first 2p orbitals.
The boxes represent orbitals, and the arrows represent electrons.

Question 4: Please summarize in your own words, why the location of the electrons in an atom is important?

When we create an orbital diagram for a particular atom, we fill in electrons starting with a bare nucleus and add one electron at a time. (This is not how atoms are created in nature.) You may have noticed that the lowest-energy orbitals have two electrons in them. Also, some of the higher-energy orbitals have only one or none.

This results from the Aufbau principle (from the German Aufbauen, "to build up"). It states that electrons fill orbitals starting with the lowest-energy orbitals.

For the hydrogen atom in its ground state, its electron is in the 1s orbital.

You may have also noted that no more than two electrons occupy each orbital.

This is the basis for the Pauli Exclusion Principle, which states that a maximum of two electrons can occupy each orbital and have opposite spins.

Electrons in the same orbital are represented by arrows that point in opposite directions.

An electron can spin in one of two directions. We represent these spins with an up arrow and a down arrow.

For example, helium’s ground-state orbital diagram consists of two electrons in the 1s orbital:

[Diagram showing helium's ground-state orbital diagram with 2s and 2p orbitals and 2 electrons in the 1s orbital]
For lithium, with three electrons, two electrons go in the 1s orbital. The first principal energy level is filled. We can now proceed to the second principal energy level. Because the 2s sublevel is lower in energy than the 2p sublevel, the third electron goes into the 2s orbital.

Lithium has an atomic number of 3 (3 electrons). 2 electrons will be placed in the 1s orbital and the remaining 1 will be placed in the 2s orbital.

Boron, with five electrons, has an orbital diagram with two electrons in the 1s orbital, two electrons in the 2s orbital, and one electron in one of the 2p orbitals. It makes no difference which p orbital we place the electron in because they are equal in energy. The orbital diagram for boron is:

Boron has an atomic number of 5 (5 electrons). 2 electrons will be placed in the 1s orbital, 2 electrons in the 2s orbital and the remaining 1 will be placed in the first 2p orbital.

What happens when more than one electron in a sublevel contains more than one orbital, such as a p sublevel? Are electrons paired up right away? Are they kept in separate orbitals until pairing is required? Did you notice in carbon’s orbital diagram that the electrons in the p sublevel are unpaired in separate p orbitals?

This brings us to the third rule:

**Hund’s rule:** Electrons are distributed into orbitals of identical energy (same sublevel). This is done in such a way as to give the maximum number of unpaired electrons.

**Hund’s rule is a consequence of the fact that negatively charged electrons repel each other.** It follows that electrons should be found in separate orbitals if no energy is required to get there.
It is common to show a simpler orbital diagram, where all the orbitals are represented on one line, with sublevels labeled. We must remember that the energy of the sublevels increases from left to right. For example, we can represent the orbital diagram for carbon as

Following Hund’s rule, the arrows (electrons) in the 1s orbital should face opposite directions, same goes for the 2s orbital. The p sublevel has 3 orbitals, but we only have 2 electrons left. The remaining 2 electrons should be distributed evenly.

Question 5: In your own words can you summarize the meaning of Hund’s rule.

Question 6: (possible exam question)
Which element in its ground state has exactly one unpaired electron?

(A) Al  (B) Mg  (C) P  (D) Si

Question 7: (possible exam question)
Which picture shows a p orbital?

A.  
B.  
C.  
D.  

Question 8: Please briefly describe the differences and similarities between an energy level diagram, a Bohr model, and an orbital diagram (as shown in the text above). You most likely will encounter some of these in exams and quizzes.
3. Molecular Shapes

3-Dimensional Shapes of Molecules

What to expect in this chapter...

This chapter discusses the relationship between the 3-dimensional shape of a molecule and its properties. While the chemical make-up of a molecule is given by the chemical formula, only a few predictions about properties can be made based only on this information.

However, the 3-dimensional shape of a molecule and the position of its atoms within the molecule determine how molecules interact with other molecules of the same kind and with other substances.

This chapter will guide you through a couple of steps that will allow you to determine molecular shapes. You will see that the arrangement of atoms and the location of electrons within the molecule play an important role.

Let’s look at an interesting real-world example first – the senses of smell and taste!

The 2004 Nobel Prize in Physiology or Medicine was given to Richard Axel of Columbia University and Linda Buck of the Fred Hutchinson Cancer Center in Seattle for their studies of the sense of smell.

Although senses have a chemical basis, determining how they operate has not been simple. It has become clear that there are receptor sites in the nose and tongue where molecules can fit. The receptors are built from proteins that make up the membranes of cells. The proteins are interlinked in various ways, creating pockets in the structure of the cell membrane. The pockets act as receptors from other molecules if two conditions are met.

First, the molecules must be the right size and shape to fit in them. Second, the molecules must interact in a certain way with atoms in the membrane protein, causing a change that can trigger a nerve impulse.

The importance of molecular shape – an example:

Recognizable tastes fall into many categories. One is sweet, and it is highly attractive to humans for a good reason. Lactose is a sweet substance found in mothers’ milk. The sweet taste makes babies drink more. Other sweet substances include glucose and sucrose (two different forms of sugar), which happen naturally in plants. While it has been difficult to relate the structures of molecules to their tastes, a common feature of sweet molecules is the size of a particular portion of the molecule. This part of a sweet molecule likely fits into the receptor site.

A receptor site is a protein, on the surface of a cell. Sweet molecules commonly have a $\text{—H (or —OH)}$ separated from a $\text{—O—}$ atom by about 300 pm, as illustrated in Figure 8.23
Figure 8.23 Glucose is sweet because it has —H and —OH groups that fit into a taste receptor site on the tongue.

Although humans know thousands of odors, one theory proposes that there are only seven primary odors. Each odor is linked with a different type of receptor in the nose. When a gaseous molecule enters the nose and connects with a certain receptor, a nerve impulse develops and is sent to the brain. A molecule that can fit into more than one type of receptor causes many signals. The signals develop a composite smell.

How does science explain molecular shape?

The Valence-Shell Electron-Pair Repulsion Theory

As the senses of taste and smell show, the visible properties of substances develop from the three-dimensional shapes of their molecules. Shape, in turn, is a function of the arrangement of atoms in a molecule. The relative locations of electron pairs around a central atom play a large role in determining a molecule’s three-dimensional shape. Negatively charged electrons push away one another. Which is makes electron pairs in different orbitals stay as far apart as possible (maximize the distance).

Definition: The tendency of electron pairs to adjust the orientation of their orbitals to maximize the distance between them is the basis of the valence-shell electron-pair repulsion (VSEPR) theory. (Valence shell is another name for valence level.)

Question 1: Based on your knowledge about Lewis structures, what is the center atom in sulfur dioxide, SO₂, and what number and type (bonding pairs or lone pairs) of electron pairs are located around it? Explain!
A Lewis formula does not show the shape of a molecule, but it does help us to determine the molecular shape.

It is hard to see how atoms are arranged in a two-dimensional line drawing. Chemists often use a system of solid lines, dashed lines, and wedges to represent the three-dimensional structure of molecules. Solid lines mean bonds in the plane of the paper. Dashed lines are bonds that point back from the plane of the paper. Wedges mean bonds that come in front from the plane of the paper (this way of drawing bonds becomes especially important in Organic Chemistry!):

To predict the geometric shape of a molecule or ion using VSEPR theory, we first need to know how electrons are arranged in a molecule. In particular, we need to know how many unshared electron pairs and atoms surround the central atom.

We can get this information by examining the Lewis formula. For example, CH₄ has four atoms and no unshared electron pairs surrounding the carbon atom. In the CO₂ molecule, carbon has only two atoms bonded to it, as shown in the Lewis formula, and it has no unshared pairs of electrons. The NH₃ molecule has three bonded atoms and one unshared electron pair (see figures below).

The bonded atoms and unshared electron pairs are arranged around the central atom. They are as far apart as possible. The result is a shape characterized by the bond angle between the central atom and the atoms bonded to it.

What shapes and angles would you predict for molecules having two, three, and four pairs of unshared electrons or atoms around a central atom? How would you make these predictions based on repulsions of electron pairs?
Example: To see what angles to predict, let's examine the shape commonly found in hydrocarbons and many other molecules that arises from four electron pairs or atoms. The Lewis formulas look flat, as in CH₄:

\[
\begin{array}{c}
  \text{H} \\
  \text{H-C-H} \\
  \text{H} \\
\end{array}
\]

This structure looks as if it would have bond angles of 90°:

\[
\begin{array}{c}
  \text{H} \\
  \text{H-C-H} \\
  \text{H} \\
\end{array}
\]

(incorrect bond angle)

However, this does not correctly represent the three-dimensional structure of the CH₄ molecule, which is not flat. If we move atoms to correct the flatness, we change the bond angles. The larger the angles, the farther away from one another the atoms are. If we move only the carbon atom, the angles actually get smaller. The only way to make the angles larger is to move two hydrogen atoms up and two down:

Before

After

How large can the angles get if we move two up and two down? When the angles all become equal, they have values of 109.5°, giving a tetrahedral shape. This structure is usually shown in a rotated form:

Table 8.5 shows the geometries that achieve the maximum distance between mixtures of two, three, or four atoms, or unshared electron pairs. Any set of objects adopts the geometries shown in the table. The objects are attached at a common point, and that stay as far apart as possible. For example, the balloons shown in Figure 8.25 adopt the same geometries as atoms (or unshared pairs of electrons) around a central atom. These structures, called parent structures, partly predict a molecule's shape.
Table 8.5

<table>
<thead>
<tr>
<th>Number of Atoms or Electron Pairs</th>
<th>Parent Structure</th>
<th>Geometric Arrangement of Atoms or Electron Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Trigonal planar</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Tetrahedral</td>
<td></td>
</tr>
</tbody>
</table>

Macroscopically this looks like this (-with a little help of balloons):

![linear structure](image1)

![trigonal planar structure](image2)

![tetrahedral structure](image3)

Figure 8.25: Macroscopic objects that are fastened to a common center take the same structures as molecules because, like electron pairs, they stay as far apart as possible.

The shape we give a molecule includes only the groups of bonding electrons within the parent structure. It doesn’t include the unshared pairs of electrons. The shape is a description of the locations of the atoms in the molecule.

Consider, as an example, the water molecule, which has two atoms and two unshared pairs of electrons around the central atom. The four electron pairs in $\text{H}_2\text{O}$ arrange themselves tetrahedrally around the oxygen atom.

![tetrahedral water molecule](image4)

We consider only the two bonding pairs when we describe the molecular shape. So, we do not say that the water molecule is tetrahedral. Rather, we describe it as bent.

Consider the Lewis formulas for several molecules and ions (Figure 8.26) having the same general composition $AX_n$, $A$ being the central atom, $X$ being the terminal atoms.
Figure 8.26 Some molecules and ions with the formula $AX_2$ have a trigonal planar shape, while others have a trigonal pyramidal shape.

So, how would you know what the correct shape is? You can determine the shape if you know the number of atoms that are bonded to the center atom of a molecule and the number of lone electron pairs on the center atom.

All possible shapes for molecules that have two to four electron pairs are summarized in Table 8.6. The bond angles for these structures are approximately those of the parent structures.

<table>
<thead>
<tr>
<th>General Formula</th>
<th>Number of Bonded Atoms</th>
<th>Number of Unshared Pairs</th>
<th>Molecular Shape</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AX_2$</td>
<td>2</td>
<td>0</td>
<td>Linear</td>
<td>$\text{BeCl}_2$, $\text{CO}_2$, $\text{HCN}$</td>
</tr>
<tr>
<td>$AX_3$</td>
<td>3</td>
<td>0</td>
<td>Trigonal planar</td>
<td>$\text{BF}_3$, $\text{BH}_3$, $\text{SO}_2$, $\text{NO}_3^-$</td>
</tr>
<tr>
<td>$AX_2$</td>
<td>2</td>
<td>1</td>
<td>Bent</td>
<td>$\text{SO}_2$, $\text{NO}_2^-$</td>
</tr>
<tr>
<td>$AX_4$</td>
<td>4</td>
<td>0</td>
<td>Tetrahedral</td>
<td>$\text{CH}_4$, $\text{CH}_2\text{Cl}_2$, $\text{SiCl}_4$, $\text{POCl}_3$, $\text{BrO}_4^-$</td>
</tr>
<tr>
<td>$AX_3$</td>
<td>3</td>
<td>1</td>
<td>Trigonal pyramidal</td>
<td>$\text{NH}_3$, $\text{PF}_3$, $\text{NH}_2\text{Cl}$</td>
</tr>
<tr>
<td>$AX_2$</td>
<td>2</td>
<td>2</td>
<td>Bent</td>
<td>$\text{H}_2\text{O}$, $\text{OF}_2$, $\text{BrO}_2^-$, $\text{SCl}_2$</td>
</tr>
</tbody>
</table>
**Table 8.6 Arrangement of Electron Pairs and Molecular Shapes (textbook pg. 322)**

Question 2: Consider the carbonate ion - do you expect this molecule to have unshared electron pairs on the center atom? What shape will it be?

Questions 3: Please check table 8.6: Which molecular shapes result from unshared electron pairs on the center atom?

Notice in *Table 8.6* that CO₂ is linear, but SO₂— with the same number of atoms—is bent.

We can understand this difference using the VSEPR theory. Examine the Lewis formulas of these molecules:

*What is different about them?* The carbon in CO₂ has two bonded atoms and no unshared electron pairs, so it has a linear structure. However, sulfur in SO₂ has two bonded atoms and one unshared electron pair. The unshared pair causes the molecule to be bent. Models of these molecules are shown below.

![Lewis formulas](image)

**Figure 8.28** Carbon dioxide is linear, whereas sulfur dioxide is bent because there is an unshared electron pair on the sulfur atom.

Question 4: Try to explain in more detail how non-bonding electron pairs influence molecular shape (use terms as “attraction” or “repulsion”).

Now, let’s take a look at what we need to do to predict the shape of a molecule according to VSEPR theory; you can use the following four steps.

Before we get to the different steps, it is important to know that the bond angles in real molecules often differ a little from the values predicted by the VSEPR theory. Differences
happen because unshared pairs of electrons occupy more space than bonded pairs. The bonded pairs are forced together somewhat. This results in slightly smaller bond angles than predicted. For example, ammonia, which has one unshared pair of electrons, has a bond angle of 107° instead of the predicted 109.5°. Water has two unshared pairs of electrons and a bond angle of about 105°. A similar effect is caused by a double bond, which occupies more space than a single bond.

**Steps for Predicting the Shape of a Molecule**

1. Draw a Lewis formula. Please make sure that the Lewis formula includes all valence electrons!
2. Count the number of atoms bonded to the central atom and count unshared electron pairs on the central atom.
3. Add the numbers of atoms and the number of unshared electron pairs around the central atom. *The total shows the parent structure.*
4. The molecular shape is derived from the parent structure by considering only the positions in the structure occupied by bonded atoms.

**Question 5:** Is it really important to start by drawing the Lewis structure when predicting the molecular shape? What piece of information that a Lewis structure can provide is so crucial?

**What do I do if a molecule has more than one central atom?**

*For molecules with more than one central atom, we can repeat the procedure for each central atom. A process that allows us to predict the structures of molecules as large and complex as proteins.* Let’s consider one amino acid, glycine, which might be found in a protein. It has a sweet taste and is found in gelatin and other animal products. Its formula is H\(_2\)NCH\(_2\)CO\(_2\)H. How do we predict its structure?

Glycine color Key:
- White: Hydrogen
- Red: Oxygen
- Blue: Nitrogen
- Black: Carbon

*We start, as before, by writing a Lewis formula for the molecule:*

Would you please take a piece of paper and try it yourself? You can see the molecular structure in the figure below. *Just add the remaining valence electrons. You can also follow along with the description written underneath the figure to complete the structure.*
The molecule contains four atoms acting as central atoms: the nitrogen atom (blue), both carbon atoms (black atoms (red)).

The nitrogen atom has three atoms bonded to it and one unshared electron pair. Thus, the structure around this nitrogen atom is based on a tetrahedral parent structure. It has one unshared pair of electrons. The shape around the nitrogen atom is trigonal pyramidal. It has bond angles of about 109.5°.

The first carbon atom (left) is bonded to four other atoms (N, two H, and C). It has no unshared electron pairs. The shape around it is tetrahedral, with bond angles of about 109.5°.

The second carbon atom (right) is bonded to three other atoms (C and two O). It has no unshared electron pairs. The shape around it is trigonal planar, with bond angles of around 120°.

Finally, one of the oxygen atoms has two atoms (C and H) bonded to it and has two unshared electron pairs. The structure around it is based on a tetrahedral parent structure, but with two unshared pairs, the shape is bent. The bond angles will be around 109.5°. Verify each of these predictions by examining the molecular model of glycine in Figure 8.29 below.

Figure 8.29: VSEPR Theory predicts the structure of glycine.

Question 6: In this chapter, the molecular shape has been related to the observable property of odor/smell. Can you think of other observable molecular properties that are directly related to molecular geometry?
Question 7: (possible exam question): Which molecule is linear?

A. $\text{SO}_2$  
B. $\text{NH}_3$  
C. $\text{OF}_2$  
D. $\text{CS}_2$

Question 8: (possible exam question): What is the bond angle in Freon, $\text{CF}_2\text{Cl}_2$, (shown in figure)?

A. $45^\circ$  
B. $90^\circ$  
C. $109.5^\circ$  
D. $120^\circ$
4. Covalent Bonding

Chemical Bonding: Covalent Bonding

The formation and properties of ionic compounds have been discussed in the previous reading assignment; this chapter now looks more closely into covalent bonding which has been described by Gilbert N. Lewis in 1916 as “sharing of electron pairs”. Gilbert Lewis also introduced dot structures (Lewis Dot Structures) which are still used today to represent valence electrons and covalent bonding.

What to expect in this chapter:

In this chapter, you will learn how electrons are shared in pairs, forming covalent compounds, called molecules. The chapter also discusses the nature of the attractive forces that holds atoms together in covalent bonds (single, double, or triple bonds) and introduces intermolecular forces, which are forces that are present between two or more molecules. These forces determine a variety of molecular properties, such as the melting, and boiling point.

When chemists discuss Lewis structures and 3-dimensional molecular shapes, they are talking about covalent compounds. Covalent compounds are formed through the attraction of two or more nonmetal atoms. This leads to the formation of a molecule.

From the text (Chapter 8.2): When two nonmetals form a compound, the bonds within the molecule are covalent.

Review: The ionic bond between sodium and chlorine results in the ionic chloride. The image below shows the process of the electron transfers.

\[ \text{Na}^+ + \text{Cl}^- \rightarrow [\text{Na}]^+ + [\text{Cl}]^- \]

A sodium atom has 1 valence electron, Chlorine has 7 valence electrons. When the atoms collide, the chlorine atom will remove the electron from the sodium. The sodium atom loses its only electron and becomes a positively charge sodium ion. This extra electron completes the stable octet for chlorine. Which becomes a negatively charged chloride ion.

In contrast, no electrons are being transferred in a covalent molecule. Lewis structure of covalent compounds show shared electrons (bonds). This is seen in the image showing the H₂ molecule below. There are also non-bonding, free electrons as shown in the HCl molecule.
Question 1: What type of electrons (valence or core) do participate in chemical bonding and are therefore shown in Lewis structures?

From the text (Chapter 8.3): Covalent bonds involve localized attractive forces between atoms that are held together tightly in molecules. A covalent bond is strong because each shared electron interacts simultaneously with two nuclei. Electrons and nuclei attract one another because of their opposite charges. At the same time, electrons repel one another, and nuclei repel each other because of their like charges. When the electrons are located primarily between the two nuclei, the attractions are maximized, and the repulsions are minimized. This results in a covalent bond, as shown in Figure 8.12.

FIGURE 8.12: A covalent bond results when attractive forces between opposite charges are greater than repulsive forces between like charges.

The stability and bond strength of covalent bonds are due to the attractive forces acting on the individual atoms involved. Let’s consider two nonmetal atoms, A and B: When they are close to one another, there is an attraction between atom A’s electron (a negative charge) and atom B’s nucleus (a positive charge). There is also an attraction between atom A’s electron and atom A’s nucleus. At the same time though, atom A’s electron is repelled by atom B’s electron. Also, atom B’s nucleus is repelled by atom A’s nucleus. When the attractive forces between nuclei and
electrons are stronger than the repulsive forces between electron-electron and nucleus-nucleus interactions, a covalent bond can form!

The concept of electrostatic potential energy can be used to explain why two neutral atoms (compared to ions of opposite charge) may come together to form a stable molecule. In the case of two hydrogen atoms (figure below). The potential energy in respect to each other is zero when they are sufficiently far apart so they have no interaction.

As they approach each other, the proton in the nucleus of one H atom in attracted to the electron of the other, and vice versa. This mutual attraction produces negative potential energy. As the distance between the atoms decreases, the potential energy decreases as well. Eventually it reaches a minimum when the two nuclei are 74 pm apart (bond length in H_2 molecule).

At 74 pm bond length, the atoms experience maximum attraction. If the atoms came any closer together, the repulsion between their two positive nuclei more than offsets the mutual attraction. The potential energy rises, and the atoms will move further apart.

Question 2: Would you expect the bond length in Cl_2 to be longer or shorter than that of H_2? Explain your reasoning!

From the text (Chapter 8.3): Although the attractions (bonds) between atoms within the molecule are strong, the molecules are not bonded to other molecules. Consequently, covalent compounds have low melting and boiling points. They also often exist as gases or liquids. As solids, they are brittle or soft, because their molecules are not held together strongly. For example, in solid carbon dioxide (dry ice), the individual molecules remain intact and are identifiable in the molecular model (Figure 8.13).

Attractions between molecules are called intermolecular forces (IMF). You will need to understand these forces to completely understand the properties of covalent compounds. Nevertheless, here are some important characteristics of covalent bonds. Please compare them what you have learned about ionic bonds.

-Substances with covalent bonds often exist as gases and liquids
-Covalent bonds have relatively low melting and boiling points
-Covalent solids are brittle or soft
FIGURE 8.13: In solid carbon dioxide, CO$_2$, molecules pack together in a regular array. However, they retain their identity and can be removed from the crystal easily.

**Modeling bonding in molecular compounds**

You have already discussed Lewis structures and ionic bonding. We will now take a deeper look at covalent Lewis structures as well as other models for this type of bonding.

It is important to remember that Lewis structures only **MODEL** bonding. This is a method to keep track of the valence electrons of the molecule. A Lewis structure does not show the true 3-dimensional shape of a molecule.

When writing Lewis structures, you need to follow certain rules. One of which is the **Octet Rule** (review).

**Text Definition**: the tendency of an atom to reach an electron configuration having eight valence electrons

Note that there are exceptions to this definition, especially going further down the periods of the periodic table.

**Question 3**: Why do you think the models employ the idea of elements preferring the electron octet? Do you see parallels to the Bohr model or the orbital model (electron configuration)?

A closer look at single, double, and triple bonds

The number of bonds an element can form depends on its number of filled valences. In the described Lewis model, elements reach a configuration with an octet of eight valence electrons by sharing electrons. In the oxygen molecule (O$_2$) for example, the number of filled valences for each atom is 6. This means there are still 2 valences to fill. When the atoms come close enough to attract, overlap happens. And electrons can be shared. Now each oxygen atom will share 2 of its electrons with the other atom (in total, 4 electrons are shared between them).
Question 4: Review the electron configuration of the elements carbon through fluorine. How many bonds do you think each atom will make? Do your predictions result in an electron configuration containing an octet of valence electrons?

Single Covalent Bonds

A covalent bond that consists of a pair (2 electrons) of electrons shared by two atoms is a single bond. Each atom has a half-filled orbital in the valence level. The orbitals overlap to allow the electron pair to be a part of both atoms. For example, in the formation of the diatomic hydrogen molecule, each hydrogen atom has an electron in the 1s orbital. When the atoms come together, as shown in Figure 8.15, the orbitals overlap, and the atoms share an electron pair:

\[ \text{H}^+ \cdot \text{H} \longrightarrow \text{H} \cdot \text{H} \]

The representation above of a hydrogen molecule is a Lewis formula (or electron dot formula). The atoms are shown separately. The valence electrons are represented by dots. Lewis formulas are sometimes simplified by showing each bond not as a pair of dots, but as a line. For H₂, the Lewis formula could be either H·H or H–H.

The important thing to remember here is that covalent bonds SHARE electrons. No atoms in the molecule “own” the valence electrons that are shared. They are partially their own, and partially the other atom’s. This is what is meant by a “half-filled orbital”. In the case of a hydrogen atom, 2 electrons are needed to fill its 1s orbital. When another hydrogen atom shares a space in close enough proximity. They can keep the electrons they both need to share. Because these electrons are shared, they appear as 2 dots between the 2 hydrogen atoms.

**Figure 8.15**: Hydrogen atoms do not mix unless they get close enough together. Hydrogen molecules form when orbitals overlap, creating a region in space where both of their electrons can be found.
Covalent bonding cannot happen unless the atoms are close enough for attractions to take effect!

From the text (Ch 8.3): The halogens, each have seven valence electrons. They also share one pair of electrons in diatomic molecules. Lewis formulas that show the distribution of electrons in the halogen molecules are given in Figure 8.16. Each atom in these structures has an octet. The octet is provided that the shared electrons are counted for each atom. Each of the covalent bonds in these molecules is a single bond. It arises from the sharing of a single electron pair.

![Image](image_url)

**Figure 8.16**: All the halogen elements exist as diatomic molecules. Each atom has an octet of electrons, as shown by the circles. They share one electron pair between the bonded atoms. The shared electron pair is a single covalent bond, shown here in the overlapping circles.

One electron pair (2 electrons shared within the molecule) = Single Bond

Double and Triple Covalent Bonds

Question 5: Which diatomic compounds (not elements!) form multiple bonds (double or triple) in order to achieve the electron octet

From the text (Chapter 8.3): The sharing of two pairs of electrons is a double bond. The sharing of three pairs of electrons is a triple bond. In Lewis formulas, two pairs of dots or two parallel lines represent a double bond. Three pairs of dots or three parallel lines represent a triple bond.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Number of shared electrons</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Bond</td>
<td>2</td>
<td>( :F\equiv F:)</td>
</tr>
<tr>
<td>Double Bond</td>
<td>4</td>
<td>( :O\equiv O:)</td>
</tr>
<tr>
<td>Triple Bond</td>
<td>6</td>
<td>( :N\equiv N:)</td>
</tr>
</tbody>
</table>
5. Ionic Bonding

What to expect in this chapter:

This chapter is the first of two chapters about chemical bonding. It discusses the major differences between ionic and covalent bonding and what these differences are based on. You will also learn how an element's electron configuration can help explain how ionic compounds are being formed and how this process can be expressed in chemical equations.

Lastly, you will look into the particle-level structure and properties of different ionic compounds.

Ionic and covalent bonding – what is the difference?

Ionic bonding primarily differs from covalent bonding in 2 ways:

- Ionic bonding happens between a metal and a nonmetal (or polyatomic ions in the place of the cation or anion). Covalent bonding is between a nonmetal and another nonmetal.
- In ionic bonding, electrons are being transferred. In covalent bonding, electrons are being shared.

Two concepts that are important in this context... In order to understand why some elements bond together to form covalent bonds and others result in ionic bonds, we need to look into two important concepts:

1. Bond Polarity

Definition: The degree of transfer of electrons between two atoms. Basically, which atom in the bonded pair pulls the bonding electrons (two electrons form a single bond) to itself.

Non-polar covalent bonds, in which both atoms equally share the bonding electrons. They lie at one end of the sequence shown in Figure 8.3. Ionic bonds, in which one atom pulls much stronger than the other, lie at the other. Some ionic compounds, e.g., sodium chloride (NaCl), are already familiar to you. Sodium chloride is also commonly called table salt.

2. Electronegativity

Definition: The ability of an atom to attract bonding electrons. The electronegativity of two bonded atoms determines the nature of a bond. Equal sharing of electrons between atoms of the same electronegativity (e.g., in O₂ or N₂) results in nonpolar covalent bonds. While unequal sharing between atoms of different electronegativity (e.g., HCl or CO) creates a polar covalent bond (Higher electron density around one of the bonded atoms).

If the difference in electronegativity between the bonded atoms is even greater, the result is an ionic bond.

The table below provides more detailed information about the electronegativity difference between two bonded atoms. It also shows the resulting bonding type (approximation).
Difference in Electronegativity values

<table>
<thead>
<tr>
<th>Difference</th>
<th>Bond Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>below 0.4</td>
<td>nonpolar covalent</td>
</tr>
<tr>
<td>0.4-0.9</td>
<td>moderately polar covalent</td>
</tr>
<tr>
<td>above 0.9-1.7</td>
<td>very polar covalent</td>
</tr>
<tr>
<td>above 1.7</td>
<td>ionic bonding</td>
</tr>
</tbody>
</table>

In *Figure 8.3*, it can be seen that the polar covalent bond falls between the nonpolar covalent bond and the ionic bond.

Figure 8.3

Let's dive a bit deeper into ionic bonding

Ionic bonding happens between a metal and a non-metal (or polyatomic ions in place of either). Electrons are being transferred from the less electronegative metal to the more electronegative non-metal. This will result in forming a metal cation (an ion with a positive charge), and a non-metal anion (an ion with a negative charge) held together by electrostatic forces.

With this review in mind, we can take a look at the bonding itself:

*From the book (Chapter 8.2)*: The formation of ions and ionic bonds relates to the electron configurations of the elements. We can see this relationship in the Periodic Table. Each element immediately following a noble gas (in the Periodic Table) is a metal. It has a strong tendency to lose electrons and thereby reach a stable noble-gas electron configuration. When giving up electrons to gain a noble-gas configuration, the metal develops a positive electrical charge, forming a cation. Each element immediately in front of a noble gas in the Periodic Table is a nonmetal. It has a strong tendency
to gain electrons to achieve a noble-gas configuration. In so doing, it develops a negative electrical charge, forming an anion.

Questions 1: Please summarize the main idea expressed in the paragraph above (2 sentences, and in your own words).

Lewis Symbols (Not the same as Lewis structures)

So now that we know what ionic bonding is, it’s helpful to show the valence electrons (the electrons involved in bonding). We will also show how these are transferred between the cations and anions.

A quick review from Chapter 7.3: The valence electrons are located in ns and np orbitals for the main-group elements. Here n designates the principal energy level.

From the text (Chapter 8.2): The electrons involved in bonding are the valence electrons. A proper way to show the valence electrons is with a Lewis symbol or an electron-dot symbol. The dots placed around an element’s symbol represent valence electrons. The dots are placed singly on the four sides of the elemental symbol, in any order, and then paired as necessary. An element with a noble-gas configuration is surrounded by four pairs of dots representing eight electrons, an octet.

Example: Lewis symbol for chlorine:

![Chlorine Lewis symbol](image)

Chlorine has 7 valence electrons which is why its Lewis dot structure is written with 7 dots.

The Lewis symbols for the period 2 elements show a progression. It starts with one valence electron for Li and ending with eight for Ne. You can also draw the Lewis symbols for the period 3 elements, Na through Ar. What pattern develops? It should look the same, starting with one valence electron for the group IA (1) elements and ending with eight in group VIIIA (18). All the noble-gas elements have eight valence electrons happening in four pairs, except for helium, which only has two.

Lewis symbols give a quick yet effective look at how many valence electrons an atom has. They can also show how those valence electrons will be shared during bonding. To understand how they work, take a look at Table 8.3 below. Notice how the number of valence electrons (the number of dots placed around the element) comes directly from the number of electrons in the 2s and 2p orbitals. In other words, the number of dots around the element directly corresponds to the Main Group numbers IA through VIIIA, (NOT the group number because this would include the Transition elements).

<table>
<thead>
<tr>
<th>Group</th>
<th>1</th>
<th>2</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Configuration</td>
<td>[He]2s¹</td>
<td>[He]2s²</td>
<td>[He]2s²2p¹</td>
<td>[He]2s²2p²</td>
<td>[He]2s²2p³</td>
<td>[He]2s²2p⁴</td>
<td>[He]2s²2p⁵</td>
<td>[He]2s²2p⁶</td>
</tr>
<tr>
<td>Lewis Dot Symbol</td>
<td>Li⁺</td>
<td>Be⁺</td>
<td>B⁺</td>
<td>C⁺</td>
<td>N⁺</td>
<td>O⁻</td>
<td>F⁻</td>
<td>Ne²⁻</td>
</tr>
</tbody>
</table>

*Table 8.3*
Question 2: How can you describe the location of valence electrons in an atom compared to its core electrons?

Question 3: How many electrons should be shown in the Lewis symbol of Aluminum? You can use the Bohr model of aluminum below to answer the question.

Aluminum has an atomic number of 13, (13 electrons). The 1st energy level takes 2 electrons, the 2nd takes 8 electrons. The remaining 3 will be placed on the 3rd energy level and all this adds up to 13.

The formation of ionic compounds

The loss of electrons from a metal and the gain of electrons by a nonmetal create the simplest kind of ionic bond. The transfer must happen at the same time. A neutral metal can lose electrons to make a cation. This happens only when a nonmetal is available to gain them. The nonmetal then forms an anion with a stable octet of valence electrons. Therefore, the net charge on an ionic compound stays the same as in neutral atoms, which is zero. We can’t lose electrons and have them go nowhere!

The following equations use Lewis symbols to illustrate this process in the formation of sodium chloride:

Example A: NaCl

\[ \text{Na}^- \rightarrow \text{Na}^+ + e^- \]
\[ :\text{Cl}^+ + e^- \rightarrow :\text{Cl}^- \]
\[ \text{Na}^+ + :\text{Cl}^- \rightarrow (\text{Na}^+)(:\text{Cl}^-) \text{ or NaCl} \]

The sodium atom loses one electron to form a sodium ion. The ion then has 10 electrons; it has a noble-gas configuration (same number of electrons as neon). The electron is transferred to a chlorine atom. It then becomes a chloride ion; this ion also has a noble-gas configuration. The ions join to form sodium chloride. This compound is held together by attractions between the opposite charges of the ions (electrostatic attractions).

Because sodium loses one electron and chlorine gains one, the atoms combine in a 1:1 ratio, which leads to electrical neutrality.
Remember, the metal (Na) loses its electron, which is transferred to the nonmetal (Cl). When this happens, Na has lost one negatively charged electron, so now it is positive. Because Cl has gained the electron, it is now negative.

Other ions may combine in different ratios. Consider, for example, the formation of aluminum chloride:

Example B: AlCl₃

\[
\begin{align*}
\text{Al}^+ & \quad \rightarrow \quad \text{Al}^{3+} + 3e^- \\
3\text{Cl}^- & \quad \rightarrow \quad 3\text{Cl}^{1-} \\
\text{Al}^{3+} + 3\text{Cl}^{1-} & \quad \rightarrow \quad (\text{Al}^{3+})(\text{Cl}^{1-})_3 \quad \text{or} \quad \text{AlCl}_3
\end{align*}
\]

Aluminum loses three electrons to achieve a noble-gas electron configuration. It takes only one electron to complete the chlorine atoms octet. Three chlorine atoms are required to take the three electrons given up by the aluminum atom. We now have an aluminum ion and three chloride ions. They associate in an electrically neutral 1:3 ratio to form ionic aluminum chloride, AlCl₃. A bunch of aluminum cations maintains this ratio, and chloride anions are arranged in a regular pattern.

- Important note! In the previous two examples, a series of equations was given to create the process of ionic bonding. It is important to remember that while they are displayed in stepwise equations, these processes are happening simultaneously, NOT in a series of steps.

Question 4: What is the ratio of Al and S if those elements combine to form an ionic compound? Explain how you determined the ratio.

Structure and Properties of Ionic Crystals

Now, let’s take a look at the actual structure of ionic compounds.

When an ionic compound forms from its elements, billions of cations and billions of anions form and bond to give a single ionic crystal. (Mono-atomic ions, on average, have a radius of 150 pm (10⁻¹² m)).

From the text (Chapter 8.2): The bonds that hold ions together in ionic compounds result from attractions between oppositely charged ions. If like-charged ions are close to one another, their repulsions partly offset these attractive forces, as shown in Figure 8.7. How do the ions fit together to make a stable ionic compound? An ion, which may be represented as a charged sphere, applies a force equally in all directions, so ions of opposite charge surround it. The pattern is a crystal lattice. The result is an ionic crystal, in which the ions are arranged in a regular geometric pattern. The pattern maximizes the attractive forces and minimizes the repulsive forces.

Question 5: Summarize in one sentence, why atoms bond to other atoms?
Figure 8.7

We know that ions are formed by atoms losing or gaining electrons. An electrostatic attraction happens, and a bond is formed. When there is a larger charge, there will be a larger attraction between atoms. A small ion and a large charge also result in a stronger interaction.

It is the opposite charges on ions in ionic compounds that hold them together so tightly and accounts for many of their characteristics, for example, a high melting point.

The charges and sizes of the ions largely determine the characteristic patterns of ionic crystals.

For example, many ionic salts with a 1:1 ratio of ions have the same structure as sodium chloride. Each ion is surrounded by six ions of opposite charge (Figure 8.8).

A salt, for example sodium chloride, will organize itself in a crystalline solid. It has a high boiling and melting point and the easiest way to break it apart is to dissolve it in water. This salt is very stable.

**FIGURE 8.8:** The sodium chloride crystal is represented at the molecular level in two ways. In each, look for the arrangement of one ion surrounded by six ions of opposite charge. (A) In a space-filling model, the smaller spheres are the sodium ions. The larger spheres are the chloride ions. The model shows the relative sizes of the ions correctly but masks the details of the crystal.
structure. (B) A ball-and-stick model reveals the inside of the crystal but does not show relative sizes correctly. (C) A photograph of some enlarged NaCl crystals shows how the shape of the crystals corresponds with the arrangement of ions within the crystals.

A and B are two different models of a crystalline structure. They both are meant to help you see the overall packing of atoms. C shows you an enlarged view of actual NaCl crystals.

For a crystal lattice to form, cations and anions must come close to one another. If the cations are smaller or larger relative to the anions, a different structure develops. For example, if a salt contains a large cation, such as a cesium ion, each is surrounded by eight similarly sized ions of opposite charge. The crystal lattice for cesium chloride is shown in Figure 8.9.

![Cesium chloride structure](image)

**Cesium chloride** has the body centered cubic structure. Chloride occupies the 8 corners of the cube, and cesium is in the center of the cube. Also, cesium can occupy the 8 corners, with chloride in the center.

**FIGURE 8.9**: The cesium chloride structure is adopted when cations and anions are about the same size. (The image shown for CsCl displays only a portion of the structure for this ionic compound.)

For other compositions, such as salts with 1:2 or 2:1 ratios of ions, different patterns form. A typical structure shown in Figure 8.10 is that of CaF₂, found in the mineral fluorite.

![Calcium fluoride structure](image)

**FIGURE 8.10**: Ionic compounds that have twice as many of one ion as the other often adopt
Ionic bonds are very strong because of the large number of interactions between oppositely charged ions. It takes a lot of energy to separate an ion from the solid structure. The structure directly affects the compounds properties.

Because melting and boiling require the separation of ions, ionic compounds have high melting and boiling points.

The strong attractive forces also make ionic crystals hard and fragile. If hit forcefully, ionic crystals break. They break because the force switches the alignment of ions. They go from the stable interaction of opposite charges to an unstable alignment of like charges (Figure 8.11). Along a shifted layer, strong repulsive forces replace strong attractive forces, and the crystal cracks.

![Ionic Crystal Structure](image)

**FIGURE 8.11:** When a crystal such as NaCl is hit with enough force, layers of ions shift. The attractive forces between ions of opposite charge move out of alignment. Layers of like charge align, and they are pushed apart by repulsive forces. The crystal splits along these lines.

The crystalline structure of ionic compounds also explains why solid ionic salts poor conductors of electricity are. The ions are not mobile but are held in place in the crystal lattice. However, melting greatly increases the electrical conductivity of ionic salts, because the ions in the liquid are free to move around.

Other properties of ionic molecules include:

- Dissociation in water: compounds “break apart into separate ions” when dissolved in water
- Good electrical conductivity
- Strong electrolytes
- High melting point
- Solid at room temp. (this refers right back to the high melting point)
- Brittle
- High density

Question 6: What exactly determines if a substance is conductive?

Question 7: (possible MC exam question)
Which element has the exact same number of valence electrons as carbon?
A. Boron  B. Nitrogen  C. Silicon  D. Sulfur

Question 8: (possible MC exam question)
An ionic compound is formed between a metal (M) and nitrogen with the formula M₃N₂. What is M?
A. Potassium  B. Oxygen  C. Magnesium  D. Aluminum
5. Periodic Trends

Periodic Trends

What to expect in this chapter:

Over the course of history, many scientists attempted to compare, and group chemical elements based on their properties. The development of the modern periodic table is the work of the Russian chemist Dimitri Mendeleev who presented his version of the Periodic Table in 1869 to the world. He arranged chemical elements by their atomic mass and properties and was even able to predict the existence of elements that had not yet been discovered.

This chapter will discuss patterns in regard to the properties of chemical elements on the periodic table. These reoccurring patterns (period trends) allow us to make predictions about the properties of elements based on their location in the periodic table. The electron configuration of elements plays a very important role.

Therefore, we’ll talk about how electron arrangements relate to other properties of elements, such as reactivity, ionization energy, and atomic size.

Chemical Reactivity and Electron Configurations:

The activity series (below, Fig. 7.24) shows the reactivity of metals (and hydrogen) relative to one another. Notice the elements that are at the top of the activity series, as shown in Figure 7.24. Can you see the pattern? Most are alkali metals, group IA (1). And alkaline earth metals, group IIA (2). They are the most reactive metals

In the first group in the periodic table, the alkali metals are commonly found in nature combined with oxygen as oxides. Their stable compounds with oxygen have the general formula \(\text{O}_\text{M}\). Where M represents an alkali metal:

\[
\text{Li}_2\text{O}, \text{Na}_2\text{O}, \text{K}_2\text{O}, \text{Rb}_2\text{O}, \text{Cs}_2\text{O},
\]

**Question 1**: What would be the general formula of compounds formed between group IIA elements and oxygen?
FIGURE 7.24 In this chemical activity series, the most active elements appear at the top.

Ionization Energy:

When metal elements react, they lose valence electrons and form cations. The more easily metal atoms give up their valence electrons, the more reactive they are. One important factor is ionization energy (IE). It’s a measure of the energy needed to remove a valence electron from a gaseous atom to form a gaseous ion. It is usually expressed as the energy needed to remove an electron from each atom in exactly 1 mol \((6.022 \times 10^{23})\) of atoms. For example, consider the ionization process for lithium. Which can be represented with the following equation:

\[
LI(g) \rightarrow Li(g) + e^- \quad \text{IE} = 520 \text{ KJ/mol}
\]

In other words, 520 KJ of energy would be needed to remove the outermost electron (1st ionization energy) from each atom in 1 mol of lithium. Ionization energy is related to electron arrangement. It helps explain differences in the reactivities of metals. In general, atoms with low ionization energies do not bind their valence electrons very tightly. So, they are very reactive.

Trends in Ionization Energies

The ionization energies of the main-group elements are given in Figure 7.26. Notice that the ionization energies of the alkali and alkaline earth metals are relatively low. If we look specifically at elements in the same group, the ionization energies of elements in the same group decrease as we move down a group. This happens because the valence electron that's
removed upon ionization is farther from the nucleus as we move down a group. Electrons farther from the nucleus are easier to remove. They are not as strongly attracted to the positive charge of the nucleus (Figure 7.27). Effective nuclear charge is the net positive charge experienced by an electron in an atom that contains more than one atom. It is a measure of how strongly an electron is held. In addition, valence electrons are guarded from the attraction of protons by core electrons closer to the nucleus. The effect of guarding increases with an increase in core sublevels. This explains why elements such as cesium are so reactive.

**FIGURE 7.26** Ionization energies for the main group elements are given in units of kJ/mol. They are the amount of energy needed to remove one electron from each atom in 1 mol of atoms of the element when in the gaseous state.

![Diagram](image)

In smaller atoms, electrons are closer to the nucleus, and therefore strongly attracted by the positive nuclear charge.

**FIGURE 7.27** A valence electron in a lower principal energy level is closer to the nucleus than a valence electron in a higher principal energy level. The attraction between the nucleus and the valence electron is greater for smaller atoms. This results in a greater ionization energy.
Question 2: Which element, carbon or fluorine, should have the greater first ionization energy? Why? Please give your reasoning.

Question 3: Which element, strontium or magnesium, should have the greater first ionization energy? Why? Please give your reasoning.

You may have by now recognized a pattern in ionization energies from Figure 7.26. They increase from left to right on the periodic table. What is different about atoms in the same period that makes ionization energy increase? The increase in the number of electrons does not explain this trend. As we move across a period from left to right, electrons are added to the same principal energy level. This has a small effect on ionization energy. However, increasing the number of protons in the nucleus as we move across the periodic table causes ionization energy to increase. This is because of the additional positive charge. This increase in nuclear charge pulls the electrons in the valence level closer to the nucleus. It makes the removal of a valence electron more difficult. The general tendency is for ionization energy to increase from bottom to top and from left to right across the periodic table (Figure 7.28).

Question 4: Please summarize in one sentence and in your own words, the main idea in the paragraph above.

![Diagram of ionization energy](image)

**FIGURE 7.28** Ionization energy tends to increase going up the periodic table and from left to right.

Atomic Size:

Another trend that shows a pattern throughout the periodic table is the size of atoms. The size of an atom is often described in terms of its atomic radius. The distance from the center of the nucleus to the outer edge of the atom. The radius of an atom is often reported in units of picometers (1 pm = m). Because the outer edge of an atom is not sharply defined, scientists measure the distance between the centers of two identical bonded atoms to determine atomic radii. The radius is one-half this distance (Figure 7.29).
Scientists measure the distance between the center of the two nuclei of two identical bonded atoms, as e.g., in Cl₂ and divide it by 2 to determine the atomic radius in Pico meters. This is done because the outer edge of an atom is not very well defined. As you can see here, the distance between the nuclei is 199 pm. The distance is then divided by 2 to give 99.5 pm and that's the radius. You can see in figure 7.30 which element this is.

**FIGURE 7.29** To determine the size of an atom, scientists measure the distance between the centers of two bonded atoms. For identical atoms, the atomic radius is one-half this distance.

Atomic radii for the main-group elements are shown in Figure 7.30. Do you observe any patterns? Notice that the atomic radius generally increases as we move down a group. How might you explain this trend? The electron configurations for the elements in a group provide the answer.

For example, remember the electron configurations for the alkali metals, group IA (1):

- Li [He]2
- Na [Ne]3
- K [Ar]4
- Rb [Kr]5
- Cs [Xe]6

Lithium’s valence electron is in the 2s orbital. The valence level is n = 2, very close to the nucleus. At the bottom of the group is cesium. Its valence level is n = 6, much farther from the nucleus. As we go from top to bottom in a group, the atomic radius increases because the valence electrons are in larger orbitals farther away from the nucleus.

**Question 5:** What can you say about the nuclear attraction on one of the electrons in the principle energy level with n = 6 (in comparison to electrons in lower energy levels)?

As we move from left to right across a period, atomic size generally decreases. You might think that size should increase because the number of electrons increases. However, the
electrons are added to the same principal energy level while the positive charge in the nucleus increases. As we move from left to right across a period, the increased positive charge in the nucleus becomes more effective at drawing the valence electrons closer to the center of the atom. This causes atoms to the right on the periodic table to be smaller in size. Trends in atomic size are shown in Figure 7.31.

FIGURE 7.30 This periodic table shows the relative atomic size of the main-group elements, along with their atomic radii in units of picometers. (Except for the noble gases, the atomic radius is determined as half the distance between two bonded atoms.)

FIGURE 7.31 Atomic size increases down a group and from right to left in a period.

Question 6: Which atom is larger, carbon or fluorine? Explain.

Question 7: Which atom is smaller, strontium or magnesium? Explain.

Sizes of Ions:

When ions form from neutral atoms, the radii of the atoms change. Consider what happens when lithium ionizes (Figure 7.32A). A neutral atom of lithium has 3 electrons and 3 protons. The ion has 2 electrons and 3 protons. The nuclear charge remains the same. The number of electrons decreases. In the ion, the protons draw the remaining electrons closer to the nucleus. Consequently, the Li⁺ ion is smaller than the neutral atom.
FIGURE 7.32 (A) A cation is smaller than the neutral atom from which it forms. The nucleus holds the cation’s fewer electrons more tightly. (B) An anion is larger than the neutral atom from which it forms. The nucleus holds the anion’s greater number of electrons less tightly.

The opposite happens with anions. For example, consider the formation of the fluoride ion (Figure 7.32B). The neutral atom has 9 electrons and 9 protons. The $F^-$ ion has 10 electrons and 9 protons. Because there are more electrons, the protons cannot hold the electrons as close to the nucleus. Thus, the ion is larger than the neutral atom. A summary of the sizes of many main-group ions is given in Figure 7.33.

There are so many factors involved in determining the sizes of ions that no single trend spans the entire periodic table. However, for a series of ions with the same number of electrons—an isoelectronic series—consider the following ions:

<table>
<thead>
<tr>
<th>Ion</th>
<th>Radius (pm)</th>
<th>Electron Configuration</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^{2-}$</td>
<td>184</td>
<td>$1s^22s^22p^63s^23p^6$</td>
<td>16</td>
</tr>
<tr>
<td>$Cl^-$</td>
<td>181</td>
<td>$1s^22s^22p^63s^23p^6$</td>
<td>17</td>
</tr>
<tr>
<td>$K^+$</td>
<td>133</td>
<td>$1s^22s^22p^63s^23p^6$</td>
<td>19</td>
</tr>
<tr>
<td>$Ca^{2+}$</td>
<td>99</td>
<td>$1s^22s^22p^63s^23p^6$</td>
<td>20</td>
</tr>
<tr>
<td>$Sr^{2+}$</td>
<td>81</td>
<td>$1s^22s^22p^63s^23p^6$</td>
<td>21</td>
</tr>
</tbody>
</table>

All of the ions in this series have the same number of electrons and the same electron configuration. However, they have different numbers of protons (atomic numbers). For any isoelectronic series, as the number of protons increases, the ion size decreases.
FIGURE 7.33 Shown here are the ionic radii for ions of the main-group elements. Note the trends down a group and for ions that are iso-electronic.

*Question 8: how does this all relate to electronegativity?*
6. Properties and Changes:

Properties and Changes

What to expect in this chapter:

Science depends on observations and accurate descriptions of e.g. phenomena and experimental results. Each substance can be described by their physical and chemical properties and its behavior. In this chapter, you will discuss the various categories of properties that are used to describe and also changes that substances can undergo. In addition, you will learn about two properties, density and temperature, in more detail.

Changes in matter are part of the properties of matter. Their observations could be either qualitative, based on some quality of the matter, or quantitative, based on a numerical value. When making qualitative observations, color, shape, texture, shininess and physical state are described.

In this chapter you will be introduced to some important physical changes, temperature and density.

Properties

When reporting qualitative data, we can classify properties as either physical or chemical.

A physical property is a characteristic that we can see or measure without changing the composition of a substance.

Other examples of physical properties are odor, taste, hardness, mass, volume, density, magnetism, conductivity, and the temperatures at which a substance changes from one physical state to another (e.g. freezing or boiling point).

As you can see above, there are many physical properties. Some of which depend on the size of a sample, like mass and volume. Some of which are independent of the sample size, meaning they do not change whether you investigate a large or a small sample size. Examples for this are odor, hardness, density, conductivity, and color.

Physical properties that are dependent on sample size are called extensive physical properties.
Properties that do not depend on the sample size are called intensive physical properties.

Chemical properties are different. A chemical property of a substance is defined by what it is composed of and what chemical changes it can undergo.

It is, for example, a chemical property of iron that it can rust when exposed to the environment. A substance's reactivity with water is another example – some elements or compounds react strongly; some do not react at all.
Question 1: Can you name/describe other chemical properties?

Important examples of physical properties: density and temperature
Let's take a close look at density and temperature -. These properties are quantitative, they involve numerical values - like also e.g. mass and volume.

Density:
The density of an object is the ratio of its mass to its volume.
This ratio can be expressed using an equation: or

While mass and volume both depend on the size of the object or sample, density does not.
Density is a steady property of a substance. It doesn't matter how much of it is present, as long as temperature and pressure are constant. The densities of a few substances are listed in Table 1.6.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Physical State</th>
<th>Density in g/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>gas</td>
<td>0.000178</td>
</tr>
<tr>
<td>Oxygen</td>
<td>gas</td>
<td>0.00143</td>
</tr>
<tr>
<td>Cooking Oil</td>
<td>liquid</td>
<td>0.92</td>
</tr>
<tr>
<td>Water</td>
<td>liquid</td>
<td>1</td>
</tr>
<tr>
<td>Mercury</td>
<td>liquid</td>
<td>13.6</td>
</tr>
<tr>
<td>Gold</td>
<td>solid</td>
<td>19.3</td>
</tr>
<tr>
<td>Copper</td>
<td>solid</td>
<td>8.92</td>
</tr>
<tr>
<td>Zinc</td>
<td>solid</td>
<td>7.14</td>
</tr>
<tr>
<td>Ice</td>
<td>solid</td>
<td>0.92</td>
</tr>
</tbody>
</table>

*Table 1.6: Densities of some common Substances*

The graduated cylinder below contains several liquids with different densities. The densities of antifreeze, corn oil, dish detergent, maple syrup, shampoo, and water in g/mL are 1.13, 0.93, 1.03, 1.32, 1.01, and 1.00, respectively.
Question 2: What is the pink liquid and what is its density?

If we compare equal volumes of two different substances, such as aluminum and gold, as shown in Figure 1.19, the substance with the greater mass has the greater density.

How, though, can we compare densities if we do not have equal volumes? The mathematical relationship of mass, volume, and density reveals the answer.

\[ \text{density} = \frac{\text{mass}}{\text{volume}} \]

The graduated cylinder above contains several liquids with different densities. From top to bottom the density of the liquids increases. We have Corn oil (0.93), water (1.00), shampoo (1.01), dish detergent (1.03), antifreeze (1.13) and maple syrup (1.32).

Figure 1.19:

Question 3: What is the unit for density? Does the unit depend on the state of matter of the substance?

Atoms in metals are tightly packed together in a defined volume, some metals pack more closely than others. The atoms in gold are tightly packed than those in aluminum, which is why gold is denser than aluminum.

Figure 1.20 Gold (Au) has a greater density than aluminum (Al) because gold has a greater mass per unit volume.

Question 4: Why do different solids have different densities?

Water is unique among liquids because its solid form (ice) floats on its liquid form. This results from the relatively open structure adopted by water molecules in the solid state. What would happen to fish during the winter if ice were like other solids that sink in their liquid form? Why
do substances have different densities? Gases, in general, have very low densities because gas particles spread out and occupy large volumes. Metals tend to have high densities because their atoms pack together tightly. Because ice floats on water, we can infer that water in its solid form must have a lesser density than water in its liquid form. Example 1.8 shows how to use molecular pictures to predict relative densities.

Question 5: How do the molecular diagrams of ice and water (see below) help explain why ice is less dense than water? And - what fills the space between water molecules?

In ice, there is more space around the water molecules. They aren’t tightly packed. In liquid water, the water molecules are tightly packed. There is little to no space around them.

Here is something to think about:

Question 6: Does one water molecule have the same density as a drop of water? Explain!

Temperature (a physical intensive property)

Some days you might not be happy with your lunch; the pizza is cold, and the soda is warm. When we make such comparisons, we are observing relative temperatures. Temperature is a measure of how hot or cold something is relative to some standard. We measure temperature with a thermometer. In the United States, we often use the Fahrenheit scale to measure body temperature and air temperature. Fahrenheit is rarely used in science. Two other temperature scales are standard: the Celsius scale and the Kelvin scale. The relationships between the three temperature scales, Fahrenheit (°F), Celsius (°C), and Kelvin (K), are shown in Figure 1.22.
Temperatures are written differently for the different scales. While Celsius and Fahrenheit use the superscript ° to indicate degrees, the Kelvin scale does not. The unit is written as K (the capital letter), but temperatures are measured in kelvins (lowercase).

Another property of matter that is independent of sample size is the temperature at which the substance changes from one physical state to another. The boiling point is the temperature at which the liquid form of a substance changes to the gaseous form. At the melting point, the substance changes from a solid to a liquid. Between these two temperatures, the substance is normally in its liquid state. For example, on the Celsius scale, the boiling point of water is 100°C. Water melts (or freezes, depending on its original state) at 0°C. On the Kelvin scale, these values are 373.15 K and 273.15 K, respectively. On the Fahrenheit scale, they are 212°F and 32°F, respectively.

Question 7: please summarize in your own words and in two sentences the paragraph above.

There are no negative values on the Kelvin scale. It is an absolute temperature scale because its zero point is the lowest possible temperature observable in the universe. This value is absolute zero, which is equivalent to −273.15°C. The temperature scale on the Kelvin scale are the same as those on the Celsius scale. The difference in temperature between the boiling point of water and the freezing point of water is 100 in both the Celsius (100°C − 0°C) and kelvin (373.15 K − 273.15 K) scales. While the difference is 180 on the Fahrenheit scale (212°F − 32°F). Because the temperature in Kelvin is always 273.15 greater than the temperature in degrees Celsius, we can easily convert between them.
Question 8: Why do we have different temperature scales? How could you set up a new temperature scale?

Physical and Chemical Changes:
As you have just seen, when water changes its state of matter, it does not change the overall composition of the substance (H₂O molecules stay intact). Any change like this is called a physical change.

On the other hand, changes in which substances change their composition, and these changes result in the formation of one or more new substances, is called a chemical change or chemical reaction.

Summary of new terms:

A physical property is a characteristic that we can observe or measure without changing the composition of a substance.

Accordingly, a physical change is a process that changes the physical properties of a substance without changing its composition.

In contrast, a chemical change (or chemical reaction) is a process in which one or more substances are converted into one or more new substances.

A substance is a particular kind of matter with the same properties.

Question 9: According to these definitions, what is the correct answer to the question below?

What is shown in the representation?

A. A compound undergoing a chemical change.
B. A compound undergoing a physical change.
C. An element undergoing a chemical change.
D. An element undergoing a physical change.
8. Formula Calculations:

**Formula Calculations**

What to expect in this chapter:
This chapter will introduce you to the way chemists describe and calculate with large amounts of particles that are too small to see. You will be introduced to a unit called "the mole", which has a value of $6.022 \times 10^{23}$ (Avogadro's Number). The mole allows chemists to translate masses (measured in grams) into the amount of particles a sample contains. In this context, it is very helpful to work with molar masses (mass of one mole of particles) for different elements. The molar mass of each element and compound is very different due to the fact that atoms of different elements have different masses. In addition to mass-particle calculations, this chapter will also explain how Avogadro's number and molar masses can be used to determine empirical and molecular formulas.

**Formula calculations:**

Formula calculations are calculations that are based on the ratios of elements given in the chemical formula. Let's look at some examples:

What information does the formula $\text{Na}_2\text{SO}_4$ provide?

1. It provides information about the type of compound. In the case of sodium sulfate, the compound is ionic (review).
2. The formula also gives the total number of atoms in one formula unit. For sodium sulfate, the total number is 7.
3. The formula gives the element ratios: one formula unit of sodium sulfate for example has four times as many oxygen atoms as it contains sulfur atoms. It has twice as many oxygen atoms as sodium atoms. And has double the amount of sodium atoms as there are sulfur atoms.

**Question 1:** Describe the atomic ratios in the molecular compound ethanol, $\text{CH}_3\text{CH}_2\text{OH}$.

**The Mole: Describing larger quantities**

Chemical formulas are helpful more than the ways described above. They also let us calculate larger quantities of those components. Quantities that we can work with in a laboratory environment. For the previous example of sodium sulfate, we describe the atom ratios in one formula unit. In a laboratory setting though, chemists are not working with single molecules. The sheer number of molecules involved in a given reaction would be completely impractical.

*Unfortunately, we cannot see atoms and molecules because they are too small. Although we can use a scanning tunneling microscope to "see" atoms and molecules on the surface of a solid. As shown in Figure 4.7, this technique reveals only atoms on a surface, not those below.*
Atoms and molecules cannot be seen with bare eyes, because they are too small, which is why a scanning tunneling microscope was used to see atoms and molecules on the surface of this solid.

**Figure 4.7:** The “bumps” in this image are atoms on the surface of a mica crystal. Mica is a mineral containing potassium and aluminum cations and silicate and hydroxide anions.

**Did you know...**

... a dust-sized piece of a solid contains over $10^{16}$ of each type of atom. We certainly wouldn't want to count that many atoms individually, even if we could. Fortunately, we don't have to see atoms to count them. Instead we can find the relative masses of the elements in a compound.

**Units of Quantity:**

**From the text (Chap. 4.2):** In Chapter 2, we saw that the average masses of the elements can be expressed as their relative atomic masses. For the elements in hydrogen sulfide, the relative atomic masses are 1.008 amu for hydrogen and 32.07 amu for sulfur.

Relative atomic masses are very useful for comparing the masses of elements. Atomic mass units are not useful to chemists weighing substances to use in chemical reactions like those for processing copper oxides.

Common laboratory balances measure masses in grams, not atomic mass units. We cannot weigh one or even a few atoms, molecules, or formula units of a substance. Since the masses of most atoms and common molecules are less than $10^{-21}$ g, we have to measure a number of formula units greater than $10^{21}$. For example, to get 1.0 g of H$_2$S, we would need almost $2 \times 10^{23}$ molecules. To get an idea of how large this number is, consider a teaspoon of water.

There are as many molecules of water in this teaspoon (about $1.7 \times 10^{23}$) as there are teaspoonfuls of water in all the oceans on Earth. Similarly, there are about as many SiO$_2$ formula units in one grain of quartz sand as there are sand grains on all the beaches on Earth.

Numbers this large are too awkward to work with easily. We need some way to measure the amount of a substance without counting the number of atoms, formula units, or molecules.

This unit that bridges this gap is called the **mole**, or mol. It represents the amount of substance that contains as many atoms, molecules, formula units, etc. As there are atoms in exactly 12g of Carbon. (Definition!!)
The number of atoms in 12g of C has been experimentally determined as 6.022 x 10^{23} atoms. It is commonly referred to as Avogadro's Number \( N_A \).

**Avogadro's Number** = \( N_A = 6.022 \times 10^{23} \) atoms = mole

Although 1 mol contains different volumes and different masses of different materials, it is always the same number of formula units (atoms, molecules, or ionic compound formula units).

→ Important Note! We use the abbreviation mol for mole, but molecule should **not** be abbreviated.

**Calculations Involving Moles:**
We can now discuss various ways in which moles can be used to quantize and calculate chemical components.

1. **The mole as the number of particles.**

   From the text (Chap. 4.2): *We can convert between moles and formula units using the following pathway:*

   ![Mole Conversion Diagram]

   If 1 mol can be 1 mol of atoms, molecules, formula units (referring to ionic compounds), or ions, then we can easily calculate the number of copper atoms in 2 moles of copper.

   The mathematical set-up is as follows; the unwanted units cancel out.

   \[
   2 \text{ mol Cu} = \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol Cu}} = 1.204 \times 10^{24} \text{ Cu atoms}
   \]

   **Questions 2:** How many copper atoms are in 0.3 mol of copper?

2. **The mole used to calculate the number of atoms in a compound**

   *We can also calculate the number of atoms or ions in a formula unit. To determine the number of atoms or ions in a given number of moles of a substance, we extend the pathway further to include analysis of the chemical formula.*
Consider another example, copper(I) oxide. How many ions does 1 mol of Cu$_2$O contain? Analysis of the chemical formula shows that a formula unit of Cu$_2$O contains two Cu$^+\,$ ions and one O$^{2-}\,$ ion, as shown in Figure 4.9.

\[
1\,\text{mol Cu}_2\text{O} \times \frac{6.022 \times 10^{23}\,\text{formula units Cu}_2\text{O}}{1\,\text{mol Cu}_2\text{O}} \times \frac{2\,\text{Cu}^+\,\text{ions}}{1\,\text{formula unit Cu}_2\text{O}} = 1.204 \times 10^{24}\,\text{Cu}^+\,\text{ions}
\]

\[
1\,\text{mol Cu}_2\text{O} \times \frac{6.022 \times 10^{23}\,\text{formula units Cu}_2\text{O}}{1\,\text{mol Cu}_2\text{O}} \times \frac{1\,\text{O}^{2-}\,\text{ion}}{1\,\text{formula unit Cu}_2\text{O}} = 6.022 \times 10^{23}\,\text{O}^{2-}\,\text{ions}
\]

If those numbers are added up, the total number of ions in 1 mol Cu$_2$O is $1.807 \times 10^{24}\,$ ions (3 x $6.022 \times 10^{23}$).

Figure 4.9: One formula unit of Cu$_2$O, shown highlighted, contains two Cu$^+$ ions and one O$^{2-}$ ion.

**Molar Mass – (of elements and compounds)**

From the text (Chap. 4.2): The relative atomic mass is the average mass of atoms of an element in atomic mass units. This definition describes the average mass of one atom. But we can extend it to larger quantities of matter as well. Recall that the basis of the definition is that one atom of 12-C has a mass of exactly 12amu.

Avogadro’s number has been defined so that the mass of 1 mol of 12-C (that is, $6.022 \times 10^{23}$ atoms of 12-C) is exactly 12g.

Consequently, the mass of a basic particle of any substance in atomic mass units and the mass of 1 mol of the substance in grams have exactly the same numerical value.

**Question 3:** Can you express what is said in the sentence above with your **OWN WORDS**?
The definition of a mole can be restated, then, in terms of the mass of our reference, 12-C: A mole is the amount of substance that contains as many basic particles (atoms, molecules, or formula units) as there are atoms in exactly 12 g of 12C. The term that describes the mass of 1 mol of a substance is molar mass. (Definition!)

The molar mass value for any atom, in units of grams per mole (g/mol), is numerically the same as the relative atomic mass value (in units of amu per atom).

We can use the periodic table to determine the molar mass of any element or compound.
For example, the average mass of 1 hydrogen atom is 1.008 amu, and the mass of 1 mol of hydrogen atoms is 1.008 g.

The molar mass of a molecular or ionic substance has the same value as the sum of the relative atomic masses of its component elements.

For example, the average mass of a molecule of H₂S is 34.07 amu. Its molar mass is 34.07 g/mol. Molar masses of molecules (or formula units) are obtained by adding the molar masses of the component elements. Each weighted by the number of that atom in the molecule (or formula unit). For simplicity, we will abbreviate molar mass as MM.

**Molar Masses of Compounds:**

**Example question:** When copper sulfide ores are roasted in a furnace, sulfur dioxide gas, SO₂, forms. What is the molar mass of SO₂?

**Solution:** The molar mass of a compound is the sum of the molar masses of its component elements—in this case, sulfur and oxygen.

A molecule of sulfur dioxide contains one sulfur atom and two oxygen atoms. So we must multiply the molar mass of oxygen by a factor of 2. We can find the molar masses of sulfur and oxygen on a periodic table. Multiply the molar mass of oxygen by 2, and find the sum:

\[
\text{Mass of 1 mol of } S = 1 \text{ mol } \times 32.07 \text{ g/mol} = 32.07 \text{ g} \\
\text{Mass of 2 mol of } O = 2 \text{ mol } \times 16.00 \text{ g/mol} = 32.00 \text{ g} \\
\text{Mass of 1 mol of } \text{SO}_2 = 64.07 \text{ g}
\]

The molar mass of SO₂ is 64.07 g/mol. The unit for molar is g/mol.

**Question 4 (possible exam question):** What is the molar mass of aluminum hydroxide, Al(OH)₃?
Percent Composition by mass:
Another way of thinking about the composition of elements is to express it through the “percent composition by mass”. It is an expression of the portion of the total mass provided by each element. The percent composition of a substance is constant, no matter what the size of the sample.

The percent composition by mass can be calculated using the molar mass of a compound. The mass of each element that contributes to the total mass of one mole of the compound.

Let’s take the example of sulfur dioxide from above. Each of the elements contributed almost equally to the molar mass of the compound (32.07 g sulfur and 32.0 g oxygen). We can use the number to determine the exact percent composition of the compound SO₂.

\[
\% \ S = \frac{32.07 \text{ g sulfur}}{64.07 \text{ g SO}_2 \text{ sample}} \times 100\% = 50.05\%
\]

\[
\% \ O = \frac{32.00 \text{ g oxygen}}{64.07 \text{ g SO}_2 \text{ sample}} \times 100\% = 49.95\%
\]

Note that the percentages of all elements add up to the total of 100%.

Empirical and molecular formulas:
You have seen now how to express the composition of a substance in terms of masses, percent composition, moles, and atoms or molecules of the component elements.

There are two types of chemical formulas that are related to the composition of a substance.

An empirical formula expresses the simplest ratios of atoms in a compound. It is written with the smallest possible whole number subscripts. The empirical formula is not always the same as the molecular formula (for covalent compounds). However, it is the same for ionic formulas (remember, ionic formulas give the smallest whole number ratio of ions).

Question 5: Please summarize in your own words and in one sentence the paragraph above.
Table 4.1: Some empirical and molecular formulas

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecular formula</th>
<th>Empirical formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyclopentane</td>
<td>C₅H₁₀</td>
<td>CH₂</td>
</tr>
<tr>
<td>cyclohexane</td>
<td>C₆H₁₂</td>
<td>CH₂</td>
</tr>
<tr>
<td>ethylene</td>
<td>C₂H₄</td>
<td>CH₂</td>
</tr>
<tr>
<td>hydrogen sulfide</td>
<td>H₂S</td>
<td>H₂S</td>
</tr>
<tr>
<td>calcium chloride</td>
<td>CaCl₂ (there is no molecular formula for an ionic compound)</td>
<td>CaCl₂</td>
</tr>
</tbody>
</table>

Question 6: The empirical formulas of three compounds in the table are the same. What information about the molecular formula would you need to determine the correct molecular formula from the empirical formula?
SOLUTIONS

What to expect in this chapter:

Now that we know about the mole and how it can be used in calculating the quantities of compounds used in reactions, we may discuss the methods by which those reactions occur. As seen previously, the mole can be used to convert between units of particles, grams, and moles. In considering grams, or the weight of the compound in question, it is normal to think in terms of solids. However, reactions between solids usually happen over very long-time periods. These periods are not realistic for creating a reaction. If these same reactants are dissolved in a liquid to create a solution though, the reaction can occur much quicker.

In this chapter, you will be introduced to how to make a solution. On a macroscopic level, the solution will be viewed as a homogenous mixture and in this mixture, the solute particles are evenly spread among the solvent particles. This solution cannot be separated by using a filter. Chemists present solutions on a particle level where you can see ions dissociate in the solvent and molecular units staying unchanged. However, since solutions have different amounts of solvent/solute, the concentration will be used to define how much of the solute and solvent is present in the solution, and this can be done in various ways and one of the most common is the Molarity which is the number of moles of solute dissolved in 1 L of solution.

Question 1: Why do you think reactions in solution are often faster?

From the text (Chapter 4.4): Recall from Chapter 1: A solution is any mixture that is homogeneous at the molecular or ionic scale. In a solution, the substance that is dissolved is called the solute (usually present in a lesser amount). And the substance doing the dissolving is called the solvent (usually present in a greater amount). (Definitions!!)

Question 2: please summarize in one sentence and in your own words, the paragraph above.

Figure 4.17 shows a solution of copper (II) sulfate (the solute) dissolved in water (the solvent).
FIGURE 4.17 In this system, dissolved copper (II) sulfate is present in a lesser quantity than water. So, copper (II) sulfate is the solute and water is the solvent.

Solute = substance being dissolved; present in smaller amount
Solvent = substance doing the dissolving; present in greater amount
Note: If water is the solvent, we talk about an aqueous solution.

Solutions described on the molecular level

Example Question: From this picture of a solution that has CuSO₄ and water, identify the solute and the solvent.

Answer: In this image, the dark red spheres represent copper ions. The yellow/red groups of spheres represent sulfate ions (sulfate molecules). The pale red and white groups represent H₂O molecules. The number of copper and sulfate ions is equal and is less than the number of H₂O molecules. Thus, the solute is CuSO₄, which yields Cu²⁺ and SO₄²⁻ ions in solution. The solvent is H₂O since it is present in the greater amount.

Now you try!

Question/task 3: In the following image of a solution containing hydrogen sulfide and water, identify the solute and the solvent.
The particle representations above show the difference between an ionic compound dissolving in water in which we can observe dissociation of ions. And the dissolving process of molecular compounds in which the molecular unit stays undamaged.

Question 4 (possible exam question): Assuming now that the following compounds are all soluble in water, which compounds will dissociate into ions when in aqueous solution?

a) NaCl  b) CH₃OH  c) C₆H₁₂O₆  d) LiOH  e) K₃PO₄

Concentration of Solutions

From the text (Chapter 4.4): Solutions are homogeneous mixtures. However, different solutions can contain changing amounts of solute and solvent. So, how do we express the composition of a solution? One way is to describe its concentration, is by the relative amounts of solute and solvent in it.

When comparing solutions, we can describe them as either dilute or concentrated. A dilute solution contains a relatively small amount of solute. A concentrated solution contains a comparatively large amount of solute. These terms are helpful when we compare two solutions of different concentrations, indicating that one contains more or less solute than the other. We see these differences in concentration in everyday solutions. For example, when we brew a pot of tea, the color is more intense if the tea is "strong" (concentrated) than if it is "weak" (dilute).

Important concepts to remember:

- Concentration: how much solute per solvent is in the solution
- Dilute: there is more solvent than solute in the solution
- Concentrated: there is more solute than solvent in the solution

Question 5: What are some other solutions that you see in your environment where color gives you an indication of the concentration?

What other ways can you compare concentrations of solutions?

The concentrations of sugar solutions, for example, could be compared by how slowly they pour. If you compared a teaspoonful of sugar dissolved in a cup of water to molasses or syrup (also sugar solutions), which would pour more slowly?

Question 6: Can the different behavior be explained by different densities as well?
Comparing Concentrations of Solutions

A variety of experimental methods allows us to determine the concentrations of solutions. For example, if the solute is colored and the solvent is colorless, then the intensity of color in the solution is a measure of its concentration. Consider the aqueous solutions of copper (II) sulfate shown in Figure 4.18. The more copper (II) sulfate dissolved in the water, the more intense is the blue color due to the Cu^{2+} ions.

![Figure 4.18](image)

**FIGURE 4.18** The color intensity of a colored solution decreases as the concentration of the solute decreases. Compare the concentrations of ions in the solution for these copper (II) sulfate solutions. Which has more copper (II) ions? More sulfate ions? Which solution has the greatest concentration?

Question 7: Assuming that the solutions in Figure 4.18 contain 8, 5, or 3 moles of sulfate molecules (going from left to right, one sulfate molecule representing one mole), how many grams SO_4^{2-} (sulfate) are in each solution?

The relative amounts of solute and solvent vary with the concentration. This is shown in Figure 4.18. If you count the solute particles [copper (II) ions and sulfate ions] and compare them to the number of water molecules, you can see that as the solution becomes more dilute, the number of ions in a measured amount decrease. And the number of water molecules in that same measured amount increases. Because the concentration of copper (II) ions decreases relative to the number of water molecules, the solution starts to lose the blue color.

**Molarity—a measure of concentration**

The concentration of a solution can be expressed in a variety of ways. One of the most common ways is molarity (M). The molarity of a solution is the number of moles of solute dissolved in 1 L of solution. The molarity of any solution can be calculated by dividing the moles of solute by the liters of solution:
molarity = \frac{\text{moles of solute}}{\text{Liters of solution}}

For example: if 0.291 mols of NaCl are added to 150mL of solution, the molarity (M) would be represented as...

\[
molarity = \frac{0.291 \text{ mol NaCl}}{0.150 \text{ L solution}} = 1.94 \frac{\text{mol NaCl}}{\text{L solution}} = 1.94M
\]

Molarity is calculated from liters of solution, NOT liters of solvent. How large the difference is depends on the concentration of the solution. Dilute solutions contain only a small amount of solute. The volume of such solutions is very nearly the same as the volume of solvent. However, the difference can be significant for solutions in which the volume of the solvent is significantly less than the volume of the solution.

To ensure accuracy, solutions of the desired molarity are usually prepared in volumetric flasks. This is shown in the pictures below.

![Volumetric flask, Funnel, Water](image)

**Figure 4.19:** In the laboratory, solutions of known molarity are usually prepared in volumetric flasks. They are calibrated to contain a specific volume. (A) To prepare 250 mL of a 0.100 M solution of CuSO\textsubscript{4} \cdot 5H\textsubscript{2}O, weigh 6.24g (which is 0.0250 mol) of the solute. (B) Transfer it to the flask and add some solvent, water. Dissolve the solute by spinning. (C) Solvent is added with spinning until the bottom of the liquid surface just matches the marked line on the neck of the flask. (D) Then a stopper is put into the flask and the flask is inverted several times to thoroughly mix the contents. Convince yourself that this procedure will indeed result in a solution whose concentration is 0.100 M.

we can calculate the molarity of the solution, by knowing the mass of the solute and the volume of the solution. To begin, calculate the number of moles of solute contained in the solution. Then divide by the volume (in liters), of the solution.
Step-by-step example: You dissolve 5.5 g NaCl in 250 mL of water. The molar mass of NaCl is 58.44 g mol⁻¹.

Therefore: \[ 5.5 \text{ g NaCl} \times \frac{1\text{ mol}}{58.44\text{ g}} = 0.0941 \text{ mol (moles of solute)} \]

\[ \frac{0.0941 \text{ mol}}{0.250 \text{ L}} = 0.38 \text{ mol L}^{-1} = 0.38 \text{ M} \]

Ion Concentration in Solution—which can differ from the overall concentration of the solution

We usually express the concentration of a solution as a molarity of the solute compound. For example, a solution might contain 0.100 M CuCl₂. If we are interested in the concentrations of ions in a solution of this ionic compound, we must account for the fact that the solution contains twice as many chloride ions as copper (II) ions (Figure 4.20).

For each formula unit of CuCl₂ in the solution, we have one Cu²⁺ ion and two Cl⁻ ions. For each mole of CuCl₂ in the solution, we have 1 mol of Cu²⁺ ions and 2 mol of Cl⁻ ions. Thus, the 0.100 M CuCl₂ solution contains 0.100 M Cu²⁺ and 0.200 M Cl⁻ ions.

Calculations:

\[ 0.100 \text{ M CuCl}_2 = \left( \frac{0.100 \text{ mol}}{\text{L}} \right) \times \left( \frac{1 \text{ mol Cu}^{2+}}{1 \text{ mol CuCl}_2} \right) = 0.100 \text{ M Cu}^{2+} \]

\[ 0.100 \text{ M CuCl}_2 = \left( \frac{0.100 \text{ mol}}{\text{L}} \right) \times \left( \frac{2 \text{ mol Cl}^-}{1 \text{ mol CuCl}_2} \right) = 0.200 \text{ M Cl}^- \]

Note: This is simply a particle representation showing a formula unit of CuCl₂. It does NOT represent all Cu²⁺ and Cl⁻ ions in the solution.
FIGURE 4.20 (A) One formula unit of CuCl₂ consists of one Cu²⁺ ion and two Cl⁻ ions. (B) For every formula unit that dissolves in water, one aqueous Cu²⁺ ion and two aqueous Cl⁻ ions form.

Question 8: How many moles of chloride ions are in 0.2 L of a 0.5 molar AlCl₃ solution?

Dilution

From the text (Chapter 4.4): Suppose you taste your lemonade and find that it is too sweet. How might you make it less sweet? The easiest way is to add more water. Adding more water to lessen its concentration dilutes the lemonade. To lower the concentration of a solution, we use the process of dilution. Or adding more solvent to a solution, as depicted in Figure 4.21. In this process, the relative numbers of solute and solvent particles change. Adding more solvent increases the number of solvent particles and increases the volume. For a given amount of the original solution, the number of solute particles stays the same. But they are now spread out through a greater volume, so their concentration is less.

Dilution proceeds from higher concentration to lower concentration. Adding solvent reduces the concentration. Dilution is almost never carried out by removing solute from the solution. Think how difficult it would be to remove sugar from your glass of lemonade. Now think how easy it is to simply add more water!

Process of Dilution

![Dilution process diagram]

FIGURE 4.21 (A) A pipet is used to accurately measure 25.00 mL of 1.000 M CuSO₄ solution. (B) deliver it into a 250.0-mL volumetric flask. (C and D) Water is added with spinning until the diluted solution fills the flask to the marked level. (E) As water is added, the amount of water increases. This leads to a lesser concentration of solute. A stopper is placed in the flask. And the flask is inverted several times to completely mix the solution. The number of Cu²⁺ ions and SO₄²⁻ ions in a given volume of solution decreases. However, the total number of Cu²⁺ ions and SO₄²⁻ ions in the flask is constant. The new solution has a concentration of 0.1000 M.
Question 9: In performing dilutions, what part(s) of the solution (solute, solvent, concentration, components) is NOT changed?

Calculations Involving Dilutions:

The number of moles of solute contained in the volume of the more concentrated solution ($V_{conc}$) is found by multiplying the molarity ($M_{conc}$) of this solution by its volume in liters:

$$\text{moles}_{conc} = M_{conc} \times V_{conc}$$

Since we are adding only solvent, the moles of solute do not change upon dilution. So, the moles of solute before and after dilution are equal:

$$\text{moles}_{conc} = \text{moles}_{dl}$$

The moles of solute in the diluted solution also equal the product of molarity ($M_{dl}$) and volume ($V_{dl}$) in liters. Where the volume is the total volume after dilution:

$$M_{dl} \times V_{dl} = M_{conc} \times V_{conc}$$

We can rearrange this equation to solve for the molarity of the diluted solution:

$$M_{dl} = \frac{M_{conc} \times V_{conc}}{V_{dl}}$$

Example Question (possible exam questions): You are given 0.1000M NaCl solution. Initially, this solution has a volume of 25mL. Upon dilution, the new volume is found to be 250mL. Find the molarity of the diluted solution.

$$M_{dl} = \frac{0.1000M \times 0.02500L}{0.2500L} = 0.01000M$$

(Note: The final volume is given here correctly as 0.2500 L or 250.00 mL. What would the final volume be if the questions stated that 250.00 mL of water had been added to the initial volume? How would this change the new concentration? Please always read the questions very carefully!)

Question 10 (Possible exam questions): If the volume of a solution stays the same but you double the amount of solute, how does the concentration of the solution change?
10. Chemical Reactions:

Chemical reactions

What to expect in this chapter:

A chemical reaction is the change of one substance. It is also a change in a set of substances into another. We start with a reactant. A new substance that forms is a product. Products are different from reactants in the arrangement of their component atoms. Chemical reactions neither destroy atoms nor create new atoms. They happen because the bonds that hold atoms together can be broken and rearranged.

In this chapter, you will be introduced to what a chemical reaction is in terms of knowing when a chemical reaction occurs, how a chemical reaction is represented with a chemical equation, how chemical reactions are classified, how the products of different classes of chemical reactions can be predicted, and how chemical reactions are represented in aqueous solutions.

Consider the reaction of hydrogen gas with oxygen gas, as shown in Figure 5.5. Hydrogen and oxygen both happen naturally as diatomic molecules. If they mix, they react slowly, but if set on fire, the reaction is powerful, even explosive. In either case, the reactants form the same product. Which are gaseous water molecules. Each contains two hydrogen atoms and one oxygen atom.

Figure 5.5

Now consider the arrangement of atoms in Figure 5.6. What are oxygen atoms attached to in the reactants? In the products? How many hydrogen atoms? In the reactants, each hydrogen atom is attached to another hydrogen atom. And each oxygen atom is attached to another oxygen atom. In the products, two hydrogen atoms are attached to one oxygen atom. The number of atoms is the same. However, their arrangement is different.
Figure 5.6 The hydrogen atoms from hydrogen molecules mix with the oxygen atoms from oxygen molecules to form gaseous water molecules.

How do we know a chemical reaction happens:
Artists use paint and stone to make works of art. Chemists use elements and compounds to make new substances. Both the artist and the chemist are supposed to use materials available to them. Both must work within the rules of nature regarding the properties and behaviors of their materials.

The clues most often used by chemists are the following:
- Change in color
- Production of light
- Formation of a solid (such as a precipitate in solution, smoke in air, or a metal coating)
- Formation of a gas (bubbles in solution or fumes in the gaseous state)
- Absorption or release of heat (sometimes appearing as a flame)

Did you come across any clues that don’t fit one of these categories?
Figure 5.8 illustrates some of these chemical reactions.

(A) $I_2(aq) + NaI(aq) + starch(aq)$
(B) $Mg(s) + O_2(g)$
(C) $Ba(OH)_2 \cdot BH_4O(s) + NH_4Cl(s)$
(D) $Cu(s) + HNO_3(aq)$
(E) $BaCl_2(aq) + Na_2SO_4(aq)$
(F) $CH_4(g) + O_2(g)$
(G) $AgNO_3(aq) + glucose(aq)$
(H) $CaCO_3(s) + HCl(aq)$

Figure 5.8 Do any of these photos of chemical reactions shows items on the list you made of nature's clues that a chemical reaction has happened?

Question 1: Xenon gas reacts with fluorine gas to form Xenon tetrafluoride gas. Identify which image represents reactants and then which image represents products.
Writing chemical equations:

Describing chemical reactions in words is hard and takes time. Chemists use a chemical equation to show what reactants are involved. And also, what products are made. A chemical equation is a significant representation of a chemical reaction. The equation must be balanced. In a balanced equation, the number of atoms of each element is the same in the products as in the reactants.

Question 2: Please summarize in one sentence and in your own words the paragraph above?

Let’s work through writing and balancing the thermite reaction. In words, it looks like this:
Aluminum + Iron (III) oxide → Aluminum oxide + Iron

\[ \text{Al}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + \text{Fe}(l) \]

This equation is not yet complete because it is not balanced. Both sides of the arrow must have the same number of each element. In its present form, it has the following numbers of atoms:

<table>
<thead>
<tr>
<th># of atoms (reactants)</th>
<th># of atoms (products)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Al</td>
<td>2 Al</td>
</tr>
<tr>
<td>2 Fe</td>
<td>1 Fe</td>
</tr>
<tr>
<td>3 O</td>
<td>3 O</td>
</tr>
</tbody>
</table>

Therefore, we need to balance the equation with coefficients:
2 Al(s) + Fe₂O₃(s) → Al₂O₃(s) + 2 Fe(s)

Question 3: write complete, balanced equations for each of the following reactions.
(a) Sodium metal reacts with oxygen gas to form solid sodium oxide.
(b) Solid copper (II) nitrate is heated to produce solid copper (II) oxide, gaseous nitrogen dioxide, and oxygen.

Balancing equations:

Build models of reactant molecules using a model kit or gumdrops and toothpicks. This is done to see how and why equations balance. Take them apart and rearrange them into product molecules. Use the smallest number of atoms possible to achieve conservation of mass. Reactions don’t actually happen this way. But we want to highlight the conservation of atoms in reactions as a means of balancing equations.

General approach to balancing equations:

1. Write correct formulas for reactants on the left side. And products on the right side of the arrow.
2. Look for elements that are seen only once on each side of the equation.
3. Do not change the subscripts! Changing subscripts in a formula would change the identity of the substance.
4. The atoms to be balanced should be those in elemental substances.
5. Make a final check by counting the atoms of each element on both sides of the equation.

Question 4: Balance the following chemical reactions

(A) Ba(s) + HCl(aq) → BaCl₂(aq) + H₂(g)
(B) Na₂CrO₄(aq) + Pb(NO₃)₂(aq) → PbCrO₄(s) + NaNO₃(aq)

Predicting chemical reactions:
In all the chemical reactions we have seen so far, the identities of the reactant and products are known. Identity of the reactants is easy enough. We usually know what we have mixed. But how do we know what products will result? The answer could be from an experiment.
Classes of Chemical reactions:

<table>
<thead>
<tr>
<th>Class</th>
<th>Reactants</th>
<th>Products</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition</td>
<td>1 compound</td>
<td>2 elements (or smaller compounds)</td>
<td>CD → C + D</td>
</tr>
<tr>
<td>Combination</td>
<td>2 elements or compounds</td>
<td>1 compound</td>
<td>A + B → AB</td>
</tr>
<tr>
<td>Single displacement</td>
<td>1 element and 1 compound</td>
<td>1 element and 1 compound</td>
<td>A + CD → C + AD</td>
</tr>
<tr>
<td>Double displacement</td>
<td>2 compounds</td>
<td>2 compounds</td>
<td>CD +EF → CF + ED</td>
</tr>
</tbody>
</table>

Decomposition:

During decomposition reaction, a compound breaks down into the elements of which it is composed or into simpler compounds.

\[
2\text{HgO(s)} \xrightarrow{\Delta} 2\text{Hg(l)} + \text{O}_2(g)
\]

Figure 5.13 when solid mercury (II) oxide, HgO, is heated, it decomposes into liquid mercury metal and oxygen gas.
The oxide ions lose their negative charge as they become oxygen atoms. The mercury (II) ions lose their positive charge to form mercury atoms.

Question 5: Complete and balance the following decomposition reactions

(a) CaCO$_3$(s) →
(b) CuSO$_4$.5H$_2$O →

Combination reactions:

In a combination reaction (also called synthesis), two substances react to produce a single compound.

\[ 2Al(s) + 3Br_2(l) \rightarrow 2AlBr_3(s) \]

Figure 5.16 Aluminum reacts with bromine to form aluminum bromide.

![Figure 5.16](image)

Figure 5.19: The combination reaction of carbon monoxide and oxygen shown on a molecular level. \[ 2CO(s) + O_2(g) \rightarrow 2CO_2 \]

Question 6: Complete and balance the following combination reactions

(a) Ca(s) + N$_2$(g) →
(b) Al(s) + O$_2$(g) →
Single displacement reaction:

In a single displacement reaction, a free element displaces another element from a compound to make a different compound and a different element.

$$2\text{Al}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + 2\text{Fe}(l)$$

Figure 5.20 calcium reacts with water to form aqueous calcium hydroxide and gaseous hydrogen.

$$\text{Cu}(s) + 2\text{AgNO}_3(aq) \rightarrow \text{Cu(NO}_3)_2(aq) + 2\text{Ag}(s)$$

Copper atoms become copper (II) ions, and silver ions become silver atoms. Nitrate ions the same in solution.

Question 7: Complete and balance the following single displacement reactions

(a) $$\text{Zn}(s) + \text{AgNO}_3(aq) \rightarrow$$

(b) $$\text{Na}(s) + \text{FeCl}_2(s) \rightarrow$$

Double displacement:
In all double displacement reactions, two compounds exchange ions or elements to form new compounds.
Figure 5.26 When solutions of barium chloride and sodium sulfate mix, a precipitate of barium sulfate forms, leaving sodium chloride in the solution.

\[ \text{BaCl}_2(aq) + \text{Na}_2\text{SO}_4(aq) \rightarrow \text{BaSO}_4(s) + \text{NaCl}(aq) \]

Question 8: complete and balance the following double displacement reactions.

(a) \[ \text{BaCO}_3(s) + \text{H}_2\text{SO}_4(aq) \rightarrow \]
(b) \[ \text{CuCl}_2(aq) + \text{AgNO}_3(aq) \rightarrow \]
11. Limiting Reactants

What to expect in this chapter:

Why don’t we use the exact amounts of each reactant that are needed for a chemical reaction? Small errors can always lead to a slight excess of one reactant that might contaminate the product. To ensure that a selected reactant is used completely, we might use an excess of the other reactant.

In this chapter we will get an understanding of which reactant limits the amount of the product that can form, by identifying the limiting reactant, we will look at the limiting reactant of a molecular level and also do some mathematical investigation of the limiting reactant.

Limiting Reactants (or also called Limiting “Reagents”)

Using exact stoichiometric amounts of reactants is often not the most practical thing to do when conducting an experiment in the lab. Why is this?

Think about what has to happen on a particle level during a chemical reaction to actually form product. Think about the reaction of hydrogen molecules ($\text{H}_2$) and oxygen molecules ($\text{O}_2$) to form water ($\text{H}_2\text{O}$).

Question/task 1: Describe what has to happen in a reaction vessel which contains oxygen and hydrogen molecules in order to form water? Is interaction between the gaseous molecules necessary?

What exactly is a “limiting reactant”?

Definition: The limiting reactant in a chemical reaction is the reactant that determines the maximum amount of product that can be formed. The limiting reactant usually reacts completely in a chemical reaction.

To gain a better understanding of limiting reactants, let’s look at a system that is not a chemical reaction.

Suppose someone wants to build a model solar-powered car.

He needs 1 frame, 1 solar cell, 1 electric motor, and 4 wheels (Figure below).

We can write an equation (like chemical equation). The equation has to represent the numbers of parts required to make one car:

$1 \text{ frame} + 1 \text{ solar cell} + 1 \text{ electric motor} + 4 \text{ wheels} \rightarrow 1 \text{ model solar car}$

or in terms of “particles”

The equations show the amount and type of parts that are needed to build exactly one solar car. This is comparable to a chemical reaction with reactants and product(s). The ratios of reactants needed to form the
product(s) is shown. These ratios/amounts shown through the stoichiometric coefficients are called stoichiometric amounts.

Question 2: please summarize in your own words and in one sentence the paragraph above.

What if you are given a certain amount of parts different from the "stoichiometric" amounts? How do you know what the limiting reactant is? How much product can you obtain?

Solution:
You need to compare the needed amounts of reactants with the available amounts of reactants. Then determine the maximum amount of product possible.

**Needed amounts for one car:**

1 frame, 1 solar cell, 1 electric motor, and 4 wheels

**Given amounts of reactants:**

Check how many cars you could build with the given amounts of each reactant. The reactant with the least amount of product (cars) is the limiting reactant!

The maximum number of cars that can be built with each type of car part......

Therefore, the maximum number of cars that can be built from the available parts is 3. The sets of wheels are the limiting reactant.
Chemical example

Silver bromide used in photographic films is prepared by the reaction of magnesium bromide and silver nitrate solutions.

\[
\text{MgBr}_2 + 2\text{AgNO}_3 \rightarrow 2\text{AgBr} + \text{Mg(NO}_3)_2 \] (reaction is done in an aqueous solution)

This equation suggests, using twice the molar amounts of silver nitrate compared to magnesium bromide. We will ensure that both reactants completely react. And the maximum amount of product can be obtained.

This is the ideal theoretical scenario. It is often not realized under laboratory conditions.

So- what can be done?

Magnesium bromide is usually used in excess. This is done to ensure that all of the more expensive silver nitrate is used completely.

Question 3: If magnesium bromide is used in excess in the reaction, which substances will be in the mixture once the reaction is completed?

More useful information about reactants in excess:

When gas burns in a car engine, we rely on oxygen in the air to support the combustion. We do not worry about running out of oxygen. A chemist would say that oxygen is in excess for the reaction.

When the space shuttle is in space, however, there is no air to provide oxygen. The shuttle must take the right amounts of hydrogen and oxygen with it. If too much of one reactant were transported, the extra reactant would have nothing to react with. It would simply add extra mass to the shuttle. Mass-mass calculations are important in such situations.

When a space shuttle takes off, it leaves with measured amounts of hydrogen and oxygen. This is done so that no extra mass is added. Many reactions, however, happen with an excess of one reactant.

Consider a single-displacement reaction between magnesium metal and aqueous hydrochloric acid:

\[
\text{Mg(s)} + 2\text{HCl (aq)} \rightarrow \text{MgCl}_2\text{(aq)} + \text{H}_2\text{(g)}
\]
How do we know if all of each reactant is used up in the reaction?

There will be some reactant left over at the end of the reaction if all the reactants don't react completely. The leftover amount will be present mixed with the product. Shown in Figure 6.7 on the following page.

![Images of three beakers labeled A, B, and C.]

**Figure 6.7:** When reactants are not mixed in relative amounts as described by the balanced equation, one reactant does not react completely. (A) Here magnesium metal reacts with hydrochloric acid to form magnesium chloride in solution and hydrogen gas.

Question 4: When the reaction is complete (see Figure 6.7), one reactant remains in excess. What is the excess reactant in beaker B? And in beaker C?

We should mix the reactants in the proper (stoichiometric) quantities. This is done to not have any unreacted magnesium or hydrochloric acid left over. Their mole ratio (NOT mass ratio!!!) has to be the same as that shown by the coefficients in the balanced equation.

*If the reactants mixed together are not present in the exact mole ratio, then we will have too much of one reactant and not enough of another. One reactant reacts completely, and some of the other is left unreacted.*

Identifying the Limiting Reactant

Iron metal is added to an aqueous solution of copper (II) chloride. The solution is blue because copper (II) ions in solution produce a blue color. When the reaction is complete, the solution is colorless. The piece of iron is coated with a granular, brownish-black metal.

Question/task 5: Which compound is the limiting reactant in this reaction? You do not have enough information to determine the limiting reactant through calculation? Do you have visual signs that gives you a clue? Explain!
Limiting Reactant - On the molecular level

Now let's look at what happens at the molecular level in a reaction that has a limiting reactant.

Let's review the combustion of hydrogen to form water. The molecular-level diagram and balanced equation in Figure 6.9 show that the molecule ratio of $\text{H}_2$ to $\text{O}_2$ is. The molecule ratio is the same as the mole ratio. They both are related to the coefficients in the balanced equation.

\[ 2\text{H}_2 (g) + \text{O}_2 (g) \rightarrow 2\text{H}_2\text{O} (g) \]

**FIGURE 6.9:** For every 2 $\text{H}_2$ molecules that react, 1 $\text{O}_2$ molecule reacts with it to form 2 $\text{H}_2\text{O}$ molecules.

In this chemical reaction, the reactant molecules are the “parts” that mix in a specific ratio to make the product $\text{H}_2\text{O}$ molecules.

If the number of $\text{H}_2$ molecules mixed is exactly two times the number of $\text{O}_2$ molecules, then all the $\text{H}_2$ and $\text{O}_2$ molecules will react. And no reactants will be left over.

**OR**

If the ratio of $\text{H}_2$ to $\text{O}_2$ molecules mixed together is not exactly, then one reactant is the limiting reactant and the other is in excess.
For example, suppose 8 molecules of H₂ are mixed with 5 molecules of O₂, as shown in Figure 6.10 (next page). The reactant ratio is not the same as in the balanced chemical reaction. Only one of the reactants is completely used up. The other is in excess.

After the reactants combine in this 2 to 1 ratio, 8 H₂O molecules form.

The H₂ reactant is the limiting reactant because it was completely used up. It limited the number of H₂O molecules that could form. The O₂ reactant is left over. It was in excess.

When the reaction is complete, the 1 leftover O₂ molecule that did not react will also be present in the reaction mixture along with the 8 H₂O molecules that formed.

2H₂ [g] + O₂ [g]  →  2H₂O [g]

**FIGURE 6.10**: Reaction of H₂ and O₂ in non-stoichiometric amounts.

**Question 6**: How can you increase the amount of product (H₂O) in Figure 6.10 that is being formed? Do you add more oxygen or more hydrogen to the reaction mixture?

**Mathematical investigation of limiting reactants**:
How can you determine the limiting reactant mathematically?

You need to compare the molar amounts of two (or more) reactants!

Here is what you have to do:

**Step 1**: Calculate the molar amount for each reactant. If you have the masses of the reactants given, divide by the molar mass.
Example (using the reaction between molecular hydrogen and molecular oxygen above):
Assuming the reaction mixture will have 4.0 grams of hydrogen and 5.0 grams of oxygen.

For hydrogen: \[\frac{4.0 \text{g} \ H_2 \times \frac{1 \text{mol}}{2.016 \text{g}}}{1.98 \text{ mol} \ H_2}\]

For oxygen: \[\frac{5.0 \text{g} \ O_2 \times \frac{1 \text{mol}}{32.0 \text{g}}}{0.16 \text{ mol} \ O_2}\]

So far you calculated the available molar amounts of reactants.

**Step 2:** Using the stoichiometric coefficients from the balanced equation calculate the molar amount of one reactant needed to react completely with the other reactant.

Let’s start with 1.98 mol of hydrogen. Using the stoichiometric coefficients from the balanced chemical equation, calculate the exact amount of oxygen needed to react completely with 1.98 mol hydrogen. (Note: You could also start with the molar amount of oxygen, 0.16 mol.)

\[1.98 \text{ mol} \ H_2 \times \frac{1 \text{ mol} \ O_2}{2 \text{ mol} \ H_2} = 0.99 \text{ mol} \ O_2\]

Your result shows that you need 0.99 mol of oxygen to react completely with 1.98 mol H₂. But you just have 0.16 mol available (see result of Step 1).

What does that mean?

You have less oxygen available (0.16 mol) than you would need to completely react with 1.98 mol of hydrogen. So, oxygen is the limiting reactant since it limits the amount of water (product) that can be made.

**Question 7:** (possible exam question, relating to reaction above) Which reactant would be the limiting reactant if you had 1.16 mol of oxygen available? Explain!

**Question 8:** (Possible exam question)

Given the reaction vessel and the balanced chemical reaction, what is the limiting reactant?
Each symbol represents 1 mol of molecules of the substance.

\[2\text{C}_2\text{H}_2(\text{g}) + 5\text{O}_2(\text{g}) \rightarrow 4\text{CO}_2(\text{g}) + 2\text{H}_2\text{O}(l)\]

A. C₂H₂ \hspace{1cm} B. O₂ \hspace{1cm} C. CO₂ \hspace{1cm} D. H₂O
12. Ideal Gases

THE IDEAL GAS LAW

What to expect in this chapter:

Some properties of gases are easy to see such as a gas being compressed into a container. A liquefy or an air balloon decreasing in size when cooled down in the refrigerator.

It is much more difficult to imagine what is actually going on with gas particles in these situations. The properties of gas particles—whether we talk about gaseous atoms (e.g., Ne, He, Ar) or gaseous molecules (O₂, N₂, CH₄, H₂O)—explain why we observe these macroscopic properties.

In this chapter, you will be introduced to the mechanical relationships between volume, pressure, temperature, and amount of gas.

Some of these particle properties are:

- Gases are made up of particles that are somewhat far apart.
  
  *The large spaces between particles explain why gases have much lower densities than liquids and solids. Because gases have so much empty space, it is easy to compress them into smaller volumes by applying outside pressure.*

- Gas particles move fast.
  
  *For example, the average velocity of oxygen gas molecules (O₂) at 20°C and normal atmospheric pressure is 0.44 km/s (980 mi/h).*

Movement of gas molecules in a contained space
• Gas particles have little effect on one another unless they bump.
  *Gas particles have only a small amount of attraction for one another at normal temperatures and pressure. They move about freely in all directions. When they bump, gas particles simply bounce off of each other.*

• Gases widen to fill their containers.
  *Gases take the volume and shape of their containers as a consequence of their random motion.*

Now you’ve heard a lot about gases and some descriptions include phrases such as “at 20°C and normal atmospheric pressure” or “at normal temperatures and pressures”.

This shows that the properties depend greatly on some variables. The main relationship between the four important variables that determine the properties of gases are:

From the text (Chapter 9.3): The properties of gases can be described by the four variables pressure (P), volume (V), absolute temperature (T), and number of moles (n). Suppose we want to describe a gas under a specific set of static conditions. The relationships between the individual gas laws can be manipulated to give us a general equation. This equation relates volume, pressure, temperature, and amount of gas.

Important relationships (or interdependencies) between these variables that are being discussed in this course are:

1) Boyle’s Law: \[ V \propto \frac{1}{P} \], as a result for two sets of conditions \[ P_1 \cdot V_1 = P_2 \cdot V_2 \] (at constant n and T)
   *Principle:* Volume and pressure are inversely related (when pressure increases, volume decreases and vice versa).

2) Charles’ Law: \[ V \propto T \], as a result for two sets of conditions \[ \frac{V_1}{T_1} = \frac{V_2}{T_2} \]
   *Principle:* Volume and temperature are directly related (when volume increases, temperature increases and vice versa). (at constant n and P)

3) Avogadro’s Hypothesis: \[ V \propto n \], as a result for two sets of conditions \[ \frac{V_1}{n_1} = \frac{V_2}{n_2} \] (at constant V and P)
   *Principle:* Volume and moles are directly related (when the amount of gas particles increases, volume increases and vice versa).

The combined gas law derives from these relations (Avogadro not included!)

Combined Gas Law: \[ \frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2} \] (at constant n)
When including Avogadro's law, an equation derives that is very useful to describe a gas under a single set of conditions. This combination of laws produces a single equation called the ideal gas law, which we will discuss here.

Volume is proportional to each of the three factors. It must be simultaneously proportional to all of them:

$$V \propto \frac{n \cdot T}{P}$$

Since these variables are proportionally related, we can use a constant to express an equivalent relationship (note: whenever a mathematical proportionality is converted into an equation, you need to introduce a constant)

$$V = \text{constant} \times \frac{n \cdot T}{P}$$

Because it relates all the terms from the individual gas laws, we have a special name for the constant in this expression. The ideal gas constant, and we use R to represent it. Substituting the ideal gas constant R into the expression, we obtain the following equation:

$$V = \frac{R \cdot n \cdot T}{P}$$

Rearranging the variables results in the equation known as the ideal gas law:

$$P \cdot V = R \cdot n \cdot T$$

Question 1: In which container in the image below will the gas pressure be higher? Please explain your answer.

Same amount of gas molecules in both containers.
Volume 1: larger container with more space.
Volume 2: smaller container with less space.

The ideal gas constant, R
An ideal gas is a gas that follows behavior predicted by the ideal gas law. Using the observation that 1 mol of an ideal gas at STP occupies 22.414 L, we can calculate the value of R as follows:

$$ R = \frac{P \cdot V}{n \cdot T} = \frac{(1.000 \text{ atm}) \cdot (22.414 \text{ L})}{(1.000 \text{ mol}) \cdot (273K)} = 0.08206 \frac{L \cdot \text{ atm}}{mol \cdot K} $$

This numerical constant is valid only if we measure volume in liters and pressure in atmospheres, absolute temperature in Kelvin and the amount of substance in moles. Measurements in other units must be converted to use this constant.

Review: an ideal gas = a gas that at 1 mol, a temperature of 273.15K, and 1 atm of pressure will occupy a volume of 22.414L.

From the text (Chapter 9.3): The ideal gas law includes all the information summarized by Boyle's law, Charles's law, and Avogadro's hypothesis. Like them, the ideal gas law is valid only for an ideal gas. It shows that the volume occupied by an ideal gas is directly proportional to the absolute temperature and to the number of moles of gas molecules. It is inversely proportional to pressure. A single equation that relates all the variables is a useful tool. When given any three values and the value of R, we can calculate the unknown quantity.

Question 2: What kind of assumptions are we making to call a gas "ideal"? Can you comment on the distance between gas particles, the interactions between them, and the volume of the particle itself? Are any of these aspects accommodated for in the ideal gas law?

Calculations with the Ideal Gas Law

From the text (Ch. 9.3): To solve a gas law problem, we must first determine what is going on in the gas system. Then select the appropriate mathematical relationship. For changes in volume, pressure, and temperature, we generally use the combined gas law (same as ideal gas law, but n is constant).

In contrast, the ideal gas law allows us to determine any one of the quantities volume, pressure, temperature, or moles of the gas given the other three. The law can also be used to determine the densities of gases. If the identity of the gas is known, we can also calculate its mass using its molar mass.

Calculating density:

In order to calculate the density of a gas \( d = \frac{m}{V} \), the amount of gas n has to be expressed differently.

Using \( n = \frac{m}{MM} \) the ideal gas law reads as \( P \cdot V = \frac{m}{MM} \cdot R \cdot T \)
Now solving for density $\left( \frac{m}{V} \right)$ results in $\frac{m}{V} = \frac{P \cdot MM}{R \cdot T}$ = density.

Calculating masses or molar masses

You can use the same expression above to solve for mass or molar mass of a gas:

For mass: $m = \frac{P \cdot MM \cdot V}{R \cdot T}$

For molar mass: $MM = \frac{m \cdot R \cdot T}{P \cdot V}$ or, if the density is known, $MM = \frac{m}{V} \cdot \frac{R \cdot T}{P}$ (with $\frac{m}{V} = d$)

Question 3: What is the density of neon at STP?

Calculating the amount (moles) of gas

From the text (Ch. 9.3): If we are given the P, V, and T conditions for a sample of a gas, we can calculate the number of moles of the gas, using the ideal gas law. We need only rearrange the equation $P \cdot V = n \cdot R \cdot T$

to solve for the number of moles. Remember that all other quantities must be in units that match the value used for the ideal gas constant.

Example:

The volume of a propane cylinder is 0.960 L. When filled, the cylinder contains liquid propane stored under pressure. When the cylinder is "empty," it contains propane gas molecules at atmospheric pressure and temperature. How many moles of propane gas remain in a cylinder when it is empty? If the surrounding atmospheric conditions are 25.0°C and 745 torr?

Solution:

1. Convert to the desired units of T and P:

$$T = 25.0°C + 273.15 = 298.2K$$

$$P = 745 \text{ torr} \cdot \frac{1 \text{ atm}}{760 \text{ torr}} = 0.980 \text{ atm}$$

2. Rearrange the ideal gas law and substitute the appropriate values to calculate the number of moles:
\[
P \cdot V = n \cdot R \cdot T \\
n = \frac{P \cdot V}{R \cdot T} = \frac{(0.980 \text{ atm}) \cdot (0.960 \text{ L})}{(0.08206 \frac{L \text{ atm}}{mol \cdot K}) \cdot (298.2 \text{ K})} = 0.0384 \text{ mol}
\]

Ask yourself - does this answer seem reasonable? (This is a very important question to ask!!)

At standard temperature (273.15 K) and pressure (1.00 atm), 1 mol of an ideal gas occupies 22.414 L, the molar volume. In this case the temperature is 25° higher than standard. The pressure is close to standard pressure. And the volume is significantly less than the molar volume of a gas. We would expect significantly fewer moles of gas present in the cylinder under these conditions. That's what our calculation shows.

Calculating the mass of a gas (equation has been discussed above)

Once the number of moles of gas is determined from the ideal gas law, we can calculate the mass of the gas if we know its identity. Knowing the number of moles, we can use the molar mass of the gas to convert moles to grams.

Now knowing the number of moles of propane and the identity of the gas, we can determine the mass of propane (you have done this type of calculation often before)

Answering the questions: What mass of propane, C\textsubscript{3}H\textsubscript{8}, is left in the cylinder of Example 1?

Solution:

Remember that molar mass gives a relationship between moles of a substance and grams of that substance. The molar mass of propane is 44.10g/mol. The mass of 0.0384 mol of propane can be determined by multiplying moles by molar mass:

\[
\text{mass} = 0.0384 \text{ mol C}_3\text{H}_8 \times \frac{44.10 \text{ g}}{1 \text{ mol C}_3\text{H}_8} = 1.69 \text{ g C}_3\text{H}_8
\]

If we know the mass and volume of a gas, we can now also determine its density.

Solution:

\[
d = \frac{m}{V} = \frac{1.69 \text{ g}}{0.960 \text{ L}} = 1.76 \frac{\text{g}}{L}
\]

Question 4: What is the mass of 15.0 L of methane at 10°C and 1.2 atm?
High Lexile reading assignments.

1. Atomic theory.

The evolution of the atomic theory

What to expect in this chapter:

The first part of this chapter introduces John Dalton’s atomic theory from 1808; he was an English schoolteacher and hobby scientist, with his theory, he revived the idea that matter consists of microscopic particles called atoms, a theory that finds its origin in ancient Greece but had been neglected for over 2000 years.

At the time Dalton published his theory, the existence of subatomic particles was not known. Subatomic particles “live” inside atoms and are considerably smaller than atoms; they are critical in the sense that they determine the properties of individual elements.

The second part of this chapter will talk about experiments that have been conducted after 1808; these experiments have accidentally or intentionally shown the existence of subatomic particles (cations, anions, or neutrons).

Based on these discoveries, the model of what an atom looks like has been revised a couple of times. Please note that models are often not an accurate mirror of the truth; models change if new information becomes available.

Dalton’s Atomic Theory

In 1808 John Dalton, who was an English chemist, physicist, and meteorologist, published his atomic theory. He contended that the law of conservation of mass and the law of definite proportions could be elucidated, only if matter was made up of atoms. His postulates can be summarized as follows:

1. All matter is composed of exceedingly small, indivisible particles, called atoms.
2. All atoms of a given element are identical, both in mass and in chemical properties. However, atoms of different elements have different masses and different chemical properties.
3. Atoms are not created or destroyed in chemical reactions.
4. Atoms combine in simple, fixed, whole-number ratios to form compounds.
5. Atoms are mixed, broken apart, or reorganized in a chemical reaction.

Many important discoveries were made about the structure of the atom; now let’s have a closer look at some important discoveries about the structure of the atom, which happened between 1897 and 1932.

Question 1: Please explain in your own words the meaning of Dalton’s second and fourth postulates. Name examples if you can think of some.

Experiments that helped determine the internal structure of the atom.
What are Subatomic Particles?

Cathode-ray tubes (CRTs) are vacuum tubes, that are made of more than one electron gun and a phosphorescent screen, they are fundamental components of older television picture tubes and computer monitors. The screen contains chemical compounds that glow when struck by fast-moving electrons. Different chemicals that glow different colors provide a color picture.

A subatomic particle is a smaller particle found inside an atom, there are more than 40 known, however only three are of interest in chemical behavior. These subatomic particles are the proton, neutron, and electron. It was not until the late 1800s that researchers developed instruments and techniques capable of detecting subatomic particles and revealing their numbers and arrangements in atoms.

Discovery of the Electron

Scientists came to the conclusion that Dalton’s atoms were made up of even smaller subatomic particles, this lead to the discovery of the electron, a negatively charged subatomic particle, demonstrated by J. J. Thomson in 1897. He conducted a series of experiments with cathode-ray tubes, showing that the rays emitted were negatively charged (Figure 2.3 next page). In a partially evacuated cathode-ray tube, a high voltage is applied by connecting each end of the tube to a battery, which makes a beam of particles to circulate form the cathode (negatively charged electrode) to the anode. Electricity then flows from one end of the tube to the other in the form of a ray. The invisible rays can only be observed when they cause certain materials coated on the glass to glow.

Although it was believed that cathode rays only traveled in straight lines, and had properties that didn’t depend on the material of the cathode (gold, silver ...). Thomson found that, in a magnetic or electric field, the rays bent toward a positively charged plate and were deflected away from a negatively charged plate outside the tube, this was done by placing a positively and a negatively charged plate around the cathode ray. He knew that like electrical charges repel each other and opposite charges attract each other. The bending of the beam toward the positive plate (and away from the negative plate) showed that the beam was composed of negatively charged particles.

Image A: Cathode ray tube without the application of an external field
FIGURE 2.5 Thomson’s Experiment - Cathode-Ray Tube (Experimental Set-Up)

Thomson showed that the rays had a negative electrical charge no matter what material was used for the source of the rays. This result indicated that the rays were composed of identical, negatively charged particles common to all matter. We call these particles electrons. Thomson was also able to determine the charge-to-mass ratio of the electron from such experiments.

**Question 2: How did the discovery of electrons make it necessary to change one of Dalton’s postulates?**

**Question 3: In figure 2.5, what’s happening in image B? Please explain.**

The discovery of the Proton

The discovery of the electron stimulated many more experiments in search of other subatomic particles. Since atoms are electrically neutral, scientists reasoned that atoms must contain positively charged particles to counter the negatively charged electrons. The positively charged
particle, called a proton, has a charge equal in magnitude to the electron but opposite in sign, 
$+1.6022 \times 10^{-19}$ C. To be electrically neutral, an atom must have equal numbers of protons and 
electrons. To make it easier to deal with electrical charges in matter, we usually express the 
charges as a multiple of the charge of an electron or of a proton, instead of in units of coulombs. 
Expressed in this way, the charge of an electron is 1-, and the charge of a proton is 1+.

The model of the atomic nucleus (core) in 1904

How might protons and electrons be arranged in an atom? Thomson's model of atomic structure 
was called the “plum pudding” model because atoms are blended objects, made of bits with 
positive and negative charges, the negatively charged bits are small compared to the positive 
ones. It assumed that protons and electrons were distributed the same way throughout the atom 
(Figure 2.7 below).

![Diagram of the plum pudding model]

**FIGURE 2.7 - The "Plum-Pudding" Model**

Thomson's model suggested that electrons in the atom might be embedded in a sphere of positive 
charge, like raisins in plum pudding.

Five years later...

**Discovery of the Nucleus - Rutherford's Gold Foil Experiment**

Ernest Rutherford designed an experiment to test the plum-pudding model, and his associate, 
Hans Geiger, carried it out.

The experiment involved blasting thin gold foil with alpha particles, the particles were expected 
to go straight through the gold foil. The gold foil was wrapped with sheets of zinc sulfide, 
emitted a beam when struck by the alpha particles. Alpha particles were known at the time as
positively charged particles thousands of times greater in mass than electrons. (Today we know them as helium atoms that have lost their electrons.) According to the plum pudding model, none of the alpha particles should have been affected by the dispersed hits of positive and negative charge in the gold atoms. They should have zipped right through the gold foil, and most did, however, some of them came off the foil at different angles, some swerved a bit, and a few actually bounced backward, as shown in Figure 2.8, next page.

The result was quite unexpected.

It was as if you fired a bullet at a sheet of tissue paper and it came back and hit you! The swerving of these massive alpha particles suggested that most of the mass of the atom had to be concentrated in a positively charged core, which is the center and major part. Rutherford called the core, the nucleus. The electrons are the smallest particles of an atom; they are also negatively charged, and had to be scattered in the large volume outside of the nucleus. Most of the alpha particles passed through the large electron space. Only if an alphas particle came close enough to the incredibly thick nucleus would it be swerved from its original path. The alpha particles that hit the nucleus of a gold atom head-on were swerved backward.

![Diagram of the Gold Foil Experiment](image)

**FIGURE 2.8 – Gold Foil Experiment (Experimental Set-Up, Hypothesis, and Actual Result)**
Question 4: Why did the alpha particles s\_n\_r\_v\_e? Please explain.

Question 5: Why did Rutherford choose gold for his experiment? Could he have used any other material? Which properties should this material have?

Question 6: What kind of evidence did Rutherford’s gold foil experiment provide?

Rutherford’s experiment was the basis for the nuclear model of the atom (Figure 2.9), developed in 1907. The model suggested that the positive charge was in the nucleus, which contains the protons and most of the mass of the atom. The electrons exist outside the nucleus in what is often called an “electron cloud.”

**FIGURE 2.9 – The nuclear model of the atom**

In the nuclear model of the atom, protons (blue spheres) and neutrons (red spheres) are located in a tiny nucleus at the center of the atom. The space outside the nucleus is occupied by the electrons.
The diameter of the nucleus is about $10^{-14}$ m, and the diameter of the atom is about $10^{-10}$ m. These relative sizes are comparable to a flea in the center of a domed stadium. The mass of a proton, $1.6726 \times 10^{-24}$ g, is nearly the same as the mass of a hydrogen atom. The proton is equal in charge (but opposite in sign) to the electron, but 1836 times greater in mass.

The Neutron

These experiments helped Rutherford and other scientists understand the structure of the atom better. They could not however account for the entire mass of the atom.

Most atoms other than the hydrogen atom have masses that are at least twice the sum of the masses of the protons and electrons they contain. For example, calcium is an alkaline earth metal that contains 20 protons and 20 electrons. Together, their mass is $3.3471 \times 10^{-23}$ g. Yet a calcium atom has a mass that is near twice this value ($6.6359 \times 10^{-23}$ g).

**Question 7:** Check the Periodic Table in your textbook (inside front cover). If calcium (Ca) has 20 protons, which element has 16 protons?

**Question 8:** For the atom presented in the following diagram,

A. Determine the number of protons and neutrons
B. Identify the atomic number and the element
C. Determine the mass number for this isotope.
To account for the extra mass, Rutherford hypothesized the neutron. A neutron is a subatomic particle, which has almost the same mass as a proton, however it is uncharged, and is located in the nucleus of the atom.

Because of the electrical neutrality of the neutron, it was difficult to find. It was not until 1932 that James Chadwick, a scientist working with Rutherford, did experiments that detected the neutron. The mass of the neutron was determined to be $1.6749 \times 10^{-24}$ g, slightly greater than the mass of a proton. The properties of the electron, proton, and neutron are summarized in Table 2.1. All of the subatomic particles in the table are important to the nuclear model of the atom as we understand it today (Figure 2.9).

**Question 9:** Which element is described in figure 2.9?

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Actual Charge</th>
<th>Relative Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$9.1094\times10^{-28}$ g</td>
<td>$-1.6022\times10^{-19}$ Coulomb</td>
<td>-1</td>
</tr>
<tr>
<td>Proton</td>
<td>$1.6726\times10^{-24}$ g</td>
<td>$+1.6022\times10^{-19}$ Coulomb</td>
<td>+1</td>
</tr>
<tr>
<td>Neutron</td>
<td>$1.6726\times10^{-24}$ g</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A coulomb is a unit of electric charge, it's equal to the amount of electricity carried in one second by a current of one ampere.

**Question 10:** Looking at the data provided in table 2.1, how much heavier are protons and neutrons compared to electrons.

**Question 11:** Dalton stated that “all atoms of a given element are identical, both in mass and in chemical properties”. Can you think of any exceptions to this rule?

**Question 12 (typical exam questions):**

- Which subatomic particles make up the mass of an atom?
  - A. protons and electrons.
  - B. protons and neutrons.
  - C. neutrons and electrons.
  - D. only electrons.

**Question 13:** Describe what you have learned about the proton in this reading assignment.
2. Modern Model of the Atom

What to expect in this chapter:

You just learned that electrons are situated outside the nucleus, and protons, and neutrons are located inside the nucleus.

The phrase “outside the nucleus” is not very specific and therefore scientists tried to determine and describe models to better describe the location of the electrons. One of the models is the Bohr model, named after the Danish physicist Niels Bohr (1885-1962) who received the Nobel Prize in Physics in 1922 for his contributions to correctly describe the structure of the atom.

Bohr’s model, also called the orbital model, described different energy levels in a hydrogen atom well but is more complicated when applied to atoms with more than one electron. The chapter describes a path where electrons in the atom can be found. Even though newer models more accurately describe where electrons can be found, the Bohr model is still very much in use.

In this chapter, you will be introduced to the most recent “modern model of the atom,” It identifies not only 3-dimensional spaces in which electrons can be found, but it also associates distinct energy levels with these locations.

The Modern Model of the Atom

By the 1920s, scientists started to work on a new model of the atom that could account for the line spectra of other elements. (Line spectra are colored lines of light emitted elements. Each element has a distinct line spectrum that can be used to identify the element. See also Chapter 7 pg. 260). In 1913, Bohr, a Danish physicist, demonstrated that electrons could be found only in certain energy levels around the nucleus. They have to gain energy to move to a higher level and lose energy to move to a lower level. In Bohr’s model, electrons also orbited the nucleus like planets orbit a star, but this model only worked for hydrogen. Erwin Schrödinger, from Austria, developed a mathematical model that seemed to work for all atoms. Schrödinger’s model of the atom was similar to Bohr’s model in that the energies of electrons were quantized, meaning they could have only certain energies.

However, the new model describes electrons as being found in regions around the nucleus, which are called orbitals, not orbits (as in Bohr’s model). An orbital is a three-dimensional region in space where the electron is likely to be found, not a circular pathway (shown in Figure 7.12). The mathematical model was based on the probability of finding an electron in a region outside the nucleus. From it, chemists created a probability map to show where an electron is likely to be found (Figure 7.11)
Figure 7.11A is the probability map for a hydrogen electron in its lowest-energy state. The darker regions represent areas where the electron is most likely to be found. Because the likelihood of finding an electron in the outer regions of the probability map is small, it is customary to show an enclosed region in space where the electron is likely to be found 95% of the time (Figure 7.11B). We will use orbital representations without dots for the rest of this chapter.

In the modern model of the atom, electrons have different amounts of energy and are found in different energy levels; however, orbitals of similar size are considered to be in the same principal energy level. For example, the first energy level can accommodate up to two electrons. The more electrons an atom has, the more energy levels are filled. The first six principal energy levels for the electron in a hydrogen atom are shown in Figure 7.12 below.

The allowed energies for the electron are the same as the energies of the Bohr orbits.

Question 1: Why are there many possible energy levels in a hydrogen atom? Hydrogen just has one electron!
Each energy level accommodates one or more orbitals, which come in different shapes and sizes. There are four types of occupied orbitals in atoms in their lowest energy states, which we label with the letters $s$, $p$, $d$, and $f$. The general shapes of these orbitals are shown in Figure 7.13. These orbitals are distributed into the principal energy levels ($n=1,2,3,\ldots$).

![Orbitals](image)

**Figure 7.13:** The $s$, $p$, $d$, and $f$ orbitals differ in shapes and number of lobes.

The grey planes in Figure 7.13 depict the 3 axes in a Cartesian coordinate system.

Transferring the images in Figure 7.13 on an actual atom, what is the probability to find electrons in the origin where the three axes intersect?

Orbitals at lower-energy levels are smaller, and those at the higher-energy levels are larger and extend farther from the nucleus. Each energy level is made up of a certain number of orbitals. Each orbital can accommodate two electrons.

**Example:**

The first principal energy level ($n = 1$) consists of a single $s$ orbital. We call this $s$ orbital a 1$s$ orbital because it is in the $n = 1$ principal energy level, and it has the $s$ orbital shape.
The second principal energy level \((n = 2)\) consists of \(s\) and \(p\) orbitals called the \(2s\) and \(2p\) orbitals. The \(2s\) orbital is like the \(1s\) orbital, but it is larger (Figure 7.14).

![Image of orbitals]

1s is the closest to the nucleus, reason why it's the smallest, followed by 2s, then 3s.

_Figure 7.14:_ The size of the orbitals increases as the principal energy level increases.

A single \(p\) orbital, as depicted in Figure 7.13, has a figure-eight or dumbbell shape. In their respective energy levels, \(p\) orbitals always come in sets of three (Figure 7.15). The three \(2p\) orbitals lie with their centers overlapping at the nucleus and perpendicular to one another. We can think of each two-lobed orbital as directed along with one of the \(x\), \(y\), or \(z\) axes that are each perpendicular to one another. We label these orbitals accordingly as \(px\), \(py\), and \(pz\) orbitals.

![Image of p orbitals]

_Figure 7.15:_ (A) Three \(p\) orbitals compose a \(p\) sublevel. They have the same shape, but they point in different directions in space. They lie perpendicular to one another, so we can imagine them lying along perpendicular lines that we call \(x\), \(y\), and \(z\) axes. The \(pz\) orbital lies along the \(z\)-axis, the \(px\) orbital lies along the \(x\)-axis, and the \(py\) orbital lies along the \(y\)-axis. (B) The three \(p\) orbitals coexist with their centers at the nucleus.

Because there are two types of orbitals in the second principal energy level, we say that there are two sublevels: the \(2s\) sublevel and the \(2p\) sublevel. A sublevel consists of just one type of orbital at a specific principal energy level. The \(2s\) sublevel consists of a single \(2s\) orbital, and the \(2p\) sublevel consists of three \(2p\) orbitals.

At the third principal energy level \((n = 3)\), three sublevels are available: the \(3s\), \(3p\), and \(3d\) sublevels. The \(3s\) sublevel consists of a single \(3s\) orbital, and the \(3p\) sublevel consists of a set of three \(3p\) orbitals. The \(3d\) sublevel consists of five \(d\) orbitals (Figure 7.16).
The fourth principal energy level (n = 4) consists of four sublevels: the 4s, 4p, 4d, and 4f sublevels. The 4f sublevel consists of seven 4f orbitals (image of f orbitals not given).

**Figure 7.16:** There are five d orbitals in a d sublevel. Most have four lobes that lie along a specific plane in space. One looks like a p orbital with a donut shape around its center.

In the modern model of the hydrogen atom, the energy levels have the same energies as the orbits described in the Bohr model. The hydrogen line spectrum is produced by the movement of electrons in an atom from orbitals in higher principal energy levels to orbitals in lower principal energy levels (transition from an “excited state” to a lower energy state, such as the “ground state,” pg. 261 in the textbook).

The hydrogen atom line spectrum is simple to explain because the orbitals in the same principal energy level have the same energy. This is not the case for atoms with more than one electron.

**Orbital Diagrams for Multi-Electron Atoms (“multi” here means more than one!)**

An orbital diagram is a convenient way to show the distribution of sublevels and orbitals in an atom. The one shown in *Figure 7.17* (next page) is specifically for the hydrogen atom. The boxes represent orbitals, and the groups of boxes represent sublevels.
Figure 7.17: The orbital diagram for the hydrogen atom shows the sublevels and orbitals that can exist at each principal energy level. Each box represents an orbital, and groups of boxes represent sublevels. For the hydrogen atom only, the sublevels within a principal energy level all have the same energy. Here we show only the first three principal energy levels for hydrogen.

The orbital diagram for a multi-electron atom looks different. It shows the same energy levels and sublevels, but the energies of some sublevels differ.

Figure 7.18: The orbital diagram for a multi-electron atom shows the same sublevels and orbitals as for the hydrogen atom. However, in atoms that contain more than one electron, the sublevels within a principal energy level have different energies. Note that the energy of the 3d sublevel is higher than the energy of the 4s sublevel.

Sublevels in the same principal energy level have the same energy only in atoms with one electron (hydrogen). In atoms with more than one electron, the interaction among electrons causes the sublevels within the same principal energy level to have different energies. The result is an orbital diagram like that shown in Figure 7.18. Notice that, within a given principal energy level, the p orbitals are higher in energy than the s orbitals, and the d orbitals are higher in energy than the p orbitals. The 3d orbitals are so high that they are slightly higher in energy than the 4s orbitals.

Question 3: What kind of interaction between electrons could it be that causes the sublevels within the same principal energy level to have different energies?

Now we have to look at how electrons are being arranged into these principal energy levels, sublevels, and orbitals.

Consider the orbital diagram that represents how electrons are arranged in a carbon atom in its ground state:

Carbon has an atomic number of 6 (6 electrons). The 1s orbital will get 2 electrons, the 2s will get 2 electrons and the remaining 2 electrons will go into the first 2p orbitals.
The boxes represent orbitals, and the arrows represent electrons.

Question 4: Please summarize in your own words, why the location of the electrons in an atom is important?

When we create an orbital diagram for a particular atom, we fill in electrons starting with a bare nucleus and add one electron at a time. (This is not how atoms are created in nature.) You may have noticed that the lowest-energy orbitals have two electrons in them, and some of the higher-energy orbitals have only one or none.

This is a result of the Aufbau principle (from the German aufbauen, "to build up"), which states that electrons fill orbitals starting with the lowest-energy orbitals.

For the hydrogen atom in its ground state, its electron is in the 1s orbital.

You may have also noted that no more than two electrons occupy each orbital.

This is the basis for the Pauli Exclusion Principle, which states that a maximum of two electrons can occupy each orbital, and they must have opposite spins.

Electrons in the same orbital are represented by arrows that point in opposite directions.

An electron can spin in one of two directions. We represent these spins with an up arrow and a down arrow.

For example, helium's ground-state orbital diagram consists of two electrons in the 1s orbital:
For lithium, with three electrons, two electrons go into the 1s orbital. The first principal energy level is filled. We can now proceed to the second principal energy level. Because the 2s sublevel is lower in energy than the 2p sublevel, the third electron goes into the 2s orbital.

Lithium has an atomic number of 3 (3 electrons). 2 electrons will be placed in the 1s orbital and the remaining 1 will be placed in the 2s orbital.

Boron, with five electrons, has an orbital diagram with two electrons in the 1s orbital, two electrons in the 2s orbital, and one electron in one of the 2p orbitals. It makes no difference which p orbital we place the electron in because they are equal in energy. The orbital diagram for boron is:

Boron has an atomic number of 5 (5 electrons). 2 electrons will be placed in the 1s orbital, 2 electrons in the 2s orbital and the remaining 1 will be placed in the first 2p orbital.

What happens when there is more than one electron in a sublevel that contains more than one orbital, such as a p sublevel? Are electrons paired up right away, or are they kept in separate orbitals until pairing is required? Did you notice in carbon’s orbital diagram that the electrons in the p sublevel are unpaired in separate p orbitals?

This brings us to the third rule:

Hund’s rule: Electrons are distributed into orbitals of identical energy (same sublevel) in such a way as to give the maximum number of unpaired electrons.

Hund’s rule is a consequence of the fact that negatively charged electrons repel each other. It follows that electrons should be found in separate orbitals if no energy is required to get there.
It is common to show a simpler orbital diagram, where all the orbitals are represented on one line, with sublevels labeled. We must remember that the energy of the sublevels increases from left to right. For example, we can represent the orbital diagram for carbon as

Following Hund’s rule, the arrows (electrons) in the 1s orbital should face opposite directions, same goes for the 2s orbital. The p sublevel has 3 orbitals, but we only have 2 electrons left. The remaining 2 electrons should be distributed evenly.

Question 5: In your own words can you summarize the meaning of Hund’s rule.

Question 6: (possible exam question)
Which element in its ground state has exactly one unpaired electron?

   (A) Al   (B) Mg   (C) P   (D) Si

Question 7: (possible exam question)
Which picture shows a p orbital?

A.  
B.  
C.  
D.  

Question 8: Please briefly describe the differences and similarities between an energy level diagram, a Bohr model, and an orbital diagram (as shown in the text above). You most likely will encounter some of these in exams and quizzes.
3. Molecular Shapes

3-Dimensional Shapes of Molecules

What to expect in this chapter...

This chapter discusses the relationship between the 3-dimensional shape of a molecule and its properties. While the chemical make-up of a molecule is given by the chemical formula, only few predictions about properties can be made based only on this information.

However, the 3-dimensional shape of a molecule and the position of its atoms within the molecule determine on how molecules not only interact with other molecules of the same kind, but also with other substances.

This chapter will guide you through a couple of steps that will allow you to determine molecular shape. You will see that the arrangement of atoms and the location of electrons within the molecule play an important role.

Let's look at an interesting real-world example first – the senses of smell and taste!

The 2004 Nobel Prize in Physiology or Medicine was given to Richard Axel of Columbia University and Linda Buck of the Fred Hutchinson Cancer Center in Seattle for their studies of the sense of smell.

Although senses have a chemical basis, determining how they operate has not been simple. It has become clear that there are receptor sites in the nose and tongue where molecules can fit. The receptors are built from proteins that make up the membranes of cells. The proteins are interlinked in various ways, creating pockets in the structure of the cell membrane. The pockets act as receptors from other molecules if two conditions met.

First, the molecules must be the right size and shape to fit in them. Second, the molecules must interact in a certain way with atoms in the membrane protein, causing a change that can trigger a nerve impulse.

The importance of molecular shape – an example.

Recognizable tastes fall into several categories. One is sweet, and it is highly attractive to humans for good reason. Aspartame, which is an artificial sweetener seems different to sucrose, which is a table sugar, but gives a sweet sensation in the mouth. Lactose is a sweet substance found in mothers' milk. The sweet taste encourages babies to consume more. Other sweet substances include glucose and sucrose (two different forms of sugar), which occur naturally in plants. While it has been difficult to relate the structures of molecules to their tastes, a common feature of sweet molecules is the size of a particular portion of the molecule. This part of a sweet molecule presumably fits into the receptor site. Sweet molecules commonly have a —H (or —OH) separated from a —O— atom by about 300 pm, as illustrated in Figure 8.23.
Figure 8.21 Glucose is sweet because it contains —H and —OH groups that fit into a taste receptor site on the tongue.

Although humans can distinguish thousands of odors, one theory proposes that there are only seven primary odors, which are musky, putrid, pungent, camphoraceous, ethereal, floral and pepperminty, each associated with a different type of receptor in the nose. When a gaseous molecule enters the nose and interacts with a particular receptor, a nerve impulse is generated and sent to the brain. A molecule that can fit into more than one type of receptor triggers multiple signals, generating a composite odor.

How does science explain molecular shape?

The Valence-Shell Electron-Pair Repulsion Theory

The geometry of individual molecules from the number of electrons pairs encircling their central atoms, is predicted by the Valence shell electron pair repulsion theory. As the senses of taste and smell demonstrate, the observable properties of substances derive from the three-dimensional shapes of their molecules. Shape, in turn, is a function of the arrangement of atoms in a molecule. The relative locations of electron pairs around a central atom play a large role in determining a molecule's three-dimensional shape. Negatively charged electrons repel one another, so electron pairs in different orbitals stay as far apart as possible.
Definition: The tendency of electron pairs to adjust the orientation of their orbitals to maximize the distance between them is the basis of the valence-shell electron-pair repulsion (VSEPR) theory. (Valence shell is another name for valence level.)

Question 1: Based on your knowledge about Lewis structured, what is the center atom in sulfur dioxide, SO₂, and what number and type (bonding pairs or lone pairs) of electron pairs are located around it? Explain!

A Lewis formula does not show the shape of a molecule, but it does help us to determine molecular shape.

A Lewis structure is a depiction of covalent molecules (or polyatomic ions), where all the valence electrons are shared about the bond atoms, as either shared electron pairs, which are bond pair or unshared electron pairs, which are lone pairs.

Since it is hard to see how atoms are arranged in a two-dimensional line drawing, chemists often use a system of solid lines, dashed lines, and wedges to depict the three-dimensional structure of molecules. Solid lines indicate bonds in the plane of the paper. Dashed lines are bonds that point back from the plane of the paper. Wedges depict bonds that come forward from the plane of the paper (this way of drawing bonds becomes especially important in Organic Chemistry!)

![Diagram of SO₂ molecule]

To predict the geometric shape of a molecule or ion using VSEPR theory, we first need to know how electrons are arranged in a molecule. In particular we need to know how many unshared electron pairs and atoms surround the central atom.

We can get this information by examining the Lewis formula. The Lewis formula is a diagram that demonstrates the bonding between atoms of a molecule and the lone pairs of electrons that are present in the molecule. For example, CH₄ has four atoms and no unshared electron pairs surrounding the carbon atom. In the CO₂ molecule, carbon has only two atoms bonded to it, as
shown in the Lewis formula, and it has no unshared pairs of electrons. The NH₃ molecule has three bonded atoms and one unshared electron pair (see figures below).

The bonded atoms and unshared electron pairs are arranged around the central atom as far apart as possible. The result is a shape characterized by the bond angle between the central atom and the atoms bonded to it.

What shapes and angles would you predict for molecules having two, three, and four pairs of unshared electrons or atoms around a central atom? How would you make these predictions based on repulsions of electron pairs?

Example: To see what angles to predict, let's examine the shape commonly found in hydrocarbons and many other molecules that arises from four electron pairs or atoms. The Lewis formulas look flat, as in CH₄:

\[
\begin{align*}
\text{H} & \\
\text{H} & \\
\text{C} & \\
\text{H} \\
\text{H} \\
\end{align*}
\]

This structure looks as if it would have bond angles of 90°:

\[
\begin{align*}
\text{H} & \quad (\text{incorrect bond angle}) \\
\text{H} & \\
\text{C} & \\
\text{H} \\
\text{H} \\
\end{align*}
\]

However, this does not accurately represent the three-dimensional structure of the CH₄ molecule, which is not flat. If we move atoms to correct the flatness, we change the bond angles. The larger the angles, the farther away from one another the atoms are. If we move only the carbon atom, the angles actually get smaller. The only way to make the angles larger is to move two hydrogen atoms up and two down:

Before

After
How large can the angles get if we move two up and two down? When the angles all become equal, they have values of 109.5°, giving a tetrahedral shape. This structure is usually shown in a rotated form:

Table 8.5 shows the geometries that achieve the maximum distance between combinations of two, three, or four atoms, or unshared electron pairs. The geometries shown in the table are adopted by any set of objects that are attached at a common point and that stay as far apart as possible. For example, the balloons shown in Figure 8.25 adopt the same geometries as atoms (or unshared pairs of electrons) around a central atom. These structures, called parent structures, partly predict a molecule’s shape.

Table 8.5

<table>
<thead>
<tr>
<th>Number of Atoms or Electron Pairs</th>
<th>Parent Structure</th>
<th>Geometric Arrangement of Atoms or Electron Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Trigonal planar</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Tetrahedral</td>
<td></td>
</tr>
</tbody>
</table>

Macroscopically this looks like this (with a little help of balloons):

Figure 8.25: Macroscopic objects that are fastened to a common center adopt the same structures as molecules because, like electron pairs, they stay as far apart as possible.

The shape we assign a molecule includes only the groups of bonding electrons within the parent structure, and not the unshared pairs of electrons; the shape is a description of the locations of the atoms in the molecule.

Consider, as an example, the water molecule, has two hydrogen atoms covalently bonded to a single oxygen atom. It has two atoms and two unshared pairs of electrons around the central atom. The four electron pairs in H₂O arrange themselves tetrahedrally around the oxygen atom.
But because we consider only the two bonding pairs when we describe the molecular shape, we do not say that the water molecule is tetrahedral. Rather, we describe it as bent.

Consider the Lewis formulas for several molecules and ions (Figure 8.16) having the same general composition AX₃, A being the central atom, X being the terminal atoms.

![Figure 8.16](image)

\[ \text{Trigonal planar} \quad \text{Trigonal pyramidal} \]

Figure 8.16 Some molecules and ions with the formula AX₃ have a trigonal planar shape, while others have a trigonal pyramidal shape.

All possible shapes for molecules that have two to four electron pairs are summarized in Table 8.6. The bond angles for these structures are approximately those of the parent structures.
Table 8.6 Arrangement of Electron Pairs and Molecular Shapes (textbook pg. 322)

Question 2: Consider the carbonate ion - do you expect this molecule to have unshared electron pairs on the center atom? What shape will it be?

Questions 3: Please check table 8.6: Which molecular shapes result from unshared electron pairs on the center atom?

Notice in Table 8.6 that CO₂ is linear, but SO₂— with the same number of atoms—is bent.

We can understand this difference using VSEPR theory. Examine the Lewis formulas of these molecules:

What is different about them? The carbon in CO₂ has two bonded atoms and no unshared electron pairs, so it has a linear structure and the oxygen atoms on each end are symmetrical. In contrast, sulfur in SO₂ has two bonded atoms and one unshared electron pair. The unshared pair causes the molecule to be bent. Models of these molecules are shown below.

\[
\text{CO}_2: \quad :\ddot{O} = \dddot{C} = \dddot{O} \\
\text{SO}_2: \quad :\dddot{O} = \dddot{S} - \dddot{O}
\]
Figure 8.28 Carbon dioxide is linear, whereas sulfur dioxide is bent, because there is an unshared electron pair on the sulfur atom.

**Question 4:** Try to explain in more detail how non-bonding electron pairs influence molecular shape (use terms as “attraction” or “repulsion”).

Now, let's take a look at the what we need to do to predict the shape of a molecule according to VSEPR theory; you can use the following four steps.

The bond angles in real molecules often differ a little from the values predicted by the VSEPR theory, they are formed between three atoms across at least two bonds. Differences occur because unshared pairs of electrons occupy more space than bonded pairs. The bonded pairs are forced together somewhat, resulting in slightly smaller bond angles than predicted. For example, ammonia, which has one unshared pair of electrons, has a bond angle of 107° rather than the predicted 109.5°. Water has two unshared pairs of electrons and a bond angle of about 105°. A similar effect is caused by a double bond, which occupies more space than a single bond.

**Steps for Predicting the Shape of a Molecule**

1. Draw a Lewis formula and be sure to draw all the valence electrons surrounding the molecule’s central atom.
2. Count the number of atoms bonded to the central atom and count unshared electron pairs on the central atom.
3. Add the numbers of atoms and the number of unshared electron pairs around the central atom. The total indicates the parent structure.
4. The molecular shape is derived from the parent structure by considering only the positions in the structure occupied by bonded atoms.

**Question 5:** Is it really important to start by drawing the Lewis structure when predicting the molecular shape? What piece of information that a Lewis structure can provide is so crucial?
What do I do if a molecule has more than one central atom?

For molecules with more than one central atom, we can repeat the procedure for each central atom, a process that allows us to predict the structures of molecules as large and complex as proteins. Let's consider one amino acid, glycine, which might be found in a protein. It has a sweet taste and is found in gelatin and other animal products, its formula is \( \text{H}_2\text{NCH}_2\text{CO}_2\text{H} \). How do we predict its structure?

![Glycine molecule]

We start, as before, by writing a Lewis formula for the molecule:

Please take a piece of paper and try yourself, you can see the molecular structure in the figure below. Just add the remaining valence electrons. You can also follow along the description written underneath the figure to complete the structure.

The molecule contains four atoms acting as central atoms: the nitrogen atom (blue), both carbon atoms (black), and one of the oxygen atoms (red).

![Glycine Lewis structure]

The nitrogen atom is in group five, so it has five valence electrons, which is why it has three atoms bonded to it and one unshared electron pair. Thus, the structure around this nitrogen atom is based on a tetrahedral parent structure with one unshared pair of electrons. The shape around the nitrogen atom is trigonal pyramidal, with bond angles of about 109.5°.

The first carbon atom (left) is bonded to four other atoms (N, two H, and C) and has no unshared electron pairs, so the shape around it is tetrahedral, with bond angles of about 109.5°.
The second carbon atom (right) is bonded to three other atoms (C and two O) and has no unshared electron pairs, so the shape around it is trigonal planar, with bond angles of around 120°.

Finally, one of the oxygen atoms has two atoms (C and H) bonded to it and has two unshared electron pairs. The structure around it is based on a tetrahedral parent structure, but with two unshared pairs, the shape is bent. The bond angles will be around 109.5°. Verify each of these predictions by examining the molecular model of glycine in Figure 8.29 below.

![Figure 8.29](image)

*Figure 8.29.* VSEPR Theory predicts the structure of glycine.

**Question 6:** In this chapter, the molecular shape has been related to the observable property of odor/smell. Can you think of other observable molecular properties that are directly related to molecular geometry?

**Question 7:** (possible exam question): Which molecule is linear?

- A. SO₂
- B. NH₃
- C. O₂
- D. CS₂

10
Question 8: (possible exam question): What is the bond angle in Freon, CF₃Cl₂, (shown in figure)?

A. 45°  B. 90°  C. 109.5°  D. 120°
4. Covalent Bonding:

Chemical Bonding: Covalent Bonding

The formation and properties of ionic compounds have been discussed in the previous reading assignment; this chapter now looks more closely into covalent bonding which has been described by Gilbert N. Lewis in 1916 as “sharing of electron pairs”. Gilbert Lewis also introduced dot structures (Lewis Dot Structures) which are still used today to represent valence electrons and covalent bonding.

What to expect in this chapter:

In this chapter, you will learn how electrons are shared in pairs, forming covalent compounds, called molecules. The chapter also discusses the nature of the attractive forces that hold atoms together in covalent bonds (single, double, or triple bonds) and introduces intermolecular forces, which are forces that are present between two or more molecules. These forces determine a variety of molecular properties, such as the melting, and boiling point.

When chemists discuss molecular shapes, and Lewis structures, they refer to covalent compounds, which form through the attractions of two or more nonmetal atoms, leading to the formation of a molecule.

From the text (Chapter 8.2): When two nonmetals form a compound, the bonds within the molecule are covalent.

Review: The ionic bond between sodium and chlorine results in the ionic compound, sodium chloride. The image below depicts both a sodium and chlorine ion, in the process of the electron transfers.

\[
\text{Na}: + \text{Cl} \quad \longrightarrow \quad [\text{Na}^+] + [\text{Cl}^-]
\]

A sodium atom has 1 valence electron, Chlorine has 7 valence electrons. When the atoms collide, the chlorine atom will remove the electron from the sodium. The sodium atom loses its only electron and becomes a positively charged sodium ion. This extra electron completes the stable octet for chlorine. Which becomes a negatively charged chloride ion.

In contrast, no electrons are being transferred in a covalent molecule. Lewis structure of covalent compounds show shared electrons (bonds) as can be seen in the image showing the H₂ molecule below, and also non-bonding, free electrons as shown in the HCl molecule.
Question 1: What type of electrons (valence or core) do participate in chemical bonding and are therefore shown in Lewis structures?

From the text (Chapter 8.3): Covalent bonds involve localized attractive forces between atoms that are held together tightly in molecules. A covalent bond is strong because each shared electron interacts simultaneously with two nuclei, electrons and nuclei attract one another because of their opposite charges. At the same time, electrons repel one another, and nuclei repel each other because of their like charges. When the electrons are located primarily between the two nuclei, the attractions are maximized and the repulsions are minimized, resulting in a covalent bond, as shown in Figure 8.12.

Covalent bonding happens when either atom has enough strength to completely remove the other atom's electron. The atoms share electrons and they both achieve an outer energy level.

For example, a hydrogen atom with 1 valence electrons needs one more electron to complete the first energy level. An oxygen atom has 6 valence electrons and needs two more to complete the second energy level. As the Hand O collide, covalent bonding is achieved by sharing of electrons. By sharing the electrons, the hydrogen completes the noble gas configuration of helium.

**Figure 8.12:** A covalent bond results when attractive forces between opposite charges are greater than repulsive forces between like charges.

The stability and bond strength of covalent bonds are due to the attractive forces acting on the individual atoms involved, the function of the strength of the covalent bonds holding the atoms together is the stability of the molecule. Let’s consider two nonmetal atoms, A and B. When they are close to one another, there is an attraction between atom A’s electron (a negative charge) and atom B’s nucleus (a positive charge), as well as between atom A’s electron and atom A’s nucleus. At the same time though, atom A’s electron is repelled by atom B’s electron, and atom B’s nucleus is repelled by atom A’s nucleus. When the attractive forces between nuclei and
electrons are stronger than the repulsive forces between electron-electron and nucleus-nucleus interactions, a covalent bond can form!

The concept of electrostatic potential energy, which is the amount of work needed to move a unit of positive charge from a reference point to a specific point inside the field without generating an precipitation, can be applied to explain why two neutral atoms (compared to ions of opposite charge) may come together to form a stable molecule. In the case of two hydrogen atoms (figure below), the potential energy in respect to each other is zero when they are sufficiently far apart so they have no interaction.

As they approach each other, the proton in the nucleus of one H atom in attracted to the electron of the other, and vice versa. This mutual attraction produces negative potential energy. As the distance between the atoms decreases, the potential energy decreases as well, eventually reaching a minimum when the two nuclei are 74 pm apart (bond length in H₂ molecule).

At 74 pm bond length, the atoms experience maximum attraction. If the atoms came any closer together, the repulsion between their two positive nuclei more than offsets the mutual attraction, the potential energy rises and the atoms will move further apart.

**Question 2:** Would you expect the bond length in Cl₂ to be longer or shorter than that of H₂? Explain your reasoning!

**From the text (Chapter 8.3):** Although the attractions (bonds) between atoms within the molecule are strong, the molecules are not bonded to other molecules, but attractions between molecules or compounds, or intermolecular forces, can be relatively weak. Consequently, covalent compounds have low melting and boiling points, and they often exist as gases or liquids. As solids, they are brittle or soft, because their molecules are not held together strongly. For example, in solid carbon dioxide (dry ice), the individual molecules remain intact and are identifiable in the molecular model (Figure 8.13).

Attractions between molecules are called intermolecular forces (IMF), they are forces that hold atoms together within a molecule. You will need to understand these forces to completely understand the properties of covalent compounds.

Nevertheless, here are some important characteristics of covalent bonds. Please compare them with what you have learned about ionic bonds.
Substances with covalent bonds often exist as gases and liquids
- Covalent bonds have relatively low melting and boiling points
- Covalent solids are brittle or soft

**Figure 1.13**: In solid carbon dioxide, CO₂, molecules pack together in a regular array, but they retain their identity and can be removed from the crystal easily.

**Modeling bonding in molecular compounds**

We have already discussed Lewis structures in ionic bonding and have very briefly looked at them in covalent bonding. We will now take a more in-depth look at covalent Lewis structures as well as other models for this type of bonding. It is important to remember that Lewis structures only MODEL bonding and is method to keep track of the valence electrons of the molecule. A Lewis structure does not depict the true 3-dimensional shape of a molecule.

When writing Lewis structures, which are diagrams that depict the bonding between atoms of a molecule and the lone pairs of electrons that may exist in the molecule, it is practical to follow certain rules, one of which is the Octet Rule (review)

**Text Definition**: the tendency of an atom to achieve an electron configuration having eight valence electrons

Note that there are exceptions to this definition, especially going further down the periods of the periodic table.

**Question 3**: Why do you think the models employ the idea of elements preferring the electron octet? Do you see parallels to the Bohr model or the orbital model (electron configuration)?

A closer look at single, double, and triple bonds

The number of bonds an element can form depends on its number of filled valences. In the described Lewis model, elements achieve a configuration with an octet of eight valence electrons by sharing electrons. In the oxygen molecule (O₂) for example, the number of filled valences for each atom is 6. This means there are still 2 valences to fill. When the atoms come close enough to attract, overlap happens, and electrons can be shared. Now each oxygen atom will share 2 of its electrons with the other atom (in total, 4 electrons are shared between them).
Question 4: Review the electron configuration of the elements carbon through fluorine. How many bonds do you think each atom will make? Do your predictions result in an electron configuration containing an octet of valence electrons?

Single Covalent Bonds

A covalent bond that consists of a pair (2 electrons) of electrons shared by two atoms is a single bond, each atom has a half-filled orbital in the valence level, and the orbitals overlap to allow the electron pair to be a part of both atoms. For example, in the formation of the diatomic hydrogen molecule, each hydrogen atom has an electron in the 1s orbital. When the atoms come together, as shown in Figure 8.15, the orbitals overlap, and the atoms share an electron pair:

\[
\text{H}^- + \text{H}^+ \rightarrow \text{H}_2^+
\]

The representation above of a hydrogen molecule is a Lewis formula (or electron dot formula), in which the atoms are shown separately and the valence electrons are represented by dots. Lewis formulas are sometimes simplified by showing each bond not as a pair of dots, but as a line. For \( \text{H}_2 \), the Lewis formula could be either \( \text{H}^-\text{H}^+ \) or \( \text{H}-\text{H} \).

The important thing to remember here is that covalent bonds SHARE electrons, no atoms in the molecule “own” the valence electrons that are shared because they are partially their own, and partially the other atom's, this is what is meant by a “half-filled orbital”. In the case of a hydrogen atom, 2 electrons are needed to fill its 1s orbital. When another hydrogen atom comes in close enough proximity, the two are able to share a space where they can keep the electrons, they both need to share, because these electrons are shared, they appear as 2 dots between the 2 hydrogen atoms.

\textbf{Figure 8.15:} Hydrogen atoms do not combine unless they get close enough together.
Hydrogen molecules form when orbitals overlap, creating a region in space where both of their electrons can be found.

Covalent bonding cannot happen unless the atoms are close enough for attractions to take effect! In order to gain stability, atoms will covalently bond with other atoms, which is obtained by forming a filled electron shell.

From the text (Ch 8.3): The halogens which are found in group VIIA of the periodic table, each with seven valence electrons, also share one pair of electrons in diatomic molecules. Lewis formulas that show the distribution of electrons in the halogen molecules are given in Figure 8.16. Each atom in these structures has an octet, provided that the shared electrons are counted for each atom, each of the covalent bonds in these molecules is a single bond, since it arises from the sharing of a single electron pair.

![Lewis structures of halogens showing single bonds.]

**FIGURE 8.16:** All the halogen elements exist as diatomic molecules, each atom has an octet of electrons, as shown by the circles, because they share one electron pair between the bonded atoms. The shared electron pair is a single covalent bond, shown here in the overlapping circles.

One electron pair (2 electrons shared within the molecule) = Single Bond

Double and Triple Covalent Bonds

Question 5: Which diatomic compounds (not elements!) form multiple bonds (double or triple) in order to achieve the electron octet?

From the text (Chapter 8.3): The sharing of two pairs of electrons is a double bond. The sharing of three pairs of electrons is a triple bond. In Lewis formulas, two pairs of dots or two parallel lines represent a double bond, three pairs of dots or three parallel lines represent a triple bond.
<table>
<thead>
<tr>
<th>Classification</th>
<th>Number of shared electrons</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Bond</td>
<td>2</td>
<td>:\-----:</td>
</tr>
<tr>
<td>Double Bond</td>
<td>4</td>
<td>:\O==O:\</td>
</tr>
<tr>
<td>Triple Bond</td>
<td>6</td>
<td>:\N==N:\</td>
</tr>
</tbody>
</table>
5. Ionic Bonding

What to expect in this chapter:

This chapter is the first of two chapters about chemical bonding. It discusses the major differences between ionic and covalent bonding and what these differences are based on. You will also learn how an element's electron configuration can help explain how ionic compounds are being formed and how this process can be expressed in chemical equations.

Lastly, you will look into the particle-level structure and properties of different ionic compounds.

Ionic and covalent bonding – what is the difference?

Ionic bonding primarily differs from covalent bonding in 2 ways:

- Ionic bonding happens between a metal and a nonmetal (or polyatomic ions in the place of the cation or anion). Covalent bonding is between two nonmetals.
- In ionic bonding, electrons are being transferred. In covalent bonding, electrons are being shared.

Two concepts that are important in this context... In order to understand why some elements bond together to form covalent bonds and others result in ionic bonds, we need to look into two important concepts:

1. Bond Polarity

Definition: The degree of transfer of electrons between two atoms. Basically, which atom in the bonded pair pulls the bonding electrons (two electrons form a single bond) to itself.

Non-polar covalent bonds, in which both atoms equally share the bonding electrons. They lie at one end of the sequence shown in Figure 8.3. Ionic bonds, in which one atom pulls much stronger than the other, lie at the other. Some ionic compounds, e.g., sodium chloride (NaCl), are already familiar to you. Sodium chloride is also commonly called table salt.

2. Electronegativity

Definition: The ability of an atom to attract bonding electrons. The electronegativity of two bonded atoms determines the nature of a bond. Equal sharing of electrons between atoms of the same electronegativity (e.g., in O₂ or N₂) results in nonpolar covalent bonds. While unequal sharing between atoms of different electronegativity (e.g., HCl or CO) creates a polar covalent bond (Higher electron density around one of the bonded atoms).

If the difference in electronegativity between the bonded atoms is even greater, the result is an ionic bond.

The table below provides more detailed information about the electronegativity difference between two bonded atoms. It also shows the resulting bonding type (approximation).
<table>
<thead>
<tr>
<th>Difference in Electronegativity values</th>
<th>Bond Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>below 0.4</td>
<td>nonpolar covalent</td>
</tr>
<tr>
<td>0.4-0.9</td>
<td>moderately polar covalent</td>
</tr>
<tr>
<td>above 0.9-1.7</td>
<td>very polar covalent</td>
</tr>
<tr>
<td>above 1.7</td>
<td>ionic bonding</td>
</tr>
</tbody>
</table>

In Figure 8.3, it can be seen that the polar covalent bond falls between the nonpolar covalent bond and the ionic bond.

![Bonds Diagram]

Figure 8.3

Let's dive a bit deeper into ionic bonding.

Ionic bonding happens between a metal and a non-metal (or polyatomic ions in place of either). Electrons are being transferred from the less electronegative metal (element to the more electronegative nonmetal, which will result in the formation of a metal cation (an ion with a positive charge) and a non-metal anion (an ion with a negative charge) held together by electrostatic forces.

With this review in mind, we can take a look at the bonding itself:

From the book (Chapter 8.2): The formation of ions and ionic bonds relates to the electron configurations of the elements, which is the dispersion of electrons of an atom or molecule in atomic or molecular orbitals. We can see this relationship in the Periodic Table. Each element
immediately following a noble gas (in the Periodic Table) is a metal, which has a strong tendency to lose electrons and thereby achieve a stable noble-gas electron configuration. When giving up electrons to gain a noble-gas configuration, the metal develops a positive electrical charge, forming a cation (positively charged ion). Each element immediately preceding a noble gas in the Periodic Table is a nonmetal, which has a strong tendency to gain electrons to achieve a noble-gas configuration. In so doing, it develops a negative electrical charge, forming an anion (negatively charged ion).

Questions 1: Please summarize the main idea expressed in the paragraph above (2 sentences, and in your own words).

Lewis Symbols (Not the same as Lewis structures)

So now that we know what ionic bonding is, it's helpful to have a method of showing the valence electrons (electrons found in the outer shell, they are associated with an atom, and aid in the formation of a chemical bond) and how they are transferred between the cations and anions.

A quick review from Chapter 7.3: The valence electrons are located in ns and np orbitals for the main-group elements, where n designates the principal energy level.

From the text (Chapter 8.2): The electrons involved in bonding are the valence electrons; a convenient way to show the valence electrons is with a Lewis symbol or an electron-dot symbol, in which dots placed around an element's symbol represent valence electrons. The dots are placed singly on the four sides of the elemental symbol, in any order, and then paired as necessary. An element with a noble-gas configuration is surrounded by four pairs of dots representing eight electrons, an octet.

Example: Lewis symbol for chlorine:

The Lewis symbols for the period 2 elements follow a progression starting with one valence electron for Li and ending with eight for Ne. You can also draw the Lewis symbols for the period 3 elements, Na through Ar. What pattern develops? It should look the same, starting with one valence electron for the group I A (1) elements and ending with eight in group VII A (18). All the noble-gas elements have eight valence electrons occurring in four pairs, except for helium, which only has two.

Lewis symbols give a quick yet efficient look at how many valence electrons an atom has, and they can also show how those valence electrons will be distributed during bonding. To understand how they work, take a look at Table 8.3 below. Notice how the number of valence electrons...
electrons (the number of dots placed around the element) comes directly from the number of electrons in the 2s and 2p orbitals. In other words, the number of dots around the element directly corresponds to the Main Group numbers IA through VIIA. (NOT the group number because this would include the Transition elements).

<table>
<thead>
<tr>
<th>Group</th>
<th>1</th>
<th>2</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Configuration</td>
<td>[He]2s(^1)</td>
<td>[He]2s(^2)</td>
<td>[He]2s(^2)2p(^1)</td>
<td>[He]2s(^2)2p(^2)</td>
<td>[He]2s(^2)2p(^3)</td>
<td>[He]2s(^2)2p(^4)</td>
<td>[He]2s(^2)2p(^5)</td>
<td></td>
</tr>
<tr>
<td>Lewis Dot Symbol</td>
<td>Li·</td>
<td>Be·</td>
<td>B·</td>
<td>C·</td>
<td>N·</td>
<td>O·</td>
<td>F·</td>
<td>Ne·</td>
</tr>
</tbody>
</table>

Table 8.3

Question 2: How can you describe the location of valence electrons in an atom compared to its core electrons?

Question 3: How many electrons should be shown in the Lewis symbol of Aluminum?
You can use the Bohr model of aluminum below to answer the question.

Aluminum has an atomic number of 13, (13 electrons). The 1\(^{st}\) energy level takes 2 electrons, the 2\(^{nd}\) takes 8 electrons. The remaining 3 will be placed on the 3\(^{rd}\) energy level and all this adds up to 13.

The loss of electrons from a metal and the gain of electrons by a nonmetal create the simplest kind of ionic bond. The transfer must happen at the same time, a neutral metal can lose electrons to form a cation only when a nonmetal is available to gain them. The nonmetal then forms an anion with a stable octet (a chemical rule of thumb, that emulates observation that atoms of main group elements tend to associate in such a way that each atom has eight electrons) of valence electrons. Therefore, the net charge on an ionic compound remains the same as in neutral atoms, which is zero. We can't lose electrons and have them go nowhere!

The following equations use Lewis symbols to illustrate this process in the formation of sodium chlorite:
Example A: NaCl

\[ \text{Na} \rightarrow \text{Na}^+ + e^- \]
\[ :\text{Cl}^- + e^- \rightarrow :\text{Cl}^- \]
\[ \text{Na}^+ + :\text{Cl}^- \rightarrow (\text{Na}^+)(:\text{Cl}^-) \text{ or NaCl} \]

The sodium atom loses one electron to form a sodium ion. The ion then has 10 electrons; it has a noble-gas configuration which is any gas that is found in group 18 (same number of electrons as neon). The electron is transferred to a chlorine atom, which becomes a chloride ion; this ion also has a noble-gas configuration. The ions associate to form sodium chloride, a compound held together by attractions between the opposite charges of the ions (electrostatic attractions).

*Because sodium loses one electron and chlorine gains one, the atoms combine in a 1:1 ratio, which leads to electrical neutrality.*

Remember, the metal (Na) loses its electron, which is transferred to the nonmetal (Cl). When this happens, Na has lost one negatively charged electron, so now it is positive. Because Cl has gained the electron, it is now negative.

*Other ions may combine in different ratios. Consider, for example, the formation of aluminum chloride:*

Example B: AlCl₃

\[ \cdot\text{Al} \rightarrow \text{Al}^{3+} + 3e^- \]
\[ 3:\text{Cl}^- + 3e^- \rightarrow 3:\text{Cl}^- \]
\[ \text{Al}^{3+} + 3:\text{Cl}^- \rightarrow (\text{Al}^{3+})(:\text{Cl}^-)_3 \text{ or AlCl}_3 \]

Aluminum is an element of group 13 and period 3, it loses three electrons to achieve a noble-gas electron configuration. Since it takes only one electron to complete the chlorine atom's octet, three chlorine atoms are required to take the three electrons given up by the aluminum atom. We now have an aluminum ion and three chloride ions, which associate in an electrically neutral 1:3 ratio to form ionic aluminum chloride, AlCl₃. This ratio is maintained by an array of aluminum cations and chloride anions arranged in a regular pattern.

- **Important note!** In the previous two examples, a series of equations was given to visualize the process of ionic bonding. It is important to remember that while they are displayed in stepwise equations, these processes are happening simultaneously, **NOT** in a series of steps.

**Question 4:** What is the ratio of Al and S if those elements combine to form an ionic compound? Explain how you determined the ratio.
Structure and Properties of Ionic Crystals

Now let’s take a look at the actual structure of ionic compounds.

When an ionic compound forms from its elements, billions of cations and billions of anions form and bond to give a single ionic crystal. (Mono-atomic ions, on average, have a radius of 150 pm ($10^{-12}$ m)).

From the text (Chapter 8.2): The bonds that hold ions together in ionic compounds result from attractions between oppositely charged ions. If like-charged ions are close to one another, their repulsions partially offset these attractive forces, as shown in Figure 8.7. How do the ions fit together to make a stable ionic compound? An ion, which may be represented as a charged sphere, exerts a force equally in all directions, so ions of opposite charge surround it. The pattern is a crystal lattice, and the result is an ionic crystal, in which the ions are arranged in a regular geometric pattern that maximizes the attractive forces and minimizes the repulsive forces.

Question 5: Summarize in one sentence, why atoms bond to other atoms?

Figure 8.7

We know that ions are formed by atoms losing or gaining electrons. An electrostatic attraction happens, and a bond is formed. When there is a larger charge, there will be a larger attraction between atoms. A small ion and a large charge also result in a stronger interaction.

The opposite charges on ions in ionic compounds hold them together so tightly and account for many of their characteristics, for example, high melting point.

The charges and sizes of the ions largely determine the characteristic patterns of ionic crystals.

For example, many ionic salts with a 1:1 ratio of ions have the same structure as sodium chloride, with each ion surrounded by six ions of opposite charge (Figure 8.8).
**FIGURE 8.8:** The sodium chloride, which is also known as salt, is an ionic compound with the chemical formula NaCl; its crystal is represented at the molecular level in two ways. In each, look for the arrangement of one ion surrounded by six ions of opposite charge. (A) In a space-filling model, the smaller spheres are the sodium ions, and the larger spheres are the chloride ions. The model shows the relative sizes of the ions accurately but masks the details of the crystal structure. (B) A ball-and-stick model reveals the inside of the crystal but does not show relative sizes correctly. (C) A photograph of some magnified NaCl crystals shows how the shape of the crystals corresponds with the arrangement of ions within the crystals.

A and B are two different models of a crystalline structure; both are meant to help you visualize the overall packing of atoms. C shows you an enlarged view of actual NaCl crystals.

For a crystal lattice to form, cations and anions must come close to one another. If the cations are smaller or larger relative to the anions, a different structure develops. For example, if a salt contains a large cation, such as a cesium ion, each is surrounded by eight similarly sized ions of opposite charge. The crystal lattice for cesium chloride is shown in **Figure 8.9**.

**FIGURE 8.9:** The cesium chloride structure is adopted when cations and anions are about the same size. (The image shown for CsCl displays only a portion of the structure for this ionic compound.)

For other compositions, such as salts with 1:2 or 2:1 ratios of ions, different patterns form. A typical structure shown in **Figure 8.10** is that of CaF₂, found in the mineral fluorite.
**FIGURE 8.10:** Ionic compounds that have twice as many of one ion as the other often adopt the same structure as CaF₂, found in the mineral fluorite.

Ionic bonds are very strong because of the large number of interactions between oppositely charged ions; it takes a lot of energy to isolate an ion from the solid structure. The structure directly affects the properties of the compound.

Because melting and boiling require the isolation of ions, ionic compounds have high melting and boiling points.

The strong, attractive forces also make ionic crystals hard and brittle; if struck forcefully, ionic crystals shatter. They break because the force shifts the alignment of ions from the stable interaction of opposite charges to an unstable alignment of like charges (Figure 8.11). Along a shifted layer, strong repulsive forces replace strong, attractive forces, and the crystal cracks.

**FIGURE 8.11:** When a crystal such as NaCl is struck with sufficient force, layers of ions shift. The attractive forces between ions of opposite charges move out of alignment. Layers of like charge align, and they are pushed apart by repulsive forces. The crystal splits along these lines.

The crystalline structure of ionic compounds also explains why solid ionic salts are poor conductors of electricity. The ions are not mobile but are held in place in the crystal lattice, which is the symmetrical three-dimensional arrangement of atoms inside a crystal. However,
melting greatly increases the electrical conductivity of ionic salts, because the ions in the liquid are free to move around.

Other properties of ionic molecules include:

- Dissociation in water: compounds “break apart into separate ions” when dissolved in water
- Good electrical conductivity
- Strong electrolytes
- High melting point
- Solid at room temp. (this refers right back to the high melting point)
- Brittle
- High density

Question 6: What exactly determines if a substance is conductive?

Question 7: (possible MC exam question)
Which element has the exact same number of valence electrons as carbon?
A. Boron B. Nitrogen C. Silicon D. Sulfur

Question 8: (possible MC exam question)
An ionic compound is formed between a metal (M) and nitrogen with the formula M₃N₂. What is M?
A. Potassium B. Oxygen C. Magnesium D. Aluminum
Periodic Trends

What to expect in this chapter:

Over the course of history, many scientists attempted to compare, and group chemical elements based on their properties. The development of the modern periodic table is the work of the Russian chemist Dimitri Mendeleev who presented his version of the Periodic Table in 1869 to the world. He arranged chemical elements by their atomic mass and properties and was even able to predict the existence of elements that had not yet been discovered.

This chapter will discuss patterns in regard to the properties of chemical elements on the periodic table. These reoccurring patterns (period trends) allow us to make predictions about the properties of elements based on their location in the periodic table. The electron configuration of elements plays a very important role.

Therefore, we'll talk about how electron arrangements relate to other properties of elements, such as reactivity, ionization energy and atomic size.

Chemical Reactivity and Electron Configurations:

The activity series (below, Fig. 7.24) demonstrates the relative reactivity of metals (and hydrogen) relative to one another. Notice the elements that are at the top of the activity series, as shown in Figure 7.24. Can you see the pattern? Most are alkali metals, group IA (1), and alkaline earth metals, group II A (2), they are the most reactive metals.

The alkali metals, in the first group in the periodic table, are commonly found in nature as oxides, their stable compounds with oxygen have the general formula $M_2O$, where $M$ represents an alkali metal:

$I_2O$, $Na_2O$, $K_2O$, $Rb_2O$, $Cs_2O$,

Question 1: What would be the general formula of compounds formed between group IIA elements and oxygen?
 Ionization Energy:

When metal elements react, they lose valence electrons and form cations, the more easily metal atoms give up their valence electrons, the more reactive they are. One important factor is ionization energy (IE), which is a measure of the energy required to remove a valence electron from a gaseous atom to form a gaseous ion, it is usually expressed as the energy required to remove an electron from each atom in exactly 1 mol (6.022 x 10^23) of atoms. For example, consider the ionization process for lithium, which can be represented with the following equation:

\[
Li(g) \rightarrow Li^+(g) + e^- \quad IE = 520 \text{ kJ/mol}
\]

In other words, 520 kJ of energy would be required to remove the outermost electron from each atom in 1 mol of lithium. Ionization energy is related to electron arrangement and helps explain differences in the reactivities of metals. In general, atoms with low ionization energies do not bind their valence electrons very tightly, so they are very reactive.

Trends in Ionization Energies:
The ionization energies of the main-group elements are given in Figure 7.26. What patterns can you find? Notice that the ionization energies of the alkali and alkaline earth metals are relatively low; if we look specifically at elements in the same group, we can see that their ionization energies decrease as we move down a group. This happens because the valence electron that's removed upon ionization is farther from the nucleus as we move down a group. Electrons farther from the nucleus are easier to remove, they are not as strongly attracted to the positive charge of the nucleus (Figure 7.27). Effective nuclear charge $Z_{\text{eff}}$ is the net positive charge experienced by an electron in an atom that contains more than one atom, it is a measure of how strongly an electron is held. In addition, valence electrons are shielded from the attraction of protons by core electrons closer to the nucleus. As the number of core sublevels increases, so does the effect of shielding, which explains why elements such as cesium are so reactive.

**Figure 7.26** Ionization energies for the main group elements are given in units of kJ/mol. They are the amount of energy needed to remove one electron from each atom in 1 mol of atoms of the element when in the gaseous state.
In smaller atoms, electrons are closer to the nucleus, and therefore strongly attracted by the positive nuclear charge.

**FIGURE 7.27** A valence electron in a lower principal energy level is closer to the nucleus than a valence electron in a higher principal energy level. The attraction between the nucleus and the valence electron is greater for smaller atoms, resulting in a greater ionization energy.

**Question 2:** Which element, carbon or fluorine, should have the greater first ionization energy? Why? Please give your reasoning.

**Question 3:** Which element, strontium or magnesium, should have the greater first ionization energy? Why? Please give your reasoning.

You may have observed another pattern in ionization energies from Figure 7.26. They increase from left to right on the periodic table. What is different about atoms in the same period that makes ionization energy increase? The increase in the number of electrons does not explain this trend, as we move across a period from left to right, electrons are added to the same principal energy level, this has a negligible effect on ionization energy. However, an increase in the number of protons in the nucleus as we move across the periodic table causes ionization energy to increase because of the additional positive charge. This increase in nuclear charge pulls the electrons in the valence level closer to the nucleus and makes removal of a valence electron more difficult. The general tendency is for ionization energy to increase from bottom to top and from left to right across the periodic table (Figure 7.28).

**Question 4:** Please summarize in one sentence and in your own words, the main idea in the paragraph above.
FIGURE 7.28 Ionization energy tends to increase going up the periodic table and from left to right.

**Atomic Size:**

Another trend that shows a pattern throughout the periodic table is the size of atoms. The size of an atom is often described in terms of its atomic radius, the distance from the center of the nucleus to the outer edge of the atom. The radius of an atom is often reported in units of picometers (1 pm = 10^{-12} m). Because the outer edge of an atom is not sharply defined, scientists measure the distance between the centers of two identical bonded atoms to determine atomic radii. The radius is one-half this distance (Figure 7.29).

![Diagram of atomic radius](image)

The distance between the middle of the nucleus and the outer edge of the atom is the atomic size. This is referred to as the radius of the atom. It's measured in picometers, \(10^{12}\) meters. In this image, the distance between the centers of two identical bonded atoms is measured as 199 pm. This is done because the outer edge of an atom is not very well defined. The distance is then divided by 2 to give 99.5 pm, which is then defined as the atomic radius.

FIGURE 7.29 To determine the size of an atom, scientists measure the distance between the centers of two bonded atoms. For identical atoms, the atomic radius is one-half this distance.
Atomic radii for the main-group elements are shown in Figure 7.30. Do you observe any patterns? Notice that the atomic radius generally increases as we move down a group. How might you explain this trend? The electron configurations for the elements in a group provide the answer.

For example, recall the electron configurations for the alkali metals, group I A (1):

Li \quad [He]2s\(^{1}\) \quad Rb \quad [K]5s\(^{1}\)

Na \quad [Ne]3s\(^{1}\) \quad Cs \quad [Xe]6s\(^{1}\)

K \quad [Ar]4s\(^{1}\)

Lithium’s valence electron is in the 2s orbital; the valence level is \(n = 2\), very close to the nucleus, at the bottom of the group. Cesium, its valence level is \(n = 6\), much farther from the nucleus, as we go from top to bottom in a group, the atomic radius increases because the valence electrons are in larger orbitals farther away from the nucleus.

**Question 5:** What can you say about the nuclear attraction on one of the electrons in the principle energy level with \(n = 5\) (in comparison to electrons in lower energy levels)?

As we move from left to right across a period, atomic size generally decreases. You might think that size should increase because the number of electrons increases, but the electrons are added to the same principal energy level while the positive charge in the nucleus increases. As we move from left to right across a period, the increased positive charge in the nucleus becomes more effective at drawing the valence electrons closer to the center of the atom, causing atoms to the right on the periodic table to be smaller in size. Trends in atomic size are shown in Figure 7.31.
Figure 7.30 This periodic table shows the relative atomic size of the main-group elements, along with their atomic radii in units of picometers. (Except for the noble gases, the atomic radius is determined as half the distance between two bonded atoms.)

Figure 7.31 Atomic size increases down a group and from right to left in a period.

Question 6: Which atom is larger, carbon or fluorine? Explain.

Question 7: Which atom is smaller, strontium or magnesium? Explain

sizes of ions:

7
When ions form from neutral atoms, the radii of the atoms change, consider what happens when lithium ionizes (Figure 7.32A). A neutral atom of lithium has 3 electrons and 3 protons, the ion has 2 electrons and 3 protons. The nuclear charge remains the same, while the number of electrons decreases. In the ion, the protons draw the remaining electrons closer to the nucleus, consequently, the Li+ ion is smaller than the neutral atom.

![Diagram of lithium and fluorine ions]

When an atom loses one or more electrons, it becomes a positively charged ion, called a cation. In Figure 7.32, the metal lithium loses an electron to form a single positive lithium ion. On the other hand, the image shows that if neutral atoms gain electrons, an anion is formed. As an example, her, fluorine gains one electron to form a negatively charged fluoride ion.

**FIGURE 7.32 (A)** A cation is smaller than the neutral atom from which it forms, the nucleus holds the cation’s fewer electrons more tightly. **(B)** An anion is larger than the neutral atom from which it forms, the nucleus holds the anion’s greater number of electrons less tightly.

The opposite happens with anions. For example, consider the formation of the fluoride ion (Figure 7.32B), the neutral atom has 9 electrons and 9 protons, the F− ion has 10 electrons and 9 protons. Because there are more electrons, the protons cannot hold the electrons as close to the nucleus. Thus, the ion is larger than the neutral atom. A summary of the sizes of many main-group ions is given in Figure 7.33.

There are so many factors involved in determining the sizes of ions that no single trend spans the entire periodic table. However, for a series of ions with the same number of electrons—an isoelectronic series—consider the following ions:

<table>
<thead>
<tr>
<th>Ion</th>
<th>Radius (pm)</th>
<th>Electron Configuration</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2−</td>
<td>184</td>
<td>1s2 2s2 2p6 3s2 3p6</td>
<td>16</td>
</tr>
<tr>
<td>Cl−</td>
<td>181</td>
<td>1s2 2s2 2p6 3s2 3p6</td>
<td>17</td>
</tr>
<tr>
<td>K+</td>
<td>133</td>
<td>1s2 2s2 2p6 3s2 3p6</td>
<td>19</td>
</tr>
<tr>
<td>Ca2+</td>
<td>99</td>
<td>1s2 2s2 2p6 3s2 3p6</td>
<td>20</td>
</tr>
<tr>
<td>Sc3+</td>
<td>81</td>
<td>1s2 2s2 2p6 3s2 3p6</td>
<td>21</td>
</tr>
</tbody>
</table>
All of the ions in this series have the same number of electrons and the same electron configuration, but they have different numbers of protons (atomic numbers). For any iso electronic series, as the number of protons increases, the ion size decreases.

FIGURE 7.33 Shown here are the ionic radii for ions of the main-group elements. Note the trends down a group and for ions that are iso electronic.

Question 8: how does this all relate to electronegativity?
7. Properties and Changes

Properties and Changes

What to expect in this chapter:

Science depends on observations and accurate descriptions of, e.g., phenomena and experimental results. Each substance can be described by its physical and chemical properties and its behavior. In this chapter, you will discuss the various categories of properties used to describe and changes that substances can undergo. In addition, you will learn about two properties, density, and temperature, in more detail.

Changes in matter are part of the properties of matter. Their observations could be either qualitative, based on some quality of the matter, or quantitative, based on a numerical value. When making qualitative observations, color, shape, texture, shininess, and physical state are described.

In this chapter, you will be introduced to some important physical changes, temperature, and density.

Properties

When reporting qualitative data, we can classify properties as either physical or chemical.

When you observe and describe matter, such as the color, shape, texture, shininess, and physical state of things around you, you are noting their physical properties.

A physical property is a characteristic that we can observe or measure without changing the composition of a substance.

Other examples of physical properties are odor, taste, hardness, mass, volume, density, magnetism, conductivity, polarity, and the temperatures at which a substance changes from one physical state to another (e.g., freezing or boiling point).

As you can see above, there are many physical properties, some of which depend on the size of a sample, like mass and volume, some of which are independent of the sample size, meaning they do not change whether you investigate a large or small sample size. Examples of this are odor, hardness, density, conductivity, and color.

Physical properties that are dependent on sample sizes such as mass and volume are called extensive physical properties; properties that do not depend on the sample size such as density and color are called intensive physical properties.

Chemical properties are different; a chemical property of a substance is defined by what it is composed of and what chemical changes it can undergo.

It is, for example, a chemical property of iron that it can rust when exposed to the environment; a substance’s reactivity with water is another example—some elements or compounds react vigorously, some do not react at all.

Question 1: Can you name/describe other chemical properties?

Important examples of physical properties: density and temperature

Let’s take a close look at density and temperature. These properties are quantitative; they involve numerical values—also like, e.g., mass and volume.
Density:

The density of an object is defined as the ratio of its mass to its volume.

This ratio can be expressed using an equation:

While mass and volume both depend on the size of the object or sample, density does not. Density is an unvarying property of a substance no matter how much of it is present, as long as temperature and pressure are constant. The densities of a few substances are listed in Table 1.6.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Physical State</th>
<th>Density in g/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>gas</td>
<td>0.000178</td>
</tr>
<tr>
<td>Oxygen</td>
<td>gas</td>
<td>0.00143</td>
</tr>
<tr>
<td>Cooking Oil</td>
<td>liquid</td>
<td>0.92</td>
</tr>
<tr>
<td>Water</td>
<td>liquid</td>
<td>1</td>
</tr>
<tr>
<td>Mercury</td>
<td>liquid</td>
<td>13.5</td>
</tr>
<tr>
<td>Gold</td>
<td>solid</td>
<td>19.3</td>
</tr>
<tr>
<td>Copper</td>
<td>solid</td>
<td>8.92</td>
</tr>
<tr>
<td>Zinc</td>
<td>solid</td>
<td>7.14</td>
</tr>
<tr>
<td>Ice</td>
<td>solid</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table 1.6: Densities of some common Substances

The graduated cylinder below contains several liquids with different densities, the densities of antifreeze, corn oil, dish detergent, maple syrup, shampoo, and water in g/mL are 1.13, 0.93, 1.03, 1.32, 1.01, and 1.00, respectively.

Question 2: What is the pink liquid and what is its density?

If we compare equal volumes of two different substances, such as aluminum and gold, as shown in Figure 1.19, the substance with the greater mass has a greater density.

How, though, can we compare densities if we do not have equal volumes? The mathematical relationship between mass, volume, and density reveal the answer.
The graduated cylinder above contains several liquids with different densities. From top to bottom the density of the liquids increases. We have Corn oil (0.93), water (1.00), shampoo (1.01), dish detergent (1.03), antifreeze (1.13) and maple syrup (1.32).

**Question 3:** What is the unit for density? Does the unit depend on the state of matter of the substance?

![Figure 1.19](image)

Atoms in metals are tightly packed together in a defined volume, some metals pack more closely than others. The atoms in gold are tightly packed than those in aluminum, which is why gold is denser than aluminum.

**Figure 1.20** Gold (Au) has a greater density than aluminum (Al) because gold has a greater mass per unit volume.

**Question 4:** Why do different solids have different densities?

Water is a molecule composed of one atom of oxygen bound to two hydrogen atoms; it's unique among liquids because its solid form (ice) floats on its liquid form. This results from the relatively open structure adopted by water molecules in the solid-state. What would happen to fish during the winter if ice were
like other solids that sink in their liquid form? Why do substances have different densities? Gases, in general, have very low densities because gas particles spread out and occupy large volumes. Metals tend to have high densities because their atoms pack together efficiently. Because ice floats on water, we can infer that water in its solid form must have a lesser density than water in its liquid form. Example 1.8 shows how to use molecular pictures to predict relative densities.

**Question 5:** How do the molecular diagrams of ice and water (see below) help explain why ice is less dense than water? And what fills the space between water molecules?

In ice, there is more space around the water molecules. They aren’t tightly packed. In liquid water, the water molecules are tightly packed. There is little to no space around them.

Here is something to think about:

**Question 6:** Does one water molecule have the same density as a drop of water? Explain!

Temperature (another physical intensive property)

Some days you might not be happy with your lunch; the pizza is cold, and the soda is warm; when we make such comparisons, we observe relative temperatures. Temperature measures how hotness or coldness something expresses in terms of units or degrees relative to some standard scale. We measure temperature with a thermometer; in the United States, we often use the Fahrenheit scale to measure body temperature and air temperature. Fahrenheit is rarely used in science. Two other temperature scales are standard: the Celsius scale and the Kelvin scale. The relationships between the three temperature scales, Fahrenheit (°F), Celsius (°C), and Kelvin (K), are shown in Figure 1.22.
Temperatures are written differently for the different scales; while Celsius and Fahrenheit use the superscript ° to indicate degrees, the Kelvin scale does not. The unit is written as K (the capital letter), but temperatures are measured in kelvins (lowercase).

Another property of matter that is independent of sample size is the temperature at which the substance changes from one physical state to another. The boiling point is the temperature at which the liquid form of a substance changes to the gaseous form. At the melting point, the substance changes from a solid to a liquid; between these two temperatures, the substance is normally in its liquid state. For example, on the Celsius scale, the boiling point of water is 100°C, water melts (or freezes, depending on its original state) at 0°C. On the Kelvin scale, these values are 373.15 K and 273.15 K; respectively, on the Fahrenheit scale, they are 212°F and 32°F, respectively.

Question 7: Please summarize in your own words the main idea described in paragraph above.

There are no negative values on the Kelvin scale, it is an absolute temperature scale because it’s zero points is the lowest possible temperature observable in the universe. This value is absolute zero, which is equivalent to 273.15°C. The temperature increments on the Kelvin scale are the same as those on the Celsius scale, the difference in temperature between the boiling point of water and the freezing point of water is 100 in both the Celsius (100°C – 0°C) and kelvin (373.15 K – 273.15 K) scales, while the difference is 180 on the Fahrenheit scale (212°F – 32°F). Because the temperature in Kelvins is always 273.15 greater than the temperature in degrees Celsius, we can easily convert between them.

Question 8: Why do we have different temperature scales? How could you set up a new temperature scale?

Physical and Chemical Changes

As you have just seen, when water changes its state of matter, it does not change the overall composition of the substance (H2O molecules stay intact), any change like this is called a physical change.

On the other hand, changes in which substances change their composition, and these changes result in the formation of one or more new substances, is called a chemical change or chemical reaction.

Summary of new terms:

Let’s review: A **physical property** is a characteristic that we can observe or measure without changing the composition of a substance.

Accordingly, a **physical change** is a process that changes the physical properties of a substance without changing its composition.

In contrast, a **chemical change** (or chemical reaction) is a process in which one or more substances are converted into one or more new substances.

A substance is a particular kind of matter with the same properties.
Question 9: According to these definitions, what is the correct answer to the question below?

What is shown in the representation?
A. A compound undergoing a chemical change.
B. A compound undergoing a physical change.
C. An element undergoing a chemical change.
D. An element undergoing a physical change.
8. Formula Calculations:

**Formula Calculations**

What to expect in this chapter:
This chapter will introduce you to the way chemists describe and calculate with large amounts of particles that are too small to see. You will be introduced to a unit called “the mole”, which has a value of \(6.022 \times 10^{23}\) (Avogadro’s Number). The mole allows chemists to translate masses (measured in grams) into the amount of particles a sample contains. In this context, it is very helpful to work with molar masses (mass of one mole of particles) for different elements. The molar mass of each element and compound is very different due to the fact that atoms of different elements have different masses. In addition to mass – particle calculations, this chapter will also explain how Avogadro’s number and molar masses can be used to determine empirical and molecular formulas.

**Formula Calculations:**

Formula calculations provide us the number of atoms of each element, they are calculations that are based on the ratios of elements given in the chemical formula. Therefore, let look at some examples first:

What information does the formula \(\text{Na}_2\text{SO}_4\) provide?

1. It provides information about the type of compound, in the case of sodium sulfate, the compound is ionic (review).
2. The formula also gives the total number of atoms in one formula unit, for sodium sulfate, the total number is 7.
3. The formula provides the element ratios: one formula unit of sodium sulfate for example contains four times as many oxygen atoms as it contains sulfur atoms, twice as many oxygen atoms as sodium atoms, and double the amount of sodium atoms as there are sulfur atoms.

**Question 1:** Describe the atomic ratios in the molecular compound ethanol, \(\text{C}_2\text{H}_5\text{OH}\).

**The Mole: Describing larger quantities:**

Chemical formulas are helpful more than the ways described above, they also let us calculate larger quantities of those components, quantities that we can work with in a laboratory environment. For the previous example of sodium sulfate, we describe the atom ratios in one formula unit. In a laboratory setting though, chemists are not working with single molecules, as the sheer number of molecules involved in a given reaction would be completely impractical.

*Unfortunately, we cannot see atoms and molecules because they are too small.* Although we can use a scanning tunneling microscope, which is an instrument used for imaging surfaces at atomic level, to “see” atoms and molecules on the surface of a solid, as shown in Figure 4. 7, this technique reveals only atoms on a surface, not those beneath.
Atoms and molecules cannot be seen with bare eyes, because they are too small, which is why a scanning tunneling microscope was used to see atoms and molecules on the surface of this solid.

Figure 4.7: The "bumps" in this image are atoms on the surface of a mica crystal. Mica is a mineral containing potassium and aluminum cations and silicate and hydroxide anions.

Did you know...

...a dust-sized piece of a solid contains over $10^{25}$ of each type of atom. We certainly wouldn’t want to count that many atoms individually, even if we could, fortunately, we don’t have to see atoms to count them. Instead we can find the relative masses of the elements in a compound.

Units of Quantity

From the text (Chap. 4.2): In Chapter 2, we saw that the average masses of the elements which is the sum of the masses of its isotopes, each multiplied by its natural abundance, can be expressed as their relative atomic masses. For the elements in hydrogen sulfide, the relative atomic masses are 1.008 amu for hydrogen and 32.07 amu for sulfur.

While relative atomic masses are very useful for comparing the masses of elements, atomic mass units are not useful to chemists weighing substances to use in chemical reactions like those for processing copper oxides.

Common laboratory balances measure masses in grams, not atomic mass units. We cannot weigh one or even a few atoms, molecules, or formula units of a substance, since the masses of most atoms and common molecules are less than $10^{-24}$ g, to work with a mass of about 1 g, we have to measure a number of formula units greater than $10^{24}$. For example, to get 1.0 g of $\text{H}_2\text{S}$, we would need almost $2 \times 10^{24}$ molecules. To get an idea of how large this number is, consider a teaspoon of water.

There are as many molecules of water in this teaspoon (about $1.7 \times 10^{23}$) as there are teaspoons of water in all the oceans on Earth, similarly, there are about as many $\text{SiO}_2$ formula units in one grain of quartz sand as there are sand grains on all the beaches on Earth.

Because numbers this large are too unwieldy to work with easily, we need some way to measure the amount of a substance without counting the number of atoms, formula units, or molecules.

This unit that bridges this gap is called the mole, or mol, and represents the amount of substance that contains as many atoms, molecules, formula units, etc. as there are atoms in exactly 12g of Carbon (Definition!!)

The number of atoms in 12g of $\text{C}$ has been experimentally determined as $6.022 \times 10^{23}$ atoms and is commonly referred to as Avogadro’s Number ($N_A$).
Avogadro’s number was named after the scientist Amedeo Avogadro, it’s the number of constituent particles, usually atoms or molecules, that are encompassed in the amount of substance given by one mole.

**Avogadro’s Number** = \( N_A = 6.022 \times 10^{23} \text{ atoms} = \text{mole} \)

Although 1 mol contains different volumes and different masses of different materials, it is always the same number of formula units (atoms, molecules, or ionic compound formula units).

→ Important Note! We use the abbreviation mol for mole, but molecule should not be abbreviated.

**Calculations Involving Moles**

We can now discuss various ways in which moles can be used to quantize and calculate chemical components.

1. The mole as the number of particles.

From the text (Chap. 4.2): *We can convert between moles and formula units using the following pathway:*

![Diagram](image_url)

If 1 mol can be 1mol of atoms, molecules, formula units (referring to ionic compounds), or ions, then we can easily calculate the number of copper atoms in 2 moles of copper.

The mathematical set-up is as follows; the unwanted units cancel out.

\[
2 \text{ mol Cu} = \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol Cu}} = 1.204 \times 10^{24} \text{ Cu atoms}
\]

**Questions 2:** How many copper atoms are in 0.3 mol of copper?

2. The mole used to calculate the number of atoms in a compound

*We can also calculate the number of atoms or ions in a formula unit, to determine the number of atoms or ions in a given number of moles of a substance, we extend the pathway further to include analysis of the chemical formula:*

![Diagram](image_url)
Consider another example, copper(I) oxide. How many ions does 1 mol of Cu₂O contain? Analysis of the chemical formula indicates that a formula unit of Cu₂O contains two Cu⁺ ions and one O²⁻ ion, as shown in Figure 4.9.

\[
1 \text{ mol Cu}_2\text{O} \times \frac{6.022 \times 10^{23} \text{ formula units Cu}_2\text{O}^-}{1 \text{ mol Cu}_2\text{O}} \times \frac{2 \text{ Cu}^+ \text{ ions}}{1 \text{ formula unit Cu}_2\text{O}^-} = 1.204 \times 10^{24} \text{ Cu}^+ \text{ ions}
\]

\[
1 \text{ mol Cu}_2\text{O} \times \frac{6.022 \times 10^{23} \text{ formula units Cu}_2\text{O}^-}{1 \text{ mol Cu}_2\text{O}} \times \frac{1 \text{ O}^{2-} \text{ ion}}{1 \text{ formula unit Cu}_2\text{O}^-} = 6.022 \times 10^{23} \text{ O}^{2-} \text{ ions}
\]

If those numbers are added up, the total number of ions in 1 mol Cu₂O is \(1.807 \times 10^{24}\) ions (3 x 6.022 x 10²³).

![Figure 4.9: One formula unit of Cu₂O, shown highlighted, contains two Cu⁺ ions and one O²⁻ ion.](image)

Molar Mass – (of elements and compounds)

From the text (Chap. 4.2): The relative atomic mass is the average mass of atoms of the naturally occurring form of an element in atomic mass units. This definition describes the average mass of one atom, but we can extend it to larger quantities of matter as well. Recall that the basis of the definition is that one atom of 12-C has a mass of exactly 12amu.

Avogadro's number has been defined so that the mass of 1 mol of 12-C (that is, \(6.022 \times 10^{23}\) atoms of 12-C) is exactly 12g.

Consequently, the mass of a basic particle of any substance in atomic mass units and the mass of 1 mol of the substance in grams have exactly the same numerical value.

Question 3: Can you express what is said in the sentence above with your OWN WORDS?

The definition of a mole can be restated, then, in terms of the mass of our reference, 12-C: A mole is the amount of substance that contains as many basic particles (atoms, molecules, or formula units)
as there are atoms in exactly 12 g of 12C. The term that describes the mass of 1 mol of a substance is molar mass. (Definition!!)

The molar mass is the mass of a given substance, whether it be a chemical, an element or chemical compound, divided by the amount of the substance.

Since the molar mass value for any atom, in units of grams per mole (g/mol), is numerically the same as the relative atomic mass value (in units of amu per atom),

We can use the periodic table to determine the molar mass of any element or compound.

For example, the average mass of 1 hydrogen atom is 1.008 amu, and the mass of 1 mol of hydrogen atoms is 1.008 g.

The molar mass of a molecular or ionic substance has the same value as the sum of the relative atomic masses of its component elements.

For example, the average mass of a molecule of H2S is 34.07 amu, and its molar mass is 34.07 g/mol. Molar masses of molecules (or formula units) are obtained by adding the molar masses of the component elements, each weighted by the number of that atom in the molecule (or formula unit), for simplicity, we will abbreviate molar mass as MM.

Molar Masses of Compounds:

Example question: When copper sulfide ores are roasted in a furnace, sulfur dioxide gas, SO2, forms. What is the molar mass of SO2?

Solution: The molar mass of a compound is the sum of the molar masses of its component elements— in this case, sulfur and oxygen.

A molecule of sulfur dioxide contains one sulfur atom and two oxygen atoms, so we must multiply the molar mass of oxygen by a factor of 2. We can find the molar masses of sulfur and oxygen on a periodic table, multiply the molar mass of oxygen by 2, and find the sum:

\[
\text{Mass of 1 mol of S} = 1 \text{ mol} \times 32.07 \text{ g/mol} = 32.07 \text{ g} \\
\text{Mass of 2 mol of O} = 2 \text{ mol} \times 16.00 \text{ g/mol} = 32.00 \text{ g} \\
\text{The molar mass of SO}_2 \text{ is 64.07 g/mol. The unit for molar is g/mol.}
\]

Question 4 (possible exam question): What is the molar mass of aluminum hydroxide, Al(OH)3?

Percent Composition by mass

Another way of thinking about the composition of elements is to express it through the “percent composition by mass”, which is the percent by mass of each element present in a compound or is an expression of the portion of the total mass contributed by each element. The percent composition of a substance is constant, no matter what the size of the sample.
The percent composition by mass can be calculated using the molar mass of a compound and the mass of each element that contributes to the total mass of one mole of the compound.

Let's take the example of sulfur dioxide from above, each of the elements contributed almost equally to the molar mass of the compound (32.07 g sulfur and 32.0 g oxygen), we can use the number to determine the exact percent composition of the compound $\text{SO}_2$.

\[
\% \text{ S} = \frac{32.07 \text{ g sulfur}}{64.07 \text{ g SO}_2 \text{ sample}} \times 100\% = 50.05\%
\]

\[
\% \text{ O} = \frac{32.00 \text{ g oxygen}}{64.07 \text{ g SO}_2 \text{ sample}} \times 100\% = 49.95\%
\]

Note that the percentages of all elements add up to the total of 100%.

**Empirical and molecular formulas**

You have seen now how to express the composition of a substance in terms of masses, percent composition, moles, and atoms or molecules of the component elements.

There are two types of chemical formulas that are related to the composition of a substance.

An empirical formula expresses the simplest ratios of atoms in a compound, it gives the proportions of existing elements in a compound, but not the actual numbers or arrangement of atoms, it is written with the smallest possible whole number subscripts. The **empirical formula** is not always the same as the molecular formula (for covalent compounds), but it is the same for ionic formulas (remember, ionic formulas give the smallest whole number ratio of ions).

*Question 5: Please summarize in your own words and in one sentence the paragraph above.*
Solutions:

SOLUTIONS

Now that we know about the mole, which is an SI unit that measures the number of particles in a specific unit, and how it can be used in calculating the quantities of compounds used in reactions, we may discuss the methods by which those reactions occur. As seen previously, the mole can be used to convert between units of particles, grams, and moles. In considering grams, or the weight of the compound in question, it is normal to think in terms of solids. However, reactions between solids typically occur over very long time periods that are not realistic for creating a reaction. If these same reactants are dissolved in a liquid to create a solution though, the reaction can occur much quicker.

In this chapter, you will be introduced to how to make a solution. On a macroscopic level, the solution will be viewed as a homogenous mixture and in this mixture, the solute particles are evenly spread among the solvent particles. This solution cannot be separated by using a filter. Chemists present solutions on a particle level where you can see ions dissociate in the solvent and molecular units staying unchanged. However, since solutions have different amounts of solute/solvent, the concentration will be used to define how much of the solute and solvent is present in the solution, and this can be done in various ways and one of the most common is the Molarity which is the number of moles of solute dissolved in 1 L of solution.

Question 1: Why do you think reactions in solution are often faster?

From the text (Chapter 4.4): Recall from Chapter 1: A solution is any mixture that is homogenous at the molecular or ionic scale and is composed of two or more substances. In a solution, the substance that is dissolved is called the solute (usually present in a lesser amount), and the substance doing the dissolving is called the solvent (usually present in a greater amount). (Definitions!!)

Question 2: please summarize in one sentence and in your own words, the paragraph above.

Figure 4.17 shows a solution of copper (II) sulfate (the solute) dissolved in water (the solvent).

![Image of blue solution being poured into a beaker.]

FIGURE 4.17 In this system, dissolved copper (II) sulfate is present in a lesser quantity than water, so copper (II) sulfate is the solute and water is the solvent.
Solute = substance being dissolved; present in lesser amount
Solvent = substance doing the dissolving; present in greater amount
Concentration = measurement of the amount of solute present in a solution.

Note: If water is the solvent, we talk about an aqueous solution.

Solutions described on the molecular level

Example Question: From this picture of a solution containing copper (II) sulfate CuSO₄ and water, identify the solute and the solvent.

![Image of copper (II) sulfate and water molecules]

Answer: In this image, the dark red spheres represent copper ions, the yellow/red groups of spheres represent sulfate ions (sulfate molecules), and the pale red and white groups represent H₂O molecules. The number of copper and sulfate ions is equal and is less than the number of H₂O molecules. Thus, the solute is CuSO₄, which yields Cu²⁺ and SO₄²⁻ ions in solution, the solvent is H₂O since it is present in the greater amount.

Now you try!

Question/task 3: In the following image of a solution containing hydrogen sulfide and water, identify the solute and the solvent.

![Image of hydrogen sulfide and water molecules]
The particle representations above show the difference between an ionic compound, which are compounds made up of ions, dissolving in water in which we can observe dissociation of ions, and the dissolving process of molecular compounds in which the molecular unit stays intact.

Question 4 (possible exam question): Assuming now that the following compounds are all soluble in water, which compounds will dissociate into ions when in aqueous solution?

- a) NaCl  
- b) CH₃OH  
- c) C₆H₁₂O₆  
- d) LiOH  
- e) K₃PO₄

Concentration of Solutions

From the text (Chapter 4.4): Solutions are homogeneous mixtures, but different solutions can contain varying amounts of solute and solvent. So, how do we express the composition of a solution? One way is to describe its concentration, is by the relative amounts of solute and solvent in it.

When comparing solutions, we can describe them as either dilute or concentrated. A dilute solution contains a relatively small amount of solute, whereas a concentrated solution contains a comparatively large amount of solute. These terms are helpful when we compare two solutions of different concentrations, indicating that one contains more or less solute than the other, we see these differences in concentration in everyday solutions. For example, when we brew a pot of tea, the color is more intense if the tea is "strong" (concentrated) than if it is "weak" (dilute).

Important concepts to remember:

- Concentration: how much solute per solvent is in the solution
- Dilute: there is more solvent than solute in the solution
- Concentrated: there is more solute than solvent in the solution

Question 5: What are some other solutions that you see in your environment where color gives you an indication of the concentration?

What other ways can you compare concentrations of solutions?

The concentrations of sugar solutions, for example, could be compared by how slowly they pour, if you compared a teaspoonful of sugar dissolved in a cup of water to molasses or syrup (also sugar solutions), which would pour more slowly?

Question 6: Can the different behavior be explained by different densities as well?
Comparing Concentrations of Solutions

A variety of experimental methods allows us to determine the concentrations of solutions. For example, if the solute is colored and the solvent is colorless, then the intensity of color in the solution is a measure of its concentration. Consider the aqueous solutions of copper (II) sulfate, which is blue in color shown in Figure 4.18. The more copper (II) sulfate dissolved in the water, the more intense is the blue color due to the Cu²⁺ ions.

![Image of copper (II) sulfate solutions]

**FIGURE 4.18** The color intensity of a colored solution decreases as the concentration of the solute decreases. Compare the concentrations of ions in the solution for these copper (II) sulfate solutions. Which has more copper (II) ions? More sulfate ions? Which solution has the greatest concentration?

**Question 7:** Assuming that the solutions in Figure 4.18 contain 8, 5, or 3 moles of sulfate molecules (going from left to right, one sulfate molecule representing one mole), how many grams SO₄²⁻ (sulfate) are in each solution?

*Figure 4.18* also shows, at a molecular level which is examining up-close of the cells, how the relative amounts of solute and solvent vary with the concentration. If you count the solute particles [copper (II) ions and sulfate ions] and compare them to the number of water molecules, you can see that as the solution becomes more dilute, the number of ions in a measured amount decreases and the number of water molecules in that same measured amount increases. Because the concentration of copper (II) ions decreases relative to the number of water molecules, the color of the blue solution fades.

**Molarity—a measure of concentration**

The concentration of a solution can be expressed in a variety of ways, one of the most common ways is molarity (M). The molarity of a solution is the number of moles of solute dissolved in 1 L of solution. The molarity of any solution can be calculated by dividing the moles of solute by the liters of solution:
Molarity is calculated from liters of solution, NOT liters of solvent. How large this difference is, depends on the concentration of the solution. Dilute solutions contain only a small amount of solute, the volume of such solutions is very nearly the same as the volume of solvent, but the difference can be significant for solutions in which the volume of the solvent is significantly less than the volume of the solution.

To ensure accuracy, solutions of the desired molarity are usually prepared in volumetric flasks, as shown in the pictures below.

**Figure 4.10:** In the laboratory, solutions of known molarity are usually prepared in volumetric flasks, which are calibrated to contain a specific volume. (A) To prepare 250 mL of a 0.100 M solution of CuSO₄·5H₂O, weigh 0.24g (which is 0.0500 mol) of the solute. (B) Transfer it to the flask and add some solvent, water. Dissolve the solute by swirling. (C) Solvent is added with swirling until the bottom of the liquid surface just matches the marked line on the neck of the flask. (D) Then a stopper is inserted into the flask and the flask is inversion several times to thoroughly mix the contents. Convince yourself that this procedure will indeed result in a solution whose concentration is 0.100 M.

If we know the mass of the solute and the volume of the solution, we can calculate the molarity of the solution. To begin, calculate the number of moles of solute contained in the solution, then divide by the volume (in liters), of the solution.
Step-by-step example: You dissolve 5.5 g NaCl in 250 mL of water. The molar mass of NaCl is $58.44 \frac{g}{mol}$.

Therefore: $5.5g \text{ NaCl} \times \frac{1\text{ mol}}{58.44g} = 0.0941 \text{ mol (moles of solute)}$  

$\frac{0.0941 \text{ mol}}{0.250\text{ L}} = 0.38 \frac{\text{ mol}}{\text{ L}} = 0.38 \text{ M}$

Ion Concentration in Solution— which can differ from the overall concentration of the solution.

We commonly express the concentration of a solution as a molarity of the solute compound. For example, a solution might contain 0.100 M CuCl$_2$. If we are interested in the concentrations of ions in a solution of this ionic compound, we must account for the fact that the solution contains twice as many chloride ions as copper (II) ions (Figure 4.20).

For each formula unit of CuCl$_2$ in the solution, we have one Cu$^{2+}$ ion and two Cl$^-$ ions. For each mole of CuCl$_2$ in the solution, we have 1 mol of Cu$^{2+}$ ions and 2 mol of Cl$^-$ ions. Thus, the 0.100 M CuCl$_2$ solution contains 0.100 M Cu$^{2+}$ and 0.200 M Cl$^-$ ions.

Calculations:

$0.100 \text{ M CuCl}_2 = (\frac{0.100 \text{ mol}}{\text{ L}}) \times (\frac{1 \text{ mol Cu}^{2+}}{1 \text{ mol CuCl}_2}) = 0.100 \text{ M Cu}^{2+}$

$0.100 \text{ M CuCl}_2 = (\frac{0.100 \text{ mol}}{\text{ L}}) \times (\frac{2 \text{ mol Cl}^-}{1 \text{ mol CuCl}_2}) = 0.200 \text{ M Cl}^-$

Note: This is simply a particle representation showing a formula unit of CuCl$_2$. It does NOT represent all Cu$^{2+}$ and Cl$^-$ ions in the solution.

**FIGURE 4.20** (A) One formula unit of CuCl$_2$ consists of one Cu$^{2+}$ ion and two Cl$^-$ ions. (B) For every formula unit that dissolves in water, one aqueous Cu$^{2+}$ ion and two aqueous Cl$^-$ ions form.
Question 8: How many moles of chloride ions are in 0.2 L of a 0.5 molar AlCl₃ solution?

Dilution

From the text (Chapter 4.1): Suppose you taste your lemonade and find that it is too sweet, how might you make it less sweet? The easiest way is to add more water, adding more water to lessen its concentration dilutes the lemonade. To lower the concentration of a solution, we use the process of dilution, or adding more solvent to a solution, as depicted in Figure 4.21. In this process, the relative numbers of solute and solvent particles change. Adding more solvent increases the number of solvent particles and increases the volume. For a given amount of the original solution, the number of solute particles stays the same, but they are now spread out through a greater volume, so their concentration is less.

Dilution proceeds from higher concentration to lower concentration where adding solvent reduces the concentration. Dilution is almost never carried out by removing solute from the solution. Think how difficult it would be to remove sugar from your glass of lemonade, now think how easy it is to simply add more water!

Process of Dilution

FIGURE 4.21 (A) A pipet is used to accurately measure 25.00 mL of 1.000 M CuSO₄ solution and (B) deliver it into a 250.0-mL volumetric flask. (C and D) water is added with swirling until the diluted solution fills the flask to the marked level. (E) As water is added, the amount of water increases, leading to a lesser concentration of solute. A stopper is placed in the flask, and the flask is inverted several times to completely mix the solution. The number of Cu²⁺ ions and SO₄²⁻ ions in a given volume of solution decreases, but the total number of Cu²⁺ ions and SO₄²⁻ ions in the flask is constant. The new solution has a concentration of 0.1000 M.

Question 9: In performing dilutions, what part(s) of the solution (solute, solvent, concentration, components) is NOT changed?
Calculations Involving Dilutions
The number of moles of solute contained in the volume of the more concentrated solution \( V_{\text{conc}} \) is found by multiplying the molarity \( M_{\text{conc}} \) of this solution by its volume in liters:

\[
\text{moles}_{\text{conc}} = M_{\text{conc}} \times V_{\text{conc}}
\]

Since we are adding only solvent, the moles of solute do not change upon dilution, so the moles of solute before and after dilution are equal:

\[
\text{moles}_{\text{conc}} = \text{moles}_{\text{dil}}
\]

The moles of solute in the diluted solution also equal the product of molarity \( M_{\text{dil}} \) and volume \( (V_{\text{dil}}) \) in liters, where the volume is the total volume after dilution:

\[
M_{\text{dil}} \times V_{\text{dil}} = M_{\text{conc}} \times V_{\text{conc}}
\]

We can rearrange this equation to solve for the molarity of the diluted solution:

\[
M_{\text{dil}} = \frac{M_{\text{conc}} \times V_{\text{conc}}}{V_{\text{dil}}}
\]

**Example Question (possible exam questions):** You are given 0.1000M NaCl solution. Initially, this solution has a volume of 25mL. Upon dilution, the new volume is found to be 250mL. Find the molarity of the diluted solution.

\[
M_{\text{dil}} = \frac{0.1000M \times 0.02500L}{0.2500L} = 0.01000M
\]

(Note: The final volume is given here correctly as 0.2500 L or 250.00 mL. What would the final volume be if the questions stated that 250.00 mL of water had been added to the initial volume? How would this change the new concentration? - Please always read the questions very carefully!)

Question 10: (Possible exam questions): If the volume of a solution stays the same but you double the amount of solute, how does the concentration of the solution change?
10. Chemical Reactions:

Chemical reactions

What to expect in this chapter:

A chemical reaction is the change of one substance or a set of substances into another. The starting material(s) is called reactant(s); the newly formed substances are called products. Products are different from reactants in the arrangement of their component atoms and, therefore, also their properties. It is important to mention at this time that chemical reactions neither destroy atoms nor create new atoms; atoms are just rearranged to form new products. This rearrangement happens because the bonds that hold atoms together on the reactant side will be broken, and new bonds are formed to form new products.

This chapter discusses common, observable signs that chemical reactions happen and talk about how chemical reactions are represented through a chemical equation using chemical symbols, and particle representations. This chapter also introduces different categories of chemical reactions and how these can be used to predict reaction products.

Consider the reaction of hydrogen gas with oxygen gas, as shown in Figure 5.5. Hydrogen and oxygen both occur naturally as diatomic molecules; if they mix, they react slowly, but if ignited, the reaction is vigorous, even explosive. In either case, the reactants form the same product: gaseous water molecules, each containing two hydrogen atoms and one oxygen atom.

![A reaction of hydrogen gas and oxygen set on fire.](image)

Symbolic Representation: \(2\text{H}_2(g) + \text{O}_2 \rightarrow 2\text{H}_2\text{O}(g)\)

Figure 5.5

Now consider the arrangement of atoms in Figure 5.6. What are oxygen atoms attached to in the reactants? In the products? How many hydrogen atoms? In the reactants, each hydrogen atom is attached to another hydrogen atom, and each oxygen atom is attached to another oxygen atom. In the products, two hydrogen atoms are attached to one oxygen atom, the number of atoms is the same, but their arrangement is different.
How do we know a chemical reaction occurs:

Just as artists use paint and stone to create works of art, chemists use elements and compounds to create new substances; both the artist and the chemist are constrained by the materials accessible to them; both must work within the rules of nature regarding the properties and behaviors of their materials.

The clues most often used by chemists are the following:

- Change in color
- Production of light
- Formation of a solid (such as a precipitate in solution, smoke in the air, or a metal coating)
- Formation of a gas (bubbles in solution or fumes in the gaseous state)
- Absorption or release of heat (sometimes appearing as a flame)

Did you come across any clues that don’t fit one of these categories?

Figure 5.8 illustrates some of these chemical reactions.
Figure 5.8 Do any of these photos of chemical reactions illustrate items on the list you made of nature’s clues that a chemical reaction has occurred?

(A) \( I_2(aq) + NaI(aq) \rightarrow \text{starch}(aq) \)
(B) \( Mg(s) + O_2(g) \)
(C) \( Ba(OH)_2 + 8H_2O(s) + NH_4Cl(s) \)
(D) \( Cu(s) + HNO_3(aq) \)
(E) \( BaCl_2(aq) + Na_2SO_4(aq) \)
(F) \( CH_4(g) + O_2(g) \)
(G) \( AgNO_3(aq) + glucose(aq) \)
(H) \( CaCO_3(s) + HCl(aq) \)

(i) Question 1: Xenon gas reacts with fluorine gas to form Xenon tetrafluoride gas. Identify which image represents reactants and then which image represents products.

Writing chemical equations:

Describing chemical reactions in words is awkward and time-consuming; for this reason, chemists use a chemical equation to show what reactants are involved and what products are created. A chemical equation is a symbolic representation of a chemical reaction in the form of symbols and formulas, where the reactants are on the left-hand side of the arrow and the products are on the right-hand side of the arrow. The equation must be balanced. In a balanced equation, the number of atoms of each element is the same in the products as in the reactants.

Question 2: please summarize in one sentence and in your own words the paragraph above?

Let’s work through writing and balancing the thermite reaction. In words, it looks like this:

Aluminum + Iron (III) oxide → Aluminum oxide + Iron

\[ Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + Fe(l) \]
This equation is not yet complete because it is not balanced, the same number of atoms of each
element must appear on both sides of the arrow. In its present form, it has the following numbers
of atoms:

<table>
<thead>
<tr>
<th># of atoms (reactants)</th>
<th># of atoms (products)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Al</td>
<td>2 Al</td>
</tr>
<tr>
<td>2 Fe</td>
<td>1 Fe</td>
</tr>
<tr>
<td>3 O</td>
<td>3 O</td>
</tr>
</tbody>
</table>

Therefore, we need to balance the equation with coefficients:

\[ 2 \text{Al}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + 2 \text{Fe}(s) \]

Question 3: Write complete, balanced equations for each of the following reactions.
(a) Sodium metal reacts with oxygen gas to form solid sodium oxide.
(b) Solid copper (II) nitrate is heated to produce solid copper (II) oxide, gaseous nitrogen
dioxide, and oxygen.

To see how and why equations balance, use a model kit or gummydrops and toothpicks to build
models of reactant molecules, take them apart and rearrange them into product molecules. Use
the smallest number of atoms possible to achieve conservation of mass. Reactions don’t actually
occur this way, but we want to emphasize the conservation of atoms in reactions as a means of
balancing equations.

A general approach to balancing equations

1. Write correct formulas for reactants on the left side and products on the right side of the
   arrow.
2. Look for elements that appear only once on each side of the equation.
3. Do not change the subscripts! Changing subscripts in a formula would change the
   identity of the substance.
4. The atoms to be balanced should be those in elemental substances.
5. Make a final check by counting the atoms of each element on both sides of the equation.

Question 4: Balance the following chemical reactions
(A) \( \text{Ba}(s) + \text{HCl}(aq) \rightarrow \text{BaCl}_2(aq) + \text{H}_2(g) \)
(B) \( \text{Na}_2\text{CrO}_4(aq) + \text{Pb(NO}_3)_2(aq) \rightarrow \text{PbCrO}_4(s) + \text{NaNO}_3(aq) \)

Predicting chemical reactions:
In all the chemical reactions we have considered so far, the identities of the reactant and products are known; the identity of the reactants is easy enough since we usually know what we have mixed. But how do we know what products will result? The answer could be from an experiment.

Classes of Chemical reactions:

<table>
<thead>
<tr>
<th>Class</th>
<th>Reactants</th>
<th>Products</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition</td>
<td>1 compound</td>
<td>2 elements (or smaller compounds)</td>
<td>CD → C + D</td>
</tr>
<tr>
<td>Combination</td>
<td>2 elements or compounds</td>
<td>1 compound</td>
<td>A + B → AB</td>
</tr>
<tr>
<td>Single displacement</td>
<td>1 element and 1 compound</td>
<td>1 element and 1 compound</td>
<td>A + CD → C + AD</td>
</tr>
<tr>
<td>Double displacement</td>
<td>2 compounds</td>
<td>2 compounds</td>
<td>CD + EF → CF + ED</td>
</tr>
</tbody>
</table>

Decomposition:

When a compound undergoes a decomposition reaction, it breaks down into the elements of which it is composed or into simpler compounds; it yields two or more products.

\[ 2\text{HgO}(s) \xrightarrow{\Delta} 2\text{Hg}(l) + \text{O}_2(g) \]

*Figure 5.13* when solid mercury (II) oxide, HgO, is heated, it decomposes into liquid mercury metal and oxygen gas.
The oxide ions lose their negative charge as they are converted to oxygen atoms. The mercury (II) ions lose their positive charge to form mercury atoms.

**Question 5:** Complete and balance the following decomposition reactions

(a) \( CaCO_3(s) \rightarrow \)

(b) \( CuSO_4 \cdot 5H_2O \rightarrow \)

**Combination reactions:**

In a combination reaction (also called synthesis), two substances react to produce a single compound.

\[
2Al(s) + 3Br_2(l) \rightarrow 2AlBr_3(s)
\]

![Figure 5.16](image)

*Figure 5.16* Aluminum reacts with bromine to form aluminum bromide.

![Figure 5.19](image)

*Figure 5.19* : The combination reaction of carbon monoxide and oxygen shown on a molecular level.

\[
2CO(s) + O_2(g) \rightarrow 2CO_2
\]
Question 6: Complete and balance the following combination reactions
(a) $Ca(s) + N_2(g) \rightarrow$
(b) $Al(s) + O_2(g) \rightarrow$

Single displacement:
In a single displacement reaction, a free element displaces another element from a compound to produce a different compound and a different element.

$$2Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + 2Fe(l)$$

Figure 5.20 calcium reacts with water to form aqueous calcium hydroxide and gaseous hydrogen.

$$Cu(s) + 2AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2Ag(s)$$

Copper atoms are converted to copper (II) ions, and silver ions are converted to silver atoms. Nitrate ions remain unchanged in solution.

Question 7: Complete and balance the following single displacement reactions
(a) $Zn(s) + AgNO_3(aq) \rightarrow$
(b) $Na(s) + FeCl_2(s) \rightarrow$

Double displacement:
In all double displacement reactions, two compounds exchange ions or elements to form new compounds.
Figure 5.26 When solutions of barium chloride and sodium sulfate mix, a precipitate of barium sulfate forms, leaving sodium chloride in the solution.

\[ \text{BaCl}_2(aq) + \text{Na}_2\text{SO}_4(aq) \rightarrow \text{BaSO}_4(s) + \text{NaCl}(aq) \]

Question 8: complete and balance the following double displacement reactions.

(a) \( \text{BaCO}_3(s) + \text{H}_2\text{SO}_4(aq) \rightarrow \)

(b) \( \text{CuCl}_2(aq) + \text{AgNO}_3(aq) \rightarrow \)
11. Limiting Reactants:

Limiting Reagents

What to expect in this chapter:

Why don’t we use the exact amounts of each reactant that is needed for a chemical reaction? Small errors can always lead to a slight excess of one reactant that might contaminate the product. To ensure that a selected reactant is used completely, we might use an excess of the other reactant.

In this chapter, we will get an understanding of which reactant limits the amount of the product that can form, by identifying the limiting reactant, we will look at the limiting reactant of a molecular level and also do some mathematical investigation of the limiting reactant.

Limiting Reactants (or also called Limiting “Reagents”)

Using exact stoichiometric amounts of reactants is often not the most practical thing to do when conducting an experiment in the lab. Why is this?

Think about what has to happen on a particle level during a chemical reaction to actually form a product. Also, think about the reaction of hydrogen molecules (H₂) and oxygen molecules (O₂) to form water (H₂O).

Question 1: Describe what has to happen in a reaction vessel that contains oxygen and hydrogen molecules in order to form water! Is the interaction between the gaseous molecules necessary?

A reactant is a substance that we start a reaction with, it takes part in and undergoes change during a reaction, and a product is what’s formed during a reaction. The number and kind of atoms on the reactants side of the equation are the same as the number and kind of atoms in the products.

What exactly is a “limiting reactant”?

Definition: The limiting reactant in a chemical reaction is the reactant that determines the maximum quantity of product that can be formed; the amount of product made is limited by this reactant, since the reaction can’t continue without it. The limiting reactant usually reacts completely in a chemical reaction.

To better understand limiting reactants, let’s look at a system that is not a chemical reaction.

Suppose someone wants to build a model solar-powered car.

He needs 1 frame, 1 solar cell, 1 electric motor, and 4 wheels (Figure below).

We can write an equation (like a chemical equation) to represent the numbers of parts required to make one car:

1 frame + 1 solar cell + 1 electric motor + 4 wheels → 1 model solar car

or in terms of “particles”
The equations show the amount and type of parts that are needed to build exactly one solar car. This is comparable to a chemical reaction with reactants and product(s) that show the ratios of reactants needed to form the product(s); these ratios/amounts indicated through the stoichiometric coefficients are called stoichiometric amounts.

Question 2: Summarize in your own words the main idea expressed in the paragraph above.

What if you are given a certain amount of parts different from the “stoichiometric” amounts? How do you figure out what the limiting reactant is, and how much product can you obtain?

Solution:

You need to compare the needed amounts of reactants with the available amounts of reactants and then determine the maximum amount of product possible.

Needed amounts for one car
Given amounts of reactants

Check how many cars you could build with the given amounts of each reactant. The reactant that allows for the least amount of product (cars) is the limiting reactant!

The maximum number of cars that can be built with each type of car part.....

Therefore, the maximum number of cars that can be built from the available parts is 3; the sets of wheels are the limiting reactant.

Excess, unused material; “leftover reactant”.

Chemical example

Silver bromide, known for its unusual sensitivity to light, is used in photographic films is prepared by the reaction of magnesium bromide and silver nitrate solutions.

\[ \text{MgBr}_2 + 2\text{AgNO}_3 \rightarrow 2\text{AgBr} + \text{Mg(NO}_3\text{)_2} \] (reaction is conducted in aqueous solution)
As this equation suggests, using twice the molar amounts of silver nitrate compared to magnesium bromide will ensure that both reactants completely react, and the maximum amount of product can be obtained.

This is the ideal, theoretical scenario but is often not realized under laboratory conditions.

So what can be done?

Magnesium bromide is usually used in excess to ensure that all of the more expensive silver nitrate is used completely.

Question 3: If magnesium bromide is used in excess in the reaction, which substances will be in the mixture once the reaction is completed?

More practical information about reactants in excess:

When gas burns in a car engine, we rely on oxygen in the air to support the combustion; we do not worry about running out of oxygen. A chemist would say that oxygen is in excess for the reaction.

When the space shuttle is in space, however, there is no air to provide oxygen; the shuttle must take the right amounts of hydrogen and oxygen with it. If too much of one reactant were transported, the extra reactant would have nothing to react with; it would simply add extra mass to the shuttle. Mass-mass calculations are important in such situations.

When a space shuttle takes off, it leaves with measured amounts of hydrogen and oxygen so that no extra mass is added. Many reactions, however, occur with an excess of one reactant.

Consider a single-displacement reaction between magnesium metal and aqueous hydrochloric acid:

$$\text{Mg(s)} + 2\text{HCl (aq)} \rightarrow \text{MgCl}_2(\text{aq}) + \text{H}_2(\text{g})$$

How do we know if all of each reactant is used up in the reaction?

If one of the reactants does not react completely, there will be some of it leftover at the end of the reaction; the leftover amount will be present mixed with the product, as shown in Figure 6.7 on the following page.
**FIGURE 6.7**: When reactants are not mixed in relative amounts as described by the balanced equation, one reactant does not react completely. (A) Here magnesium metal reacts with hydrochloric acid to form magnesium chloride in solution and hydrogen gas.

**Question 4**: When the reaction is complete (see Figure 6.7), one reactant remains in excess. What is the excess reactant in beaker B? And in beaker C?

If we do not want any unreacted magnesium or hydrochloric acid left over, we should mix the reactants in the proper (stoichiometric) quantities so that their mole ratio (NOT mass ratio!!) is the same as that shown by the coefficients in the balanced equation.

*If the reactants mixed together are not present in the exact mole ratio, then we will have too much of one reactant and not enough of another, one reactant reacts completely, and some of the other is left unreacted.*

**Identifying the Limiting Reactant**

Iron metal is added to an aqueous solution, (which is a solution that has water as its solvent) of copper (II) chloride. The solution is blue because copper (II) ions in the solution produce a blue color; when the reaction is complete, the solution is colorless. The piece of iron is coated with a granular, brownish-black metal.

**Which compound is the limiting reactant in this reaction?** You do not have enough information to determine the limiting reactant through calculation? Do you have visual signs that give you a clue? Explain!

![Images of iron and copper solutions]

**Limiting Reactant - On the molecular level**

Now let's look at what occurs at the molecular level in a reaction that has a limiting reactant.

Let's review the combustion of hydrogen to form water, the molecular-level diagram, and the balanced equation in **Figure 6.9** show that the molecule ratio of \(H_2\) to \(O_2\) is. The molecule ratio is the same as the mole ratio because both are related to the coefficients in the balanced equation.
Reactants are available in "stoichiometric" molar amounts.

$$2\text{H}_2 (g) + \text{O}_2 (g) \rightarrow 2\text{H}_2\text{O} (g)$$

**Figure 6.9:** For every 2 $\text{H}_2$ molecules that react, 1 $\text{O}_2$ molecule reacts with it to form 2 $\text{H}_2\text{O}$ molecules.

In this chemical reaction, the reactant molecules are the "parts" that combine in a specific ratio to make the product $\text{H}_2\text{O}$ molecules.

If the number of $\text{H}_2$ molecules mixed is exactly two times the number of $\text{O}_2$ molecules, then all the $\text{H}_2$ and $\text{O}_2$ molecules will react, and no reactants will be leftover.

**OR**

If the ratio of $\text{H}_2$ to $\text{O}_2$ molecules mixed together is not exactly, then one reactant is the limiting reactant, and the other is in excess.

For example, suppose 8 molecules of $\text{H}_2$ are mixed with 5 molecules of $\text{O}_2$, as shown in Figure 6.10 (next page). The reactant ratio is not the same as in the balanced chemical reaction, so only one of the reactants is completely consumed. The other is in excess.

After the reactants combine in this 2 to 1 ratio, 8 $\text{H}_2\text{O}$ molecules form.

The $\text{H}_2$ reactant is the limiting reactant because it was completely used up; it limited the number of $\text{H}_2\text{O}$ molecules that could form. The $\text{O}_2$ reactant is left over, it was in excess.

When the reaction is complete, the 1 leftover $\text{O}_2$ molecule that did not react will also be present in the reaction mixture along with the 8 $\text{H}_2\text{O}$ molecules that formed.
FIGURE 6.10: Reaction of H₂ and O₂ in non-stoichiometric amounts.

Question: How can you increase the amount of product (H₂O) in Figure 6.10 that is being formed? Do you add more oxygen or more hydrogen to the reaction mixture?

Mathematical investigation of limiting reactants

How can you determine the limiting reactant mathematically?

You need to compare the molar amounts of two (or more) reactants; the molar amount is the numerical value of the Avogadro constant, it has the unit mol⁻¹, and depicts the molar mass of an amount of substance to its mass.

Here is what you have to do:

Step 1: Calculate the molar amount for each reactant, if you have the masses of the reactants given, divide by the molar mass.

Example (using the reaction between molecular hydrogen and molecular oxygen above):
Assuming the reaction mixture will contain 4.0 grams of hydrogen and 5.0 grams of oxygen.

For hydrogen:

\[ 4.0 \text{ g H}_2 \times \frac{1 \text{ mol}}{2.016 \text{ g}} = 1.98 \text{ mol H}_2 \]

For oxygen:

\[ 5.0 \text{ g O}_2 \times \frac{1 \text{ mol}}{32.0 \text{ g}} = 0.16 \text{ mol O}_2 \]

So far you calculated the available molar amounts of reactants.
Step 2: Using the stoichiometric coefficients from the balanced equation calculate the molar amount of one reactant needed to react completely with the other reactant.

Let's start with 1.98 mol of hydrogen and using the stoichiometric coefficients from the balanced chemical equation, calculate the exact amount of oxygen needed to react completely with 1.98 mol hydrogen. (Note: You could also start with the molar amount of oxygen, 0.16 mol.)

\[
1.98 \text{ mol H}_2 \times \frac{1 \text{ mol O}_2}{2 \text{ mol H}_2} = 0.99 \text{ mol O}_2
\]

Your result shows that you need 0.99 mol of oxygen to react completely with 1.98 mol H₂, but you just have 0.16 mol available (see the result of Step 1).

What does that mean?

You have less oxygen available (0.16 mol) than you would need to completely react with 1.98 mol of hydrogen, therefore oxygen is the limiting reactant since it limits the amount of water (product) that can be produced.

**Question 7:** (possible exam question, relating to reaction above) Which reactant would be the limiting reactant if you had 1.16 mol of oxygen available? Explain!

**Question 8:** (Possible exam question)

Given the reaction vessel and the balanced chemical reaction, what is the limiting reactant?

Each symbol represents 1 mol of molecules of the substance.

\[2\text{C}_2\text{H}_2(\text{g}) + 5\text{O}_2(\text{g}) \rightarrow 4\text{CO}_2(\text{g}) + 2\text{H}_2\text{O}(\text{l})\]

A. \(\text{C}_2\text{H}_2\)  B. \(\text{O}_2\)  C. \(\text{CO}_2\)  D. \(\text{H}_2\text{O}\)
12. Ideal Gases:

THE IDEAL GAS LAW

What to expect in this chapter:

The properties and behavior of gases are often not easy to observe. Some properties of gases are easy to see, e.g., when an air-filled balloon decreases in size when cooled down in the refrigerator (gas volume decreases!), but it is much more difficult to imagine what happens to gas particles in these situations. The properties of gas particles—whether we talk about gaseous atoms (e.g., Ne, He, Ar) or gaseous molecules (O₂, N₂, CH₄, H₂O) depend on a couple of variables, such as the volume (V), temperature (T), pressure (P), the amount of gas (n), and sometimes also the identity of the gas (what type of gas). All these variables explain why we observe macroscopic properties of gases but to really understand them, we need to look at gases at the particle level as well.

In this chapter, you will be introduced to gas laws that explain the relationships between the properties (V, T, P, n) and how you can use them to calculate and predict gases’ behavior.

Some of these particle properties are:

- Gases consist of particles that are relatively far apart.

Gas particles fill a container by evenly spreading out; the large spaces between particles explain why gases have much lower densities than liquids and solids. Because gases have so much empty space, which has a large amount of kinetic energy, it is easy to compress them into smaller volumes by applying external pressure.

- Gas particles move rapidly.

For example, the average velocity of oxygen gas molecules (O₂) at 20°C and normal atmospheric pressure is 0.44 km/s (980 mi/h).
• Gas particles have little effect on one another unless they collide.

Gas particles have only a small amount of attraction for one another at normal temperatures and pressures, so they move about freely in all directions, and in straight lines until they collide. When they collide, gas particles simply bounce off of each other, and total kinetic energy is conserved.

• Gases expand to fill their containers.

Gases take the volume and shape of their containers as a consequence of their random motion.

Now you've heard a lot about gases, and some descriptions include phrases such as "at 20°C and normal atmospheric pressure" or "at normal temperatures and pressures."

This indicates, that the properties depend greatly on certain variables. The main relationship between the four important variables that determine the properties of gases are:

From the text (Chapter 9.3): The properties of gases can be described by the four variables pressure (P), volume (V), absolute temperature (T), and the number of moles (n). Suppose we want to describe a gas under a specific set of static conditions; the relationships among the individual gas laws can be manipulated to give us a general equation that relates volume, pressure, temperature, and amount of gas.

Important relationships (or interdependencies) between these variables that are being discussed in this course are:

1) Boyle's Law: \( V \propto \frac{1}{P} \), therefore two sets of conditions \( P_1 \cdot V_1 = P_2 \cdot V_2 \) (at constant \( n \) and \( T \))

   Principle: Volume and pressure are inversely related (when pressure increases, volume decreases and vice versa).

2) Charles' Law: \( V \propto T \), therefore two sets of conditions \( \frac{V_1}{T_1} = \frac{V_2}{T_2} \)

   Principle: Volume and temperature are directly related (when volume increases, temperature increases and vice versa). (at constant \( n \) and \( P \))

3) Avogadro's Hypothesis: \( V \propto n \), therefore two sets of conditions \( \frac{V_1}{n_1} = \frac{V_2}{n_2} \) (at constant \( V \) and \( P \))

   Principle: Volume and moles are directly related (when the amount of gas particles increases, volume increases and vice versa).

The combined gas law derives from these relations (Avogadro not included!)
Combined Gas Law: \[ \frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2} \] [at constant n]

When including Avogadro's law, an equation derives that is very useful to describe a gas under a single set of conditions; this combination of laws produces a single equation called the ideal gas law, which we will discuss here.

Since volume is proportional to each of the three factors, it must be simultaneously proportional to all of them:

\[ V \propto \frac{n \cdot T}{P} \]

Since these variables are proportionally related, we can use a constant to express an equivalent relationship (note: whenever a mathematical proportionality is converted into an equation, you need to introduce a constant)

\[ V = \text{constant} \times \frac{n \cdot T}{P} \]

Because it relates all the terms from the individual gas laws, we have a special name for the constant in this expression, the ideal gas constant, and we use \( R \) to represent it, substituting the ideal gas constant \( R \) into the expression, we obtain the following equation:

\[ V = \frac{R \cdot n \cdot T}{P} \]

Rearranging the variables results in the equation known as the ideal gas law:

\[ P \cdot V = R \cdot n \cdot T \]

Question 1: In which container in the image below will the gas pressure be higher? Please explain your answer?

Same amount of gas molecules in both containers.
Volume 1: larger container with more space.
Volume 2: smaller container with less space.
The ideal gas constant, \( R \)

An ideal gas is a gas that follows behavior predicted by the ideal gas law, using the observation that 1 mol of an ideal gas at STP occupies 22.414 L, we can calculate the value of \( R \) as follows:

Important Note: STP = Standard Temperature and Pressure (273.15 K and 1 atm).

\[
R = \frac{P \cdot V}{n \cdot T} = \frac{(1.000 \text{ atm}) \cdot (22.414 \text{ L})}{(1.000 \text{ mol}) \cdot (273 \text{ K})} = 0.08206 \text{ L \cdot atm \over mol \cdot K}
\]

This numerical constant is valid only if we measure volume in liters and pressure in atmospheres, the absolute temperature in Kelvin, and the amount of substance in moles. Measurements in other units must be converted to use this constant.

Review: an ideal gas is a gas that at 1 mol, a temperature of 273.15K, and 1 atm of pressure will occupy a volume of 22.414L.

From the text (Chapter 9.3): The ideal gas law includes all the information summarized by Boyle's law, Charles's law, and Avogadro's hypothesis. Like them, the ideal gas law is valid only for an ideal gas, it indicates that the volume occupied by an ideal gas is directly proportional to the absolute temperature and the number of moles of gas molecules, it is inversely proportional to pressure. A single equation that relates all the variables is a useful tool because, given any three values and the value of \( R \), we can calculate the unknown quantity.

Question 2: Please summarize the paragraph above, in your own words and in one sentence.

Question 3: What kind of assumptions are we making to call a gas “ideal”? Can you comment on the distance between gas particles, the interactions between them, and the volume of the particle itself? Are any of these aspects accommodated for in the Ideal gas law?

Calculations with the Ideal Gas Law

From the text (Ch. 9.3): To solve a gas law problem, we must first determine what is going on in the gas system and then select the appropriate mathematical relationship. For changes in volume, pressure, and temperature, we generally use the combined gas law (same as ideal gas law, but \( n \) is constant).

In contrast, the ideal gas law allows us to determine any one of the quantities volume, pressure, temperature, or moles of the gas given the other three. The law can also be used to
determine the densities of gases and if the identity of the gas is known, we can also calculate its mass using its molar mass.

Calculating density:

In order to calculate the density of a gas \( d = \frac{m}{V} \), the amount of gas \( n \) has to be expressed differently.

Using \( n = \frac{m}{MM} \) the ideal gas law reads as \( P \cdot V = \frac{m}{MM} \cdot R \cdot T \).

Now solving for density \( \left( \frac{m}{V} \right) \) results in \( \frac{m}{V} = \frac{P \cdot MM}{R \cdot T} = \text{density} \).

Calculating masses or molar masses

You can use the same expression above to solve for mass or molar mass of a gas:

For mass: \( m = \frac{P \cdot MM \cdot V}{R \cdot T} \).

For molar mass: \( MM = \frac{m \cdot R \cdot T}{P \cdot V} \) or, if the density is known, \( MM = \frac{m \cdot R \cdot T}{P} \) (with \( \frac{m}{V} = d \)).

Question 4: What is the density of neon at STP?

Calculating the amount (moles) of gas

From the text (Ch. 9.3): If we are given the \( P \), \( V \), and \( T \) conditions for a sample of gas, we can calculate the number of moles of the gas, using the ideal gas law, we need only rearrange the equation \( P \cdot V = n \cdot R \cdot T \) to solve for the number of moles. Remember that all the other quantities must be in units that match the value used for the ideal gas constant.

Example:

The volume of a propane cylinder is 0.960 L when filled, the cylinder contains liquid propane stored under pressure. When the cylinder is "empty," it contains propane gas molecules at
atmospheric pressure and temperature. How many moles of propane gas remains in a cylinder when it is empty if the surrounding atmospheric conditions are 25.0°C and 745 torr?

Solution:

1. Convert to the desired units of T and P:
   \[ T = 25.0°C + 273.15 = 298.2K \]
   \[ P = 745 \text{ torr} \cdot \frac{1 \text{ atm}}{760 \text{ torr}} = 0.980 \text{ atm} \]

2. Rearrange the ideal gas law and substitute the appropriate values to calculate the number of moles:
   \[ n = \frac{P \cdot V}{R \cdot T} = \frac{(0.980 \text{ atm}) \cdot (0.960 \text{ L})}{(0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}})(298.2 \text{ K})} = 0.0384 \text{ mol} \]

Ask yourself - does this answer seem reasonable? (This is a very important question to ask!!)

At standard temperature (273.15 K) and pressure (1.00 atm), 1 mol of an ideal gas occupies 22.414 L, the molar volume. In this case, the temperature is 25°C higher than standard, the pressure is close to standard pressure, and the volume is significantly less than the molar volume of a gas, we would expect significantly fewer moles of gas present in the cylinder under these conditions, and that's what our calculation shows.

Calculating the mass of gas (equation has been discussed above)

Once the number of moles of gas is determined from the ideal gas law, we can calculate the mass of the gas if we know its identity, knowing the number of moles, we can use the molar mass of the gas to convert moles to grams.

Now knowing the number of moles of propane and the identity of the gas, we can determine the mass of propane (you have done this type of calculation often before)

Answering the questions: What mass of propane, \( \text{C}_3\text{H}_8 \), is left in the cylinder of Example 1?

Solution:

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Recall that molar mass provides a relationship between moles of a substance and grams of that substance, the molar mass of propane is 44.10 g/mol. The mass of 0.0384 mol of propane can be determined by multiplying moles by molar mass:

\[
\text{mass} = 0.0384 \text{ mol } \text{C}_3\text{H}_8 \times \frac{44.10 \text{ g}}{1 \text{ mol } \text{C}_3\text{H}_8} = 1.69 \text{ g C}_3\text{H}_8
\]

If we know the mass and volume of a gas, we can now also determine its density.

Solution:

\[
d = \frac{m}{V} = \frac{1.69 \text{ g}}{0.960 \text{ L}} = 1.76 \frac{\text{g}}{\text{L}}
\]

Question 5: What is the mass of 15.0 L of methane at 10°C and 1.2 atm?