General Chemistry
Learning Outcomes

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About the Center for Curriculum Design

The Center for Curriculum Redesign (CCR) is a non-profit global organization dedicated to improving Education via answering the question, “What should students learn for the 21st century?”. CCR brings together international organizations, jurisdictions, academic institutions, corporations, and non-profit organizations including foundations. It focuses on both designing and propagating new curricula.

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Acknowledgments

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# Table of Contents

Introduction and Executive Summary........................................................................................................... 1

Project Goals and Definition of Learning Outcomes.................................................................................... 1

Project Approach ............................................................................................................................................. 1

Feedback......................................................................................................................................................... 5

Key Understandings......................................................................................................................................... 6

Core Concepts ................................................................................................................................................ 12

Definition of Priority and Optional Sub-LOs.................................................................................................. 14

Technology...................................................................................................................................................... 14

Prerequisites .................................................................................................................................................. 15

Other Pedagogical Remarks......................................................................................................................... 16

General Chemistry Learning Outcome Framework....................................................................................... 17

  MODULE 1: Atomic Structure and Properties .............................................................................................. 17

  MODULE 2: The Particulate Nature of Matter ............................................................................................ 29

  MODULE 3: Molecules are Three-Dimensional ......................................................................................... 40

  MODULE 4: Intermolecular Interactions and the Properties of Molecular Matter ................................... 52

  MODULE 5: Physical Stability and Change ............................................................................................... 62

  MODULE 6: Chemical Stability and Change ............................................................................................. 76

  MODULE 7: Determining How Chemical Change Occurs ........................................................................ 89

  MODULE 8: Harnessing Chemical Energy ............................................................................................... 101

  MODULE 9: Acid-Base Chemistry and Chemical Synthesis ....................................................................... 108

  MODULE 10: Acid-Base Chemistry and Chemical Analysis ..................................................................... 119

Recommended Resource Material.................................................................................................................. 130
Introduction and Executive Summary

Project Goals and Definition of Learning Outcomes
Our goals are to benchmark and develop a set of faculty and discipline-association aligned and equity-centered learning outcomes for General Chemistry. For the purposes of this work, we define learning outcomes as measurable student performance expectations based upon what the student learned in each core topic area.

Project Approach
This work represents a codified process and scalable approach to developing faculty and discipline-association aligned learning outcomes that function as measurable instructional goals for faculty teaching these courses; domain associations endeavoring to codify essential undergraduate domain knowledge; courseware providers developing rich, interactive, and adaptive curriculum resources to support instruction and assessment in gateway courses; and students as consumers and buyers of college credits to better understand the core knowledge and competencies they should gain by the completion of General Chemistry. Course curriculum is defined as the organizing principles, essential and factual content, and procedures that constitute the knowledge base of a domain. Quality curriculum includes structured learning activities that foster problem-solving and inquiry enabling students to both encode new knowledge based on prior knowledge and transfer new knowledge into additional contexts.

The Center for Curriculum Redesign (CCR) is a Boston-based international non-profit research and “education engineering” organization working with educators, researchers, organizations, associations and thought-leaders to define a 21st-century curriculum for students in K-12 and Higher Education. CCR was selected by the Bill and Melinda Gates Foundation to lead this demonstration project because:

1. Global reputation: CCR was founded by Chairman/CEO Charles Fadel in 2012 with the goal of reshaping the “What” of Education in the context of social and economic justice/equity, which are being amplified by new technologies (AI, Biotech, etc.) and planetary-wide problems (global warming, pandemic, etc.). CCR has extensive experience managing large-scale curriculum redesign and
learning outcomes development projects for global organizations such as the Organization for Economic Cooperation and Development (OECD). Its organizational focus on K-12 and Higher Ed, using innovative approaches based on science- and evidence-based, precise, and diligent processes have led CCR to become the only strategic partner to the OECD’s Education Directorate (PreK-20), with a decade-long relationship. CCR has a decade-long track record of developing equity-minded and social justice-centered policy recommendations, tools, resources, methodologies, and frameworks for making education more relevant for the 21st century and better prepare all students - particularly historically marginalized students - for life and work in a rapidly changing global economy.

2. CCR is the leading organization in Competencies - aka “21st Century Skills” and “Social-Emotional Learning” (SEL) - development, developing a sophisticated yet actionable competencies/sub-competencies framework to include 21st-century workforce skills - in addition to “Knowledge” and describes precise implementation at the instructor level, as well as formative assessments.

3. Equity is a centerpiece of this framework, as there are explicit intersections between the sub-competencies and elements of social justice.

4. Curriculum expertise: CCR is presently developing a new test called the “Primo” option for the OECD based on modern mathematics encompassing six major topics (stats/probability, Bayesian probability, exponentials, algorithms, complex systems, game theory).

5. Technology tools for deeper human analysis: CCR has made ongoing investments in technology tools to help synthesize and speed up the comprehension of deep structures in Knowledge and Competencies and their deployment to include analyzing the competency employment needs of industry. CCR’s pre-authoring environment will help Courseware developers effectively develop a range of formative assessment types aligned to learning outcomes and access a robust equity-enabling instructional strategies database to incorporate key instructional tools into the curriculum to support faculty professional development for outcome-driven course design and delivery.
6. One key ongoing project CCR is heading is to modernize the OECD’s global PISA test, by incorporating high-impact-but-low-algebraic-complexity mathematics, such as probability and statistics and discrete and computational math.

CCR combines a rigorous methodology which includes collection and analysis of multiple points of data as well as collaborations that encourage creativity to break down boundaries and highlight salient innovations for inclusion in a modern curriculum in the various disciplines.

**Higher Education Gateway Courses**

Each year, more than three million students enroll in roughly 20 general education courses in US higher education. According to research from the National Center for Academic Transformation (NCAT), just 25 courses generate roughly half of all student enrollments in community colleges and about a third of enrollments in four-year institutions. Successful completion of these courses is key to student progress toward a quality degree or credential. The Gardner Institute has identified these “gateway courses” as foundational, credit-bearing, lower-division courses, for which large numbers of students are at risk of failure, and thus stand as “gatekeepers” to degree completion.

For this project, CCR’s charter is to undertake a demonstration project to define the measurable, specific learning outcomes for four key undergraduate gateway courses, and for which successful completion is critical for college success. These four courses are Introductory Statistics, General Chemistry, Introductory Psychology, and Introductory Sociology.

For the demonstration project, CCR focused on General Chemistry, due to the following factors:

- Presents compelling opportunities for complementary exemplars with potential to impact our focus students while also driving market innovation and setting a new standard for excellence in the market.
- Courses can suffer from “mile-wide, inch-deep” approaches to content and assessments that rarely if at all elicit evidence of student understanding of chemistry’s core concepts; thus, General Chemistry can be an inequitable
gatekeeper for many, including underrepresented minorities, students of low socioeconomic status, and women. Drop-fail-withdraw-incomplete (DFWI) rates vary from institution to institution but can be as high as 50%.

- Historically offered as a requirement in its related domain of study as well as numerous allied STEMM pathways. Given the increasing number and diversity of undergraduate STEMM pathways being offered, General Chemistry has extremely high enrollments and is often one of the largest service courses at any institution. Targeting high enrollment courses also increases the potential to recruit sufficient numbers of students from our priority populations to enable rigorous research design.
- Offers opportunities to test various content approaches to improving student learning outcomes such as engaging students in relevant models and analysis.
- Has synergies with exemplars of excellence in features and function for equity-centered courseware that addresses gaps in availability, curriculum alignment between learning outcomes, activities, and assessments.

To advance the work, CCR worked with a team of experienced faculty currently teaching General Chemistry. Additionally, equity experts in the field of chemistry were commissioned to guide the development of course learning outcomes, discipline core concepts, key missing topics, and profound examples to enliven the concepts and equity focus of the work.

The lead subject matter expert for the General Chemistry Learning Outcomes is Dr. Sam Pazicni. Dr. Pazicni is on the faculty in the Department of Chemistry at the University of Wisconsin–Madison, leads a research group focused on chemistry education, and teaches General and Inorganic Chemistry at the undergraduate level. He is an active member of the American Chemical Society (ACS), serves on the ACS Committee on Education, and served as the co-chair of the ACS General Chemistry Performance Expectations initiative. He has also been involved with the Advanced Placement Chemistry program as a 2022 AP Chemistry Visiting Fellow and a member of the AP Chemistry Development Committee. Dr. Pazicni also regularly leads workshops on assessment, course design, and equity in teaching, in venues associated with the ACS and the Cottrell Scholars Collaborative.
About General Chemistry

Chemistry is so closely connected with other scientific disciplines and so integral to understanding the phenomena of everyday life that it is often referred to as “the central science.” The introductory chemistry course often named “General Chemistry” is typically selected by STEMM and/or pre-professional students who will likely take additional chemistry courses or related courses in other disciplines beyond the introductory experience. General Chemistry is operationalized at most institutions as a full-year course, where the first semester serves as a prerequisite to the next; however, modifications are often adopted for specific student populations (e.g., a one-semester course for students with strong prior preparation) or alternative academic calendar formats (e.g., a three-quarter sequence). General Chemistry very often includes a laboratory component or is associated with an introductory chemistry laboratory course. Because of the varying models of how laboratory experiences are taught and integrated with the General Chemistry lecture, this work does not include laboratory learning outcomes in its scope. This work is built upon the insightful work of others, most notably A Framework for K–12 Science Education, the American Chemical Society General Chemistry Performance Expectations Project, the National Research Council report Beyond the Molecular Frontier, and existing curricula such as Advanced Placement Chemistry; Chemistry, Life, the Universe, and Everything (CLUE); and Chemical Thinking.

Feedback

Please send any feedback on this document to HigherEdLOs@curriculumredesign.org.
Key Understandings

The following pages outline a learning outcome (LO) framework for a General Chemistry course. This LO framework was designed for a two-semester course sequence for a STEMM student audience, a common operationalization of General Chemistry at most colleges and universities. The 2003 NRC report *Beyond the Molecular Frontier* summarized the central goals and modern challenges of chemistry and suggested four main practices that characterize chemistry as a discipline: *analysis, modeling, synthesis, and transformation*. This LO framework adopts the perspective that one of these practices is more central to an introductory chemistry experience than the others: *modeling*. While the fundamental purpose of modeling is “How do I explain this?” modeling in chemistry is rooted largely in using models of submicroscopic particles to explain macroscopic phenomena. Engaging learners with the practice of modeling and supporting learners in using submicroscopic models to explain actual phenomena provides a firm foundation to explore analysis, synthesis, and transformation not only in a limited fashion via a General Chemistry course, but also in later chemistry courses or courses in allied disciplines. Thus, this LO framework challenges learners to be practitioners—to *develop models* (i.e., analyze and interpret data to yield an explanatory model) and *apply models* (adopting chemistry’s central models to explain a variety of phenomena).

The LO framework is anchored to three core concepts for chemistry (*forces govern organization, structure governs properties*, and *energy governs stability*), such that learners are expected to consistently apply these foundational concepts to explain and predict a wide variety of chemical phenomena. The framework presents one overarching LO for each of the ten topical Modules, organized in a rational sequence to support learners over time in deepening their understanding of and their experience with using these core concepts. For example, the LO “Explain atomic properties using models of atomic structure that show locations and/or energies of subatomic particles” is situated first so that learners can engage with the three core concepts in introductory ways in the context of chemistry’s basic building blocks (atoms), while the LO “Use models of structure and energy to describe how systems undergo chemical changes toward achieving equilibrium” is situated later in the course, when students have built a sufficient understanding of the three core concepts so as to engage with
the complex phenomenon of chemical reactions. While there is no perfect sequence of content to support the learning of these chemistry core concepts, some sequences will be more supportive than others. If a course developer creates an alternate sequence of overarching LOs, they should take care to articulate how doing so supports a deepening engagement with the core ideas over the year-long General Chemistry sequence.

Each Module is further delineated with a series of topical sub-modules, each with a series of sub-learning outcomes (sub-LOs) that support the learning of the Module-level LO. Color-coded articulations are provided to anchor the sub-module topic and sub-LOs to the three chemistry core concepts. Once again, the framework presents the sub-modules in a particular sequence that may be ideal for some instructors/developers, but not for others; thus, anyone who creates an alternate sequence of sub-modules within a Module should take care to articulate how doing so supports a rational learning progression.

- The LOs and sub-LOs take the form of statements of what learners should be able to do with their knowledge—in essence, how learners should be expected to “think critically” in the discipline of chemistry. This LO structure is consistent with modern notions of knowledge use in authentic contexts as well as evidence-centered design of assessments and learning support materials. So that they are grounded in authentic science practices, the LOs/sub-LOs are phrased according to the science practices outlined in NRC’s A Framework for K-12 Education. Given this LO framework’s commitment to the practice of modeling, the science practices of developing and using models, data analysis and interpretation, and constructing explanations appear more frequently; however, the practices of obtaining, evaluating, and communicating information, and using mathematical and computational thinking also appear as context dictates. Moreover, many LOs/sub-LOs describe multiple modalities in which learners can express their reasoning and understanding.

- Some sub-LOs are accompanied by articulations of potentially associated embedded abilities. Embedded abilities are defined here as potentially necessary to demonstrate learning/understanding of a particular LO/sub-LO, but alone do not demonstrate a knowledge of chemistry or its core concepts.
For example, a very common skill in General Chemistry is sketching Lewis models of molecular structure. Being able to perform this skill is very important in chemistry; however, drawing a Lewis model in isolation does not demonstrate an understanding of the core concept “structure governs properties.” Thus, although sub-LO 4.1.1 more or less requires a learner to use a Lewis model to communicate molecular structure, it does so in a way that also engages learners in the “structure governs properties” core concept and the science practice of developing and using models: “Construct a model using Coulomb’s law, molecular structure representations, and the concepts of LDFs, dipole-dipole interactions, and/or hydrogen bonding (when appropriate) to explain or predict trends in physical properties among matter composed of molecules.”

- Each sub-module contains a list of “articulations of important ideas/thinking.” These lists represent important topical points that the authors considered when designing the sub-modular connections to chemistry core concepts and the sub-LOs therein. These lists should not be considered an exhaustive unpacking of content, nor should they be considered requirements for explicit content coverage or pedagogy.

The authors of this General Chemical LO framework were committed to framing the introductory chemistry experience for a modern audience and context. To achieve this goal, the authors:

- Considered topical coverage from the perspective of (1) the chemistry practices outlined in the 2003 NRC report *Beyond the Molecular Frontier* (*analysis, modeling, synthesis, and transformation*) and (2) the three chemistry core concepts identified for this work (*forces govern organization, structure governs properties, and energy governs stability*); this is in contrast to considering content from a chemistry sub-disciplinary perspective (analytical, biochemistry, inorganic, organic, physical, etc.).

- Articulated how the LOs/sub-LOs emerge from examining content from the perspective of the three chemistry core concepts—demonstrating to instructors and developers how learners should use the chemistry core concepts to undergird any demonstrations of understanding; thus, rather than being a series
of potentially disconnected topics, this General Chemistry curriculum is united by using this core concept perspective to explain/predict chemical phenomena.

- Phrased LOs/sub-LOs according to *A Framework for K-12 Education’s science practices*, using recommendations from the Three-Dimensional Learning Assessment Protocol (3D-LAP). This science practitioner-focused approach contrasts with using more generic hierarchical taxonomies (e.g., Bloom’s or Marzano’s), where the same action word (e.g., “explain”) can be classified at different levels of cognitive process complexity based on context.

- Focused on connecting content and LOs/sub-LOs to example phenomena (including connections to UN Sustainability Goals). The Next Generation Science Standards defined phenomena as “…observable events that occur in the universe that we can use our science knowledge to predict or explain.” Linking defined phenomena to LOs/sub-LOs shows compelling applications, and though we consider each application to be a suggestion or example—not a requirement, phenomena should be central to a General Chemistry curriculum. Content knowledge, routine skills, etc. only matter if they enable learners to uncover how and why important phenomena occur, predict what may happen under new circumstances, or design solutions to pressing problems. Thus, while no LO/sub-LO is connected to a specific phenomenon, the LO framework encourages instructors and developers to connect course content to observable phenomena that are of relevance to learners.

The authors of this General Chemistry LO framework were committed to **(1) provide a culturally representative experience for all students** and **(2) counter inequities documented in the General Chemistry space**. While many considerations of equity and inclusion fall outside the scope of learning outcomes development, this LO framework incorporates three features to help faculty, course designers, and courseware developers to design learning environments that provide culturally relevant and equitable learning experiences for all students:

- Content domains and associated LOs/sub-LOs were connected by relevant examples aligned with the 2015 United Nations Sustainable Development goals. In particular, the American Chemical Society identified seven priority
Sustainable Development Goals that are used here: zero hunger, good health and well-being, clean water and sanitation, affordable and clean energy, industries, innovation, and infrastructure, responsible consumption and production, and climate action. Most sub-modules in the LO framework contain example connections to one or more UN Sustainable Development Goals. These are optional to the curriculum but serve as launch pad ideas for culturally relevant examples and relevant modern applications.

- Each sub-module posits example anchoring phenomena that can be used to make connections between sub-module content, sub-LOs, and how chemistry is helping to address questions that students may find relevant to their lives. The presentation of anchoring phenomena is consistent with a Funds of Knowledge approach, where developing an understanding of students’ overall sets of abilities and experiences can help instructors draw on these skills in learning environments to enrich students’ understanding of content while also motivating them during classroom activities. Thus, example anchoring phenomena are optional and serve as a support for the development of materials which can aid instructors in building learning environments around the personal contexts, skills, and experiences of students, which will help students scaffold their understanding of material.

- Recent chemistry education research has demonstrated that assessments (and presumably the LOs on which those assessments were built) preferring mathematical manipulations over understanding chemistry and its core concepts disadvantages students from minoritized populations. This General Chemistry LO framework enacts recommendations from this work by grounding LOs/sub-LOs in chemistry core concepts and science practices. While students should develop competency with a variety of embedded abilities (like computations), our goal is to prioritize using chemistry core concept-based models to explain and predict phenomena for all the reasons covered above. Moreover, many LOs/sub-LOs describe multiple modalities in which learners can express their understanding.
Since the goals of an education are both **Expertise AND Transfer**, our work has focused on paying deep attention to three facets, which must be intertwined and “braided” together during courseware development:

- **Essential Content:** These are the LOs and sub-LOs (and aligned content and assessments added) expanded to include the equity and modernization aspects discussed above.
- **Core Concepts:** They represent the epistemological lenses that chemists apply when looking at the world (see further description below).
- **Interdisciplinarity:** The use of connections to various allied disciplines (vis-à-vis the UN Sustainability Goals and the chemistry practices of analysis, modeling, synthesis, and transformation) ensures relevance.

These three facets are presented in the General Chemistry LO framework as follows (see example table for a sub-module below). Every sub-module leads with a topical description and example anchoring phenomenon. Next (from left to right in the table) the content for the submodule is articulated via the lenses of the three core concepts (**forces govern organization**, **structure governs properties**, and **energy governs stability**). Next, the sub-LOs for the sub-Module are delineated, using color coding to relate the sub-LO to one or more of the chemistry core concepts; potentially associated embedded abilities are also stated for each sub-LO, where appropriate. Finally, example connections to the UN sustainability Goals are presented in the right-most column.
1.1. The Atomic Nucleus. Learners use the chemistry core concepts and models of the atomic nucleus to engage with phenomena like *How can we use unstable atoms to make advances in affordable/clean energy and medicine?*; in doing so, learners gain experience with embedded skills like extracting information from the periodic table, mass–amount conversions, and computations using significant figures.

<table>
<thead>
<tr>
<th>forces-organization</th>
<th>structure-properties</th>
<th>energy-stability</th>
<th>sub-learning outcomes including potentially associated embedded skills</th>
<th>example connections to UN Sustainability Goals</th>
</tr>
</thead>
</table>
| Strong nuclear forces hold the nucleus of an atom together, despite electrostatic repulsions between like charged particles. | The number of protons in the nucleus determine the element; the number of neutrons determine the isotope. | An atom is unstable (radioactive) if nuclear forces are unbalanced—if the nucleus has an excess of internal energy (binding energy), unstable nuclei tend to transform into more stable nuclei and release energy. | LOI.1.1. (B) Using mass data of elemental samples obtained from multiple geographic locations, suggest why atoms of a single element have varying masses. (Analyzing and interpreting data)  
- Embedded skills: pull information from the Periodic Table  
LOI.1.2. (A) Using the nuclear structures of atoms of a particular element, explain why the mass of a mole sample of that element may be different depending on where on Earth it is collected. (Developing and using models)  
- Embedded skills: define a mole; perform amount-mass conversions and weighted average computations using significant figures  
LOI.1.3. (A) For a specific isotope of an atom, draw a representation of the atom’s nucleus that highlights the forces involved and use this model and the band of stability to explain the observed stability of the isotope. (Constructing explanations)  
- Embedded skills: pull information from graphs, reason with Coulomb’s law  
LOI.1.4. (D1) For a series of isotopes, use mass data to explain differences in binding energy. (Constructing explanations)  
- Embedded skills: perform mass deficit computations; perform computations using significant figures  
LOI.1.5. (B) For a series of nuclear processes, use mass data to predict which process will produce the most energy. (Constructing explanations) | - UNSG5: Good Health and Well Being. Scientists harness the energy of unstable isotopes to help locate and treat disease  
- UNSG7: Affordable and Clean Energy. The energy released by unstable atomic nuclei in the earth’s crust is harnessed as geothermal energy to provide electricity/power to society |

Finally, life and work require the mastery of “21st Century Skills/Social-Emotional Learning,” yet precious little is done in Education to insure their explicit identification and their learning - *deliberately, systematically, comprehensively, demonstrably.* Below, competencies for the Sciences are in the second row of the table (priority in descending order: top 2-dark green with dot, dark green, light green, gray). While these competencies do not appear specifically in this General Chemistry LO framework, our work provides guidance to course developers by *explicitly identifying* relevant Competencies.

<table>
<thead>
<tr>
<th>DISCIPLINE</th>
<th>COMPETENCIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creativity</td>
<td>Critical Thinking</td>
</tr>
<tr>
<td>Mathematics</td>
<td>*</td>
</tr>
<tr>
<td>Science</td>
<td>*</td>
</tr>
</tbody>
</table>

**Core Concepts**

Core Concepts are abstract principles that can be used to organize broad areas of knowledge for a given domain, make inferences within a domain, and solve a wide range of problems. Each Core Concept describes a lens that experts use to see their
domain and the world. Learning Outcomes convey what should be learned, while Core Concepts describe the “so what.”

The set of Core Concepts creates a scaffold that helps students develop meaningful connections which lead to deeper real-world understanding and more robust ability to solve problems. They are an essential piece to Transfer.

There have been a variety of chemistry core idea/concept articulations over the years. The Chemistry LO framework uses three core concepts; these are similar to more modern curricular articulations by the NRC’s *A Framework for K-12 Education*, the CLUE curriculum, and the *Chemistry Unbound Curriculum*. All LOs are grounded in these core concepts:

- **Forces govern organization.** Attractive and repulsive electrostatic forces govern the interactions between nuclear subatomic particles, the electrons and nuclei in atoms, and the interactions between all matter particles (atoms, ions, and molecules); thus, forces give rise to how matter is organized at a submicroscopic level (i.e., the structure of matter).

- **Structure governs properties.** The macroscopic physical and chemical properties of a substance are determined by its submicroscopic structure (i.e., composition and three-dimensional arrangement of particles), the nature and strength of interactions between matter particles, and the distribution of charge (electron density) within the structure.

- **Energy governs stability.** Whether a chemical or physical system changes or remains stable depends on differences in energy and energy dispersal. These energy changes can be considered on different scales: system-level energy changes provide insight into the extent to which change occurs while matter particle-level energy changes provide insight into how change is occurring.
Definition of Priority and Optional Sub-LOs

The column headings include an approximate indication of time it may take to cover all the sub-LOs within a sub-module. This is not meant to suggest a precise number of hours equally spread across the sub-LOs within that sub-module. The table column “Time on Task” gives general guidance about the priority and time commitment, legend below.

A = priority, using a substantial fraction of the time allotted to the content of the sub-Module
B = priority, using a notable fraction of time allotted to the content of the sub-Module
C = should be covered, but will likely not take a notable amount of time
D1 = optional, but it will use a notable fraction of the time allotted to the content of the sub-Module
D2 = optional, and it will not take much time
S = spiral; the sub-LO leverages previous content (beyond the chemistry core ideas) to provide insight into a new topic

Sub-LOs labeled as “optional” (labeled D1, D2) tend to be partially redundant with other sub-LOs but built to explore more complex phenomena. Thus, if developers/instructors wish to not engage learners with these phenomena (or choose other phenomena more relevant to learners), they may skip or adapt these sub-LOs.

Technology

Given that this General Chemistry LO framework foregrounds the practice of developing and using models, virtual tools that engage students in this practice (e.g., simulations of various phenomena, manipulatable representations of solid state and molecular structure, graphing tools) are recommended companions to this curriculum. Additionally, as it is essential to focus on the chemistry core concepts, moving
rudimentary computations to electronic/virtual tools frees up time to focus on conceptual reasoning/understanding; doing so provides one pathway to equitable education by removing barriers of computational skill as well as enhancing the technical proficiency necessary in many workplaces that require post-secondary education.

Concerns about student access to technology is by no means a small consideration. See the “Recommended Resource Material” list at the end of this document for some places to start a web search for examples for virtual tools. Additionally, unless there is inadequate access to the internet (even if it is only by smartphone), the purchase of a calculator is an unnecessary financial burden for students. Smartphones can run apps and access websites that obviate the need for a separate calculator device.

Prerequisites

General Chemistry often has few, if any, prerequisites. Most common is the prerequisite of a College Algebra course or placement into a Calculus I course. This LO framework assumes this most common General Chemistry prerequisite. That said, developers and instructors are reminded that, even though learners may have fulfilled this mathematics prerequisite, it is considered best practice to activate any needed mathematical resources in the specific context of when they are useful to learners.

As mentioned above, General Chemistry courses are typically associated with an introductory chemistry lab experience, either as a course component, a co-requisite course, or as a subsequent course for which the General Chemistry course serves as a prerequisite. Considering the variety of models with which the introductory laboratory experiences are deployed (and the variance in goals that such experiences have: supporting lecture content vs. building laboratory skills), this LO framework does not stipulate that any of the LOs/sub-LOs be addressed in the laboratory. However, developers and instructors can build from this General Chemistry LO framework to design engaging laboratory experiences appropriate for various programmatic goals and structures.
Other Pedagogical Remarks

While this LO framework lays the groundwork for a modern and equitable introductory chemistry experience, pedagogical decisions by developers and instructors are equally (if not more) important to realizing these goals. To the extent possible in their respective spaces, developers and instructors are encouraged to adopt evidence-based best practices with regard to the chemistry learning environment (e.g., allowing students to make mistakes, being intrusive, cultivating relationships, employing active learning and group work, fostering a sense of belonging, and validating students’ scientific identities)\(^1\) and chemistry assessment (e.g., assigning letter grades using an absolute scale,\(^2\) avoiding left-of-center grading as a course norm,\(^3\) limiting the contribution of high-stakes assessments to the overall course grade,\(^4,5\) and using evidence-centered design\(^6,7\) to construct equitable assessments\(^8\) of chemistry understanding\(^9,10\)). While this LO framework provides examples of how developers and instructors can validate students’ scientific identities (via connections to relevant phenomena), this work fundamentally supports the latter assessment best practice (using evidence-centered design to construct equitable assessments of chemistry understanding). Other best practices relating to chemistry assessment and learning environments must be adopted by courseware developers and instructors to ensure the equitable and inclusive implementation of this General Chemistry LO framework. Additionally, this LO framework supports a view of chemistry learning that values engagement with science practices to understand phenomena as explained. Thus, developers and instructors may desire to construct learning materials and environments that foreground and embed appropriate content\(^11\) to support this view. See the complete list at the end of this document.

General Chemistry Learning Outcomes

The LOs described in this document are also in a spreadsheet available at https://docs.google.com/spreadsheets/d/1m6jblI7AVw7R907LbZML1_ORZCYB2pLTA-q4JUNQ3Uo/edit?usp=sharing.
General Chemistry Learning Outcome Framework

MODULE 1: Atomic Structure and Properties
All atoms of every element are made of three particles: protons, neutrons, and electrons. Chemists want to know: How do differing quantities of just those three particles result in the 100+ different elements each with its own unique properties? How is the organization of those particles (electrons in particular) related to those properties? How are the patterns of elemental properties explained by those particle organizations? This module will introduce learners to models relevant to explaining atomic-level phenomena. Models of the atom are used to explain the existence and relative stabilities of isotopes; the nature of absorbance and emission spectra; and the periodicity of ionization energy, electron affinity, and atomic/ionic radius. Topics in this Module include:

1.1. The Atomic Nucleus
1.2. The Atom
1.3. The Quantized Model of the Atom
1.4. Models of Multi-Electron Atoms
1.5. Periodic Properties of Atoms and Ions

At the conclusion of Module 1, learners should be able to:

[LO1] Explain atomic properties using models of atomic structure that show locations and/or energies of sub-atomic particles.

Module 1 Content Notes
- Many General Chemistry courses and texts introduce embedded abilities like computations with significant figures or mass-amount conversions early in the course before any chemical phenomena are discussed. Introducing embedded abilities like these in the absence of context can often hinder learning. Here, embedded
abilities are introduced when they are needed—so that learners gain experience with them in contexts where they will be useful for demonstrating deeper knowledge of the chemistry core concepts.

- In many General Chemistry texts and courses, “nuclear chemistry” is a stand-alone chapter or module. Here, content related to the atomic nucleus is incorporated into Module 1, as this topic provides a contained introduction to the three chemistry core concepts, the practice of modeling, and potentially relevant connections to the UN Sustainability Goals.

- As it is critical to one of the three chemistry core concepts, energy is foregrounded in this discussion of atomic structure. Doing so provides a context to introduce potential energy associated with electrostatic forces (which is used consistently throughout the course to explain/predict phenomena) as well as the kinetic energy of the electron. While the kinetic energy of the electron is rarely discussed in General Chemistry, this concept is critical for explaining important phenomena like bonding, electron delocalization, and why the subatomic particles of an atom do not annihilate one another.
1.1. The Atomic Nucleus. Learners use the chemistry core concepts and models of the atomic nucleus to engage with phenomena like *How can we use unstable atoms to make advances in affordable/clean energy and medicine?* In doing so, learners gain experience with embedded abilities like extracting information from the periodic table, mass–amount conversions, and computations using significant figures.

<table>
<thead>
<tr>
<th>forces-organization</th>
<th>structure-properties</th>
<th>energy-stability</th>
<th>sub-learning outcomes including potentially associated embedded abilities</th>
<th>example connections to UN Sustainability Goals</th>
</tr>
</thead>
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| Strong nuclear forces hold the nucleus of an atom together, despite electrostatic repulsions between like charged particles. | The number of protons in the nucleus determines the element; the number of neutrons determines the isotope. | An atom is unstable (radioactive) if nuclear forces are unbalanced—if the nucleus has an excess of internal energy (binding energy); unstable nuclei tend to transform into more stable nuclei and release energy. | **LO1.1.1. (B)** Using mass data of elemental samples obtained from multiple geographic locations, suggest why atoms of a single element have varying masses. *(analyzing and interpreting data)*
  - **embedded abilities**: pull information from the Periodic Table
**LO1.1.2. (A)** Using the nuclear structures of atoms of a particular element, explain why the mass of a mole sample of that element may be different depending on where on Earth it is collected. *(developing and using models)*
  - **embedded abilities**: define a mole, perform amount-mass conversions and weighted average computations using significant figures
**LO1.1.3. (A)** For a specific isotope of an atom, draw a representation of the atom’s nucleus that highlights the forces involved and use this model and the band of stability to explain the observed stability of the isotope. *(constructing explanations)*
  - **embedded abilities**: pull information from graphs; reason with Coulomb’s law
**LO1.1.4. (D1)** For a series of isotopes, use mass data to explain differences in binding energy. *(constructing explanations)*
  - **embedded abilities**: perform mass deficit computations; perform computations using significant figures
**LO1.1.5. (B)** For a series of nuclear processes, use mass data to predict which process will produce the most energy. *(constructing explanations)* | **– SDG3: Good Health and Well Being.** Scientists harness the energy of unstable isotopes to help locate and treat disease.
**– SDG7: Affordable and Clean Energy.** The energy released by unstable atomic nuclei in the earth’s crust is harnessed as geothermal energy to provide electricity/power to society. |
Articulations of important ideas/thinking

- atoms are composed of protons, neutrons, and electrons
- number of protons in the nucleus determines the element; number of neutrons determines the isotope
- the Periodic Table is ordered by composition of the nucleus
- atomic weights are not constants of nature
- some atoms have only one stable isotope while others have many and the natural abundance of stable isotopes varies around the world; this is reflected in how some atomic weights are notated in the periodic table
- the band of stability is the range of stable nuclei on a graph that plots the number of neutrons in a nuclide against the number of protons.
- there are two major forces that contribute to the structure of the nucleus: electrostatic forces (repulsions) and the strong nuclear force; electrostatic forces can be reasoned using Coulomb’s law
- the sum of nucleon masses does not equal the mass of the isotope; this is known as a mass defect
- mass deficit calculations (using \( E = mc^2 \)) and nuclear binding energy
1.2. The Atom. Learners use the chemistry core concepts and energy vs. interparticle separation models of the atom to engage with phenomena like If an atom is composed of positively and negatively charged particles, why don’t electrons collide with the nucleus?

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| Electrostatic forces are the result of charged species interacting at short distances; there is an attractive force between the nucleus and electrons and kinetic energy of electrons can overcome electron-nucleus attractions. | Electrons occupy a volume of space around the nucleus. | Potential energy is associated with the attractive force between nucleus and electrons; kinetic energy is associated with the electron as well. Both energies factor into the overall stability of the atom. | LO1.2.1. (A) Use energy (kinetic and potential) vs. interparticle distance diagrams to explain why a hydrogen atom is stable only when the proton and electron are separated by a specific distance. (constructing explanations)  
  - embedded abilities: pull information from graphs  
LO1.2.2. (B) Use an appropriate model to explain how and why the potential energy of pairs of charged particles changes when the distance between the particles and their relative charge magnitudes are altered. (constructing explanations)  
  - embedded abilities: reason with Coulomb’s law | |

Articulations of important ideas/thinking

- the potential energies associated with attractions of nucleus and electrons can be modeled with Coulomb’s law (i.e., dependence on inter-particle separation)
- potential energy has both a magnitude and a direction (sign)
- the kinetic energy of an electron can be thought of as energy of confinement
- we can visualize energy/inter-particle separation relationships with energy vs. inter-particle separation graphs
• the total energy of the hydrogen atom is such that the atom is stable when the electron is at a certain distance from the nucleus
• exploring the kinetic and potential energy of the hydrogen atom sets up quantization in the next section
1.3. The Quantized Model of the Atom. Learners use the chemistry core concepts and models of the atom that incorporate quantization to engage with phenomena like How can we use light to identify, detect, and quantify the presence of these atoms in systems of interest?

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<td>Atomic transitions modulate the attractive force between nucleus and electron.</td>
<td>Different atoms exhibit different absorbance/emission spectra.</td>
<td>When light interacts with matter, we can relate the energy associated with electromagnetic radiation to the energy differences between quantized atomic energy levels.</td>
<td>LO1.3.1. (B) Given experimental data for light emission (e.g., wavelength or frequency of three emission lines), construct an atomic model that would qualitatively and quantitatively explain the results (analyzing and interpreting data). - Embedded abilities: perform frequency-wavelength-energy computations; perform computations using significant figures.</td>
<td>SDG3: Good Health and Well Being. SDG6: Clean Water and Sanitation. Scientists can use light/matter interactions to detect the presence of adverse substances in our bodies as well as in our air/water systems.</td>
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Articulations of important ideas/thinking
- electromagnetic radiation can be modeled as both wave-like and particle-like, depending on the observation; regardless of model, we observe that the energy of EM radiation is related to frequency
- using a particle model for EM radiation, the relationship $E = nh\nu$ allows us to quantify the energies of not only single particles, but also collections of particles
● we know that the energies of atoms are quantized because of how atoms interact with EM radiation
● Coulomb’s law can be used to explain the attraction between the nucleus and any electron, and predict when electrons in an atom are expected to be at higher or lower potential energies
● absorbance/emission phenomena for one-electron atoms using a quantized model of the atom
1.4. Models of Multielectron Atoms. Learners use the chemistry core concepts and models of multielectron atoms to engage with phenomena like *Why are substances containing Ti2+ attracted to magnets?*

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| In multi-electron atoms, electrons experience both an attraction to the nucleus and repulsions from other electrons; valence electrons experience the least attraction to the nucleus. | The number of protons versus the number of electrons determines the charge on an ion; unpaired electrons give rise to magnetism. | The electron configuration observed for atoms and ions is that which minimizes overall energy. | LO1.4.1. (A) Evaluate a model for a ground-state multi-electron atom based on the following criteria: consistency with the quantum mechanical nature of the atom; appropriate organization of electrons into shells, subshells, and orbitals; and/or appropriate orbital populations. (evaluating information)  
  - **embedded abilities:** construct/interpret electron configurations; identify shapes/labels of atomic orbitals  
LO1.4.2. (B) Construct a model using Coulomb’s law, orbital energy diagrams, and Hund’s rule to explain when a system of electrons in an atom would be expected to be at a higher or lower total energy based on their distance from the nucleus and the orbitals they populate. (developing and using models)  
  - **embedded abilities:** construct/interpret electron configurations; identify shapes/labels of atomic orbitals  
LO1.4.3. (A) Construct a model using orbital energy diagrams and representations of electrons to explain how and why substances exhibit diamagnetic and paramagnetic behaviors. (constructing explanations)  
  - **embedded abilities:** construct/interpret electron configurations  
LO1.4.4. (A) Construct a model using Coulomb’s law, the quantum mechanical nature of the atom and probable locations of electrons to explain the effective nuclear charge experienced by a core and/or valence electron for a given atom. (constructing explanations)  
  - **embedded abilities:** construct/interpret electron configurations; identify shapes/labels of atomic orbitals  
LO1.4.5. (B) Use effective nuclear charge data along with models of multielectron atoms and Coulomb’s law to explain why certain electrons in an atom are considered “valence.” (analyzing and interpreting data)  
  - **embedded abilities:** construct/interpret electron configurations; identify shapes/labels of atomic orbitals | - SDG3: Good Health and Well Being. The presence or absence of certain elements as ions in the environment can impact health and the quality of life for communities. |

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Articulations of important ideas/thinking

- in currently accepted models of the atom, electrons are modeled as three-dimensional standing *waves*; because of this, there is inherent *uncertainty* in discussing matter at the nanoscale
- we generally describe the three-dimensional distribution of electron probability *as electron density*; three-dimensional electron probability distributions are otherwise known as *orbitals*
- an electron possesses the property of *spin*, represented as either spin-up (↑) or spin-down (↓)
- the electron clouds of multi-electron atoms are organized in terms of energies and probable locations (*shells, subshells, and orbitals*)
- the *Pauli exclusion principle* states that no two electrons in the same orbital can have the same spin
- the *aufbau principle* and *Hund’s rule*, respectively, stipulate that there is an energy cost to populating a higher energy orbital and also pairing an electron in the same orbital because of electron-electron repulsion
- the *aufbau principle*, *Pauli exclusion principle*, and *Hund’s rule* are applied to predict lowest-energy electron configurations for multi-electron atoms
- *electron shielding* is a consequence of many attractive and repulsive interactions, the energies of which are moderated by distance from the nucleus
- the *valence* electrons of an atom are more shielded from the nuclear change than the core electrons; thus, the valence electrons are freer to engage in *chemistry*
1.5. Periodic Properties of Atoms and Ions. Learners use the chemistry core concepts and the effective nuclear charge model of the atom to engage with phenomena like *How do we predict when the presence or absence of an element may cause harm, or find solutions to the adverse presence of elements?*

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| Ionization energy, electron affinity, and atom/ion size are reflections on the magnitude of the overall attractive force between nucleus and electron. | Atomic structure and the effective nuclear charge model can explain the common periodic properties. | Generating cations from neutral atoms requires energy while generating anions from most neutral atoms liberates energy. | LO1.5.1. (C) Construct a model using the quantized nature of the atom and Coulomb’s law to explain how and why absorption of energy only above a certain threshold results in atom ionization. *(developing and using models)*  
LO1.5.2. (A) Construct a model using Coulomb’s law, electron configurations, and effective nuclear charge to explain how and why (1) successive ionization energies become increasingly larger, (2) why ionization energy changes as one traverses the Periodic Table (either from left-to-right or top-to-bottom), and (3) why exceptions occur in the general ionization energy trend across a period of the periodic table. *(constructing explanations)*  
- **embedded abilities**: construct/interpret electron configurations  
LO1.5.3. (B) Use electron configurations and successive ionization energy values to explain how and why an atom tends to form ions of a particular charge number. *(constructing explanations)*  
- **embedded abilities**: construct/interpret electron configurations  
LO1.5.4. (B) Construct a model using Coulomb’s law, electron configurations, and effective nuclear charge to explain how and why (1) electron affinity changes as one traverses the Periodic Table (either from left-to-right or top-to-bottom), and (2) why exceptions occur in the general electron affinity trend across a period of the periodic table. *(constructing explanations)*  
- **embedded abilities**: construct/interpret electron configurations | SDG6: Clean Water and Sanitation. Many materials and methods related to heavy metal ion removal from water rely on the different sizes of metal ions. |
LO1.5.5. (A) Construct a model using Coulomb’s law, electron configurations, and effective nuclear charge to explain (1) how and why atomic radii of the s- and p-block elements change as one traverses the Periodic Table (either from left-to-right or top-to-bottom), and (2) how and why cations are smaller than their parent atom while anions are larger than their parent atom. (constructing explanations)

- embedded abilities: construct/interpret electron configurations

Articulations of important ideas/thinking

- **effective nuclear charge** is a model that can explain periodic trends in atomic radii, ionization energy, and electron affinity
- **ionization** is the addition/subtraction of electrons from the influence of the nuclear charge
- the valence electrons of *metals* tend to experience a lower effective nuclear charge than *non-metals*; thus, metals tend to form cations and *nonmetals* tend to form anions
- the radius of an atom changes when it becomes an anion or cation; this change in radius can be modeled with effective nuclear charge
- the Periodic Table is a model that reflects how atomic structure gives rise to trends in atomic properties
MODULE 2: The Particulate Nature of Matter

Chemists seek to understand and explain the natures of different types of substances and to categorize them accordingly. Chemists want to know: What is it? What makes it that way? Why does that stuff not behave like that other stuff? What patterns help us to predict the behavior of this stuff? This module introduces learners to models of interaction between matter particles (atoms, molecules, and ions) so that they can distinguish between different types of substances (atomic, ionic, metallic, and molecular). London dispersion forces are introduced as a fundamental mechanism by which matter particles are Coulombically attracted to one another. Models of metallic and ionic bonding are then added to explain increasingly complex phenomena. Finally, the module introduces covalent bonding so that learners can distinguish between forces that define a molecular substance’s identity and forces that define the macroscopic properties of that substance. Topics in this Module include:

2.1. The Behavior of Gases, Liquids, and Solids
2.2. Metallic Substances and Their Properties
2.3. Ionic Substances and Their Properties
2.4. Molecules are Composed of Atoms Engaged in Covalent Bonds
2.5. Properties of Molecular Substances

At the conclusion of Module 2, learners should be able to:

[LO2] Construct models of atomic, ionic, metallic, and molecular substances that highlight the Coulombic attractions between matter particles and use these models to explain trends in macroscopic behavior and properties.

Module 2 Content Notes
- Many General Chemistry courses and texts will separate discussions of atomic, molecular, ionic, and metallic substances into different chapters or modules. Here, these four particulate models are united so that learners can
be challenged to compare them to rationalize how the structures of different substances give rise to different properties.

- In many General Chemistry texts and courses, London dispersion forces are introduced in a chapter or module on Intermolecular Forces. Here, to build multi-particle models of substances (crucial for rationalizing bulk properties like melting and boiling point), London dispersion forces are presented as the basic attractive interaction that all matter particles exhibit on one another. Other important interactions (ionic interactions, electron delocalization in metals, and covalent bonding) are compared to the basic London dispersion force interaction.

- Molecular orbital theory is used as a model of covalent bonding here, but only to describe the electronic structure of diatomic molecules. However, orbital overlap returns as a useful model to describe three-dimensional arrays of localized bonds in Module 3.

- The discussion of molecular matter is intentionally limited in Module 2 to non-polar diatomic and hydrocarbon molecules; Module 3 presents a more complete discussion of molecular structure and geometry. Accordingly, learners are expected to use and reason with ball-and-stick models of molecular structure so that Lewis structures can be introduced in Module 3 as “shorthand” representations of atom connectivity.

- Accompanying many presentations of covalent and ionic substances is a discussion of nomenclature; as naming chemical compounds does not increase learners’ understanding of chemistry core concepts or chemistry/science practices, nomenclature is not discussed here.
2.1. The Behavior of Gases, Liquids, and Solids. Learners use the chemistry core concepts and models consisting of multiple atoms to reason about the phases of matter and to engage with phenomena like *How can we distinguish substances from other substances?*

<table>
<thead>
<tr>
<th>forces-organization</th>
<th>structure-properties</th>
<th>energy-stability</th>
<th>sub-learning outcomes</th>
</tr>
</thead>
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| London dispersion forces (LDFs) are fleeting Coulombic attractions that all matter particles exert on other matter particles. | The strength of London dispersion forces is related to the structure of the matter particle—in particular, the size and polarizability of the particle’s electron cloud. | Temperature is a gross indication of matter particle kinetic energy; there is also a potential energy associated with LDF Coulombic attractions. | LO2.1.1. (B) Construct a model using Coulomb’s Law and LDFs to explain how and why energy changes occur when noble gas atoms approach each other. (constructing explanations)  
LO2.1.2. (D1) Construct a model using matter particles, Coulomb’s law, and kinetic energy to explain how and why the volume of a gas is dependent on temperature and pressure. (developing and using models)  
- **embedded abilities:** perform computations using combined and ideal gas laws  
LO2.1.3. (A) Construct a model using matter particles, Coulomb’s law, and kinetic energy to explain how and why the relationship of matter phase with pressure and/or temperature is dependent upon interactions between matter particles. (developing and using models)  
- **embedded abilities:** pull information from phase diagrams  
LO2.1.4. (A) Construct a model using Coulomb’s law and the concept of LDFs to explain differences in physical properties among pure matter samples composed of gaseous atoms (noble gases). (constructing explanations) |

**Articulations of important ideas/thinking**

- to consider physical properties of bulk substances we must consider many matter particles (atoms)  
- atoms in a pure sample of matter possess kinetic energy that is proportional to the temperature of the sample  
- the macroscopic observation of pressure is related to matter particle motion of a gas and the impacts those particles make with container particles  

- SDG12: Responsible Consumption and Production. We can use data regarding how a substance responds to temperature and pressure to distinguish it from others, use it in a safe way, and reuse/recycle it.
• atoms exhibit inter-particle Coulombic forces on one another—these are called London dispersion forces
• the relationship of matter particle motion and temperature is dependent upon interactions between matter particles
• the relationship of matter particle motion with pressure is dependent upon interactions between matter particles
• temperature, pressure, and the strength of matter particle interactions dictate the observed state of matter
• we can summarize information about temperature, pressure, and state of matter with a phase diagram
• the general macroscopic behavior of gases with respect to temperature and pressure are summarized in the combined and ideal “gas laws”
2.2. Metallic Substances and Their Properties. Learners use the chemistry core concepts and a model of metallic bonding to engage with phenomena like *Why can metals be continuously recycled and repurposed?*

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<td>Electrostatic forces between metal atom cores and the electron sea give rise to the structure of metallic substances.</td>
<td>The metallic bonding model provides insight into the properties and behaviors of metallic substances.</td>
<td>Coulombic interactions between metal cations and electrons give rise to metallic bond strength.</td>
<td>LO2.2.1. (A) Use the metallic bonding model to explain properties and behaviors of metallic substances (boiling points, electrical conductivity, malleability, ductility). (constructing explanations)</td>
<td>– SDG12: Responsible Consumption and Production. Metallic substances are continuously recycled and repurposed; the structure of metallic substances lends itself to this property.</td>
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**Articulations of important ideas/thinking**

- we can model the bonding in metals as cations of maximum oxidation number embedded in a delocalized “sea” of valence electrons
- the “sea” of valence electrons exists due to an overlap in valence orbitals of the metal atoms
- the strength of interactions between metal atoms depends on the number of valence electrons delocalized into the “sea”
- we can explain the physical properties (boiling points, hardness) of Groups 1–5 metals using this model
2.3. Ionic Substances and Their Properties. Learners use the chemistry core concepts and a model of ionic bonding to engage with phenomena like *Why do iron metal and iron oxide (rust) have such different properties?*

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| Electrostatic forces between anions and cations give rise to the structure of ionic substances. | The ionic bonding model provides insight into the properties and behaviors of ionic compounds. | Under typical conditions found on earth, many non-metal atoms are more stable as anions, while many metal atoms are more stable as cations. Coulombic interactions between ions give rise to ionic bond strength (lattice energy). | LO2.3.1. (B) Construct a model using Coulomb's law, effective nuclear charge, ionization energy, and electron affinity, where applicable, to explain how and why metals tend to form cations and non-metals tend to form anions. (*constructing explanations*)
  - embedded abilities: *pull information from Periodic Table*
LO2.3.2. (B) Construct a model using Coulomb's Law, electron configurations, ionization energy, electron affinity, and LDFs to explain how and why energy changes occur when a metal atom approaches, and forms an ionic interaction with, a nonmetal atom. (*constructing explanations*)
LO2.3.3. (A) Construct a model that highlights the electrostatic forces present in an ionic compound and ionic radius trends to explain differences in the lattice energies of ionic compounds. (*developing and using models*)
  - embedded abilities: *determine formula units using charge balance*
LO2.3.4. (A) Construct a model using Coulomb's law and ionic bonding concepts to explain differences in the melting/boiling points of ionic compounds. (*developing and using models*)
LO2.3.5. (B) Construct a model using Coulomb's law and/or ionic bonding concepts to explain why ionic compounds are different than metals with respect to macroscopic properties like brittleness and electrical conductivity. (*developing and using models*) | |

Articulations of important ideas/thinking

- we observe binary ionic substances being composed of metal and non-metal elements because metals tend to form cations and nonmetals tend to form anions
- the cations and anions of a binary ionic substance arrange themselves to form electrically neutral 3-D lattices
- it is necessary to express the composition of ionic substances as formula units and/or systematic names
• the lattice energy is related to the strength of the ionic bonding
• the lattice energy is defined by the difference in energy between gaseous cation/anion mixture and the cation/anion mixture as a solid
• Coulomb’s law can be used for an initial comparison of relative ionic bond strengths using the charges of the ions and periodic trends
• we can use this model of ionic compounds to explain their physical properties
• we can use electron configurations to explain magnetism in metals and ionic compounds
2.4. Molecules are Composed of Atoms Engaged in Covalent Bonds. Learners use the chemistry core concepts and the molecular orbital theory model of bonding to engage with phenomena like *Why does elemental hydrogen exist as diatomic “H₂,” but elemental helium exists as monoatomic “He”?*

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| A covalent bond is a mutual electrostatic interaction between two atoms that also permits electron delocalization over the two atoms. | Models for the electronic structure of diatomic molecules provide insight into the properties (magnetism, ionization energy, electron affinity, etc.) of that molecule. | Covalent bonding minimizes total energy—mostly due to electron delocalization. Covalent bond strength is related to bond order. Molecules also have quantized energy levels, very similar to atoms. | **LO2.4.1. (B)** Construct a model using Coulomb’s Law, electron configurations, ionization energy, electron affinity, and LDFs to explain how and why energy changes occur when a nonmetal atom approaches, and forms a covalent interaction with, another non-metal atom. *(constructing explanations)*  
**LO2.4.2. (A)** Construct a model using molecular orbital theory and energy concepts to explain how and why some atoms combine to form covalent bonds, while others do not. *(constructing explanations)*  
**LO2.4.3. (A)** Construct a model using molecular orbital theory and the concept of bond order to explain how and why the length and strength of a covalent interaction can be affected by the ionization of a diatomic molecule composed of first- or second-period elements. *(constructing explanations)*  
**LO2.4.4. (B)** Construct a model using molecular orbital theory to explain how and why some molecules and molecular ions exhibit magnetic properties while others do not. *(constructing explanations)*  
**LO2.4.5. (D1, S)** Construct a model using molecular orbital theory to explain how and why the ionization energy or electron affinity of an atom differs from its corresponding diatomic molecule *(e.g., H vs. H₂).* *(constructing explanations)*  
**LO2.4.6. (A)** Construct a model using the quantized nature of the atom, molecular orbital theory, and the concept of bond order to explain how and why specific energies are absorbed by the molecule and affect bond properties, while other energies are not absorbed. *(developing and using models)* | **SDG2: Zero Hunger.** Ammonia is the basis for much of the world’s fertilizer; however, N₂ has a very strong bond that must be broken to produce ammonia-based fertilizers for growing food to feed the world. |
Articulations of important ideas/thinking

- *molecular orbital theory* describes the formation of *covalent bonds*—if two atoms can attain a lower-energy state (compared to being separate atoms) a covalent bond will form
- the lower energy state of a covalent bond is driven predominately by lowering the kinetic energy of the electrons—by electron delocalization
- molecular orbital theory describes atomic orbitals of adjacent atoms overlapping to form molecular orbitals at different energies
- an *in-phase* combination of atomic orbitals on adjacent atoms forms a bonding molecular orbital at a lower energy, while an *out-of-phase* combination of atomic orbitals forms an *antibonding molecular orbital* at higher energy
- we can use molecular orbital theory to explain why two H atoms form a H2 molecule, but two He atoms do not form a He2 molecule
- we relate the idea of *bond order* to *bond strength*
- in second row diatomic molecules, *p* atomic orbitals afford both *σ* and *π* interactions; in general, *π* interactions are weaker (easier to disrupt) than *σ* sigma interactions
- in general, bond strength correlates to bond length
- bond length/bond strength can be rationalized using periodic trends in atomic radius
2.5. Properties of Molecular Substances. Learners use the chemistry core concepts and submicroscopic models of molecular matter to engage with phenomena like Why is F2 a gas and I2 a solid when the F–F bond is stronger than the I–I bond? or How can one element (carbon) give rise to so many distinct substances?

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| London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | The strength of London dispersion forces is related to the structure of the molecule—in particular, the size and polarizability of the molecule’s electron cloud. | Temperature is a gross indication of molecular kinetic energy; there is also a potential energy associated with LDF Coulombic attractions. | LO2.5.1. (B, S) Construct a model using Coulomb’s law, molecular representations, and the concept of LDFs to explain trends in physical properties among matter composed of homonuclear diatomic molecules. (developing and using models)  
- **embedded abilities:** interpret ball-and-stick representations of molecular structure; relate molecular formulae to ball-and-stick representations  
LO2.5.2. (D1, S) Construct a model using Coulomb’s law, molecular representations, and the concept of LDFs to explain differences between the physical properties of carbon allotropes. (developing and using models)  
LO2.5.3. (A, S) Construct a model using Coulomb’s law, molecular representations, and the concept of LDFs to explain trends in physical properties among matter composed of hydrocarbon molecules. (developing and using models)  
- **embedded abilities:** interpret ball-and-stick representations of molecular structure; relate molecular formulae to ball-and-stick representations | - SDG9: Industry, Innovation, and Infrastructure. Adding graphene makes concrete stronger, meaning that not only can less of the material be used in a structure, but also its improved durability means that the graphene-based concrete can be reused; hydrocarbon-based substances are derived from petroleum and are distinguishable from one another by their physical properties. |

**Articulations of important ideas/thinking**
- molecules are collections of atoms held together by covalent bonds  
- there are two sets of forces at work—the covalent bonds that hold the atoms together and the London dispersion forces that form interactions between molecules
● for molecular substances, phase changes do not involve the breaking or forming of covalent bonds
● the strength of London dispersion forces scales with the number of valence electrons in the molecule
● we can use *ball and stick models* as representations of molecular structure that we can use to understand LDFs and physical properties
● carbon exists as several allotropes, including diamond, graphite, graphene, nanotubes, and buckyballs
● each allotrope represents a different ratio between covalent bonding and London dispersion forces
● we can use ball and stick models as representations of hydrocarbon molecular structure that we can use to understand LDFs and physical properties
MODULE 3: Molecules are Three-Dimensional

Chemists draw and build models (representative pictures and objects) of molecules to help visualize their shapes and how they might interact with one another. Chemists use many models this way—each has a different purpose, level of sophistication, strengths, and limitations. Chemists frequently move mentally between models to better understand the location, orientation, connectivity, flexibility, and reactivity of molecules. This Module introduces learners to the models needed to explore additional aspects of molecular structure: stability, geometry, connectivity, and chirality. Models of orbital overlap and electron delocalization are all used as means to explain a variety of aspects of molecular stability. Topics in this Module include:

3.1. Molecular Structure and Structural Isomerism
3.2. Chirality
3.3. Valence Bond Theory
3.4. Electron Delocalization and Resonance
3.5. Molecular Structure is Fluxional

At the conclusion of Module 3, learners should be able to:

[LO3] Construct and use geometrically accurate three-dimensional bonding models that describe the probable valence electron distribution in the molecule; use these models to explain structural observations or parameters.

Module 3 Content Notes

- The idea that molecules have a three-dimensional structure was introduced in Module 2; in Module 3 learners are supported in representing molecular structure with Lewis models.
- In many General Chemistry texts and courses, molecules that have electron density delocalized over more than two atoms are introduced when learners are learning to construct Lewis structures. Here, engagement with these
molecules (and representing them with resonance forms/hybrids) is delayed until a model of electron delocalization (using valence bond theory) is introduced.

- Like all models, VSEPR has both affordances and limitations; that said VSEPR can be a useful model for certain systems. Here, learners engage with both the strengths and limitations of VSEPR.
- Although uncommon in General Chemistry texts and courses, vibrational spectroscopy is introduced to connect to the chemical practice of analysis and to provide experimental evidence for molecular structure. In addition, vibrational spectroscopy provides a connection for exploring greenhouse gases.
3.1. Molecular Structure and Structural Isomerism. Learners use the chemistry core concepts and 3-D models of molecular structure to engage with phenomena like \textit{How can two substances have the same chemical composition but have very different properties?}

<table>
<thead>
<tr>
<th>forces-organization</th>
<th>structure-properties</th>
<th>energy-stability</th>
<th>sub-learning outcomes including potentially associated embedded abilities</th>
<th>example connections to UN Sustainability Goals</th>
</tr>
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</table>
| Lewis structures are models for how atoms are connected via covalent bonding. | VSEPR is rooted in repulsive forces between regions of electron density. | Lewis structures are models of atomic connectivity and can be used to visualize constitutional isomers; molecules occupy three-dimensional space. | **LO3.1.1. (A)** Sketch Lewis structures consistent with experimental structural data \textit{(e.g., bond lengths, bond angles). (analyzing and interpreting data)}  
- **embedded abilities:** convert ball-and-stick representations and/or molecular formula to Lewis structures. |  |
| Lewis structures are models for how atoms are connected via covalent bonding. | VSEPR is rooted in repulsive forces between regions of electron density. | Lewis structures are models of atomic connectivity and can be used to visualize constitutional isomers; molecules occupy three-dimensional space. | **LO3.1.2. (B)** Construct a model using Coulomb’s law, effective nuclear charge, and atomic radius, and explain how and why the electronegativities of the s- and p-block elements change as one traverses the Periodic Table. (either from left-to-right or top-to-bottom). \textit{(constructing explanations)} |  |
| London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | Reducing charge distribution is a stabilizing phenomenon. Minimizing electron-electron repulsions lowers energy. The strength of LDFs depends on the shape of the electron cloud, in addition to size/polarizability. | **LO3.1.3. (A)** Evaluate molecular representations using concepts of valence electron count, the octet rule, electronegativity, formal charge, or any combination therein where appropriate. \textit{(evaluating information)}  
- **embedded abilities:** convert ball-and-stick representations and/or molecular formula to Lewis structures; recognize common atom connectivities (functional groups). |  |
| London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | Reducing charge distribution is a stabilizing phenomenon. Minimizing electron-electron repulsions lowers energy. The strength of LDFs depends on the shape of the electron cloud, in addition to size/polarizability. | **LO3.1.4. (D2)** Construct a model using covalent bonding concepts, electron density distributions, and electronegativity to explain how and why the charge of a central atom in a molecule can differ from its formal charge. \textit{(developing and using models)} |  |
| London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | Reducing charge distribution is a stabilizing phenomenon. Minimizing electron-electron repulsions lowers energy. The strength of LDFs depends on the shape of the electron cloud, in addition to size/polarizability. | **LO3.1.5. (A)** Evaluate claims regarding whether sets of molecules are the same, different, or share a constitutional isomeric relationship. \textit{(evaluating information)} |  |
| London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | London dispersion forces are fleeting Coulombic attractions that all matter particles exert on other matter particles. | Reducing charge distribution is a stabilizing phenomenon. Minimizing electron-electron repulsions lowers energy. The strength of LDFs depends on the shape of the electron cloud, in addition to size/polarizability. | **LO3.1.6. (A)** Use Coulomb’s law to explain bond angle data for various molecular compounds and make a claim as to why many molecules are more stable when regions of electron density are arranged in three dimensions (as compared to two dimensions). \textit{(analyzing and interpreting data)} |  |
**Articulations of important ideas/thinking**

- Lewis structures model the connectivity of atoms in three-dimensional molecules
- We use formal charge, bond valence, electronegativity, and the octet rule (when applicable) as guides for constructing Lewis model representations composed of C, H, O, N, and halogen atoms
- Formal charges aren’t “real,” per se, but they do often illuminate trends related to the charges on atoms in molecules
- We use Lewis structures to guide prediction of constitutional isomers for molecules composed of C, H, O, N, and halogen atoms
- We apply knowledge of common pattern connectivity (i.e., functional groups—alcohols, aldehydes, ketones, carboxylic acids, esters, amines, amides, and amino acids) when inspecting or constructing Lewis structures composed of C, H, O, N, and halogen atoms
- In many molecules, the geometry around an atom of interest (tetrahedral, trigonal pyramidal, trigonal planar, bent, or linear) can be explained using a simple model: the valence shell electron-pair repulsion model (VSEPR)
- We use wedge/dash representations to illustrate molecules in three dimensions
• VSEPR is a useful model, but given that the VSEPR isn’t based on quantum mechanics, it has many limitations—both in explaining the geometries of certain connectivities and representing lone electron pairs.
• The strength of LDFs depends not only on the size/polarizability of the electron cloud, but also the 3D shape of the electron cloud.
3.2. Chirality. Learners use the chemistry core concepts and 3-D models of molecular structure to engage with phenomena like *How can two substances have the same atom connectivity but have very different properties?*

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<tbody>
<tr>
<td>Molecules can have the same atom connectivity, but those connections can be distributed in three-dimensional space in different ways.</td>
<td>The strength of LDFs depends on the shape of the electron cloud, in addition to size/polarizability.</td>
<td>LO3.2.1. (A) Evaluate claims regarding whether sets of molecules are the same, different, or are mirror images of one another. (evaluating information) - <strong>embedded abilities:</strong> interpret ball-and-stick and/or wedge-dash representations</td>
<td>LO3.2.2. (B) Using a model incorporating 3D molecular structure and LDFs, explain why two enantiomers would be difficult to separate by boiling point. (constructing explanations) - <strong>embedded abilities:</strong> apply the VSEPR model to determine a molecular geometry</td>
<td>- SDG3: Good Health and Well Being. The expense of producing enantiomerically pure medicines is high. For some medications, one enantiomer is useful whereas the other is harmful. Removing the harmful enantiomer is difficult; this adds to the cost of some medicines.</td>
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</table>

**Articulations of important ideas/thinking**

- a new type of isomer arises from considering molecular structures in three dimensions—*optical isomers (enantiomers)*
- we identify a *stereogenic (or chiral) center* in a molecule by inspecting the groups surrounding a candidate center; we sketch the *enantiomer* of a chiral molecule by drawing its mirror image
- intentional connection of inter-particle interactions to the chemical practice of *analysis*
### 3.3. Valence Bond Theory

Learners use the chemistry core concepts and the valence-bond model to engage with phenomena like *Why aren’t the bond angles of carbon compounds the same as the angles made by p-orbitals: 90°?*

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| Orbital overlap can help us model directional, localized bonds in three-dimensional space; the length of a covalent bond is related to its strength. | Covalent bond strength is related to bond order. | LO3.3.1. (A) Use valence bond theory to create a geometrically accurate three-dimensional bonding model for molecules composed of C, H, O, N, and/or halogen atoms, including those that contain rings. *(developing and using models)*  
- **embedded abilities:** identify the hybridization of an atom using the number of bonds and lone electron pairs; relate hybridization to geometry | | |
| LO3.3.2. (B) Construct a model using valence bond theory to explain the trends in bond strength related to bond order *(e.g., C=O vs. C=O or C=C vs. C≡C)* and why a C≡C bond, for example, is not twice the strength of a C–C bond. *(developing and using models)*  
- **embedded abilities:** identify the hybridization of an atom using the number of bonds and lone electron pairs; relate hybridization to geometry | | |
| LO3.3.3. (B) Construct a model using valence bond theory to explain why a large amount of energy is necessary to instigate rotation around C=C and C≡C bonds, while C–C bonds rotate freely at room temperature. *(developing and using models)*  
- **embedded abilities:** identify the hybridization of an atom using the number of bonds and lone electron pairs; relate hybridization to geometry | | |
| LO3.3.4. (B) Use experimental or computational evidence *(electron density plots, bond angles, bond lengths, etc.)* to make an argument about the approximate hybridization, if any, of an atom in a molecule or molecular ion. *(engaging in argument from evidence)*  
- **embedded abilities:** relate hybridization to geometry | | |

Atoms in molecules are connected via covalent bonds.
**Articulations of important ideas/thinking**

- valence bond theory employs the idea of *hybrid orbitals*—combinations of valence s and p orbitals on atoms that describe the probable locations of an atom’s electrons in a molecule; s and p orbitals on atoms hybridize when they are close in energy
- the geometry about an atom of interest (*tetrahedral, trigonal pyramidal, trigonal planar, bent, or linear*) can be explained using the shapes that arise from collections of hybrid orbitals on central atoms
- overlaps between hybrid orbitals on the central atom and peripheral atom orbitals look like σ interactions from molecular orbital theory; overlaps between *unhybridized p* orbitals on the central and peripheral atoms look like π interactions
- trends in bond strength related to bond order (e.g., C–O vs. C=O or C=C vs. C≡C) can be explained using valence bond theory
3.4. Electron Delocalization and Resonance. Learners use the chemistry core concepts and the valence bond model to engage with phenomena like *Why is an amide functional group planar, when VSEPR predicts it to be pyramidal?*

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| Atoms in molecules are connected via covalent bonds. | Electron delocalization can affect structure (bond lengths, three-dimensional arrangements of bonds). | Electron delocalization is a stabilizing phenomenon—the kinetic energy of electrons is lowered. | LO3.4.1. (B) Given bond length/energy data for a series of structures exhibiting different atom-atom bond orders (e.g., H₂O₂, O₂, and O₃) make a claim regarding the utility of a bonding model that includes only single, double, or triple bonds. *(analyzing and interpreting data)*  
LO3.4.2. (A) Construct a series of resonance structures and a resonance hybrid to explain experimental bond lengths, and/or computed valence electron distributions/atom charges in structures with covalent bonds where electron delocalization occurs. *(developing and using models)*  
- **embedded abilities:** drawing resonance forms and hybrids  
LO3.4.3. (A) Use electronegativity and formal charge to rationalize why only a limited set of resonance structures is needed to explain the bond lengths and/or computed valence electron distributions/atom charges of certain structures containing covalent bonds. *(constructing explanations)*  
LO3.4.4. (C) Construct a model using resonance structures, a resonance hybrid, valence bond theory, and electron kinetic energy to explain how and why electrons in covalent bonds are more stable when delocalized over amide, ester, carboxylic acid, and deprotonated carboxylic acid functional groups. *(constructing explanations)*  
- **embedded abilities:** drawing resonance forms and hybrids; constructing valence-bond models of bonds/molecules  
LO3.4.5. (B) Construct a model using resonance structures, a resonance hybrid, valence bond theory, and electron delocalization to explain how and why amide, ester, carboxylic acid, and deprotonated carboxylic acid functional groups adopt planar geometries. *(constructing explanations)*  
- **embedded abilities:** drawing resonance forms and hybrids; constructing valence-bond models of bonds/molecules |

- **SDG13: Climate Action.** Ozone is an important UV-B absorber in the upper atmosphere.
Articulations of important ideas/thinking

- delocalization of valence electrons occurs via overlapping unhybridized p orbitals (π-conjugation)
- Lewis structures have limitations when used to depict molecules that have π-delocalized electron density; *resonance structures* can be used as a means of representing electron delocalization that occurs through π-conjugation
- a *resonance hybrid* can be used to describe the structure of a molecule having delocalized electrons—it can be used to illustrate unexpected geometries and/or bond properties
- we assess the *contribution* of each resonance structure to the resonance hybrid using experimental data and explain these contributions using electronegativity, formal change, and the octet rule when applicable
- the planar geometries of certain functional groups (amides, carboxylic acids, esters) imply that O and N atom “lone pairs” participate in resonance delocalization by occupying unhybridized p orbitals
3.5. Molecular Structure is Fluxional. Learners use the chemistry core concepts and submicroscopic models of molecular matter to engage with phenomena like *What makes a molecular substance a greenhouse gas?*

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<tbody>
<tr>
<td>Rigid structures can result in molecules having the same atom connectivity, but those connections being distributed in three-dimensional space in different ways; different atom connectivities give rise to different IR spectroscopy signals.</td>
<td>There are energies associated with bond rotations, molecular vibrations, and different molecular conformations; molecular vibrations correspond to the IR region of the EM spectrum.</td>
<td>LO3.5.1. (B) Construct a model using electron-electron repulsions and three-dimensional molecular structure to explain how and why potential energy changes as a function of the dihedral angle across the conformations of small molecules with linear structures. <a href="link">(developing and using models)</a> LO3.5.2. (A) Construct a model using electron-electron repulsions and three-dimensional molecular structure to explain how and why one conformation of a molecule is more stable when compared to another. <a href="link">(developing and using models)</a> LO3.5.3. (A) Evaluate claims regarding whether sets of molecules are the same, different, or share a geometric isometric relationship. <a href="link">(evaluating information)</a> LO3.5.4. (D1) Use infrared spectroscopy data to infer atom connectivity in molecules containing C, O, N, H, and halogen atoms. <a href="link">(analyzing and interpreting data)</a></td>
<td>- SDG13: Climate Action. The fluxional structures of molecules permit the absorption and emission of energy; when a molecule does this with energy in the infrared range, it is a greenhouse gas.</td>
<td></td>
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</tbody>
</table>

**Articulations of important ideas/thinking**

- the bonds of molecules can rotate and vibrate
- there is an energy barrier to free rotation around C–C bonds; however, C–C bonds constantly rotate at room temperature
- free bond rotations give rise to *conformers* such as *anti*, *staggered*, *eclipsed*, and *gauche* for small linear hydrocarbons and chair and boat for cyclohexane; conformers are not isomers
- we can explain the energy differences between conformers using *electron-electron repulsions*
• we explain the observation that C=C, C≡C, and amide C–N bonds do not rotate using valence bond theory and π-delocalization
• a new type of isomer arises from considering molecular structures whose bonds cannot rotate (bond orders > 1, cyclic molecules) —*geometric*
• molecules exhibit a wide variety of vibrational motions and the energy difference between vibrational states depends on bond strength and the mass of the atoms involved; the absorption of infrared electromagnetic radiation can be used to detect the presence of specific bonds.
MODULE 4: Intermolecular Interactions and the Properties of Molecular Matter

Chemists explain the properties of molecular matter using models that highlight the interactions between molecules. Chemists apply models of molecular connectivity to predict the type and strength of intermolecular interactions. Chemists explain macroscopic phenomena according to the energy involved in those interactions. This module introduces learners to models of intermolecular forces (LDF, dipole-dipole interactions, and hydrogen bonding). These models are applied first to discrete molecular substances and then polymers and other macromolecules. The module then returns to the core concept of energy by looking at the energy associated with disrupting or forming these IMFs during phase changes and solution formation. These ideas are extended to explain phenomena related to macromolecules. The module concludes with the tools (calorimetry) and concepts (endothermic and exothermic) to quantify the energy and the direction of its movement. Topics in this Module include:

4.1. Intermolecular Forces
4.2. Macromolecules and Their Behaviors
4.3. Energy Flows Associated with Phase Changes
4.4. Energy Flows Associated with Dissolution and Precipitation

At the conclusion of Module 4, learners should be able to:

[LO4] Construct models of molecules (including polymers and biomolecules) and the interactions between them that include energy flows between system and surroundings and use these models to explain trends in physical properties.

Module 4 Content Notes

- Many General Chemistry courses and texts separate discussions of intermolecular forces (and how they are related to physical properties like melting and boiling point) from the energy flows that accompany melting and
boiling. Here, these ideas are intentionally connected so that learners can reason about macroscopic energy changes using submicroscopic models of disrupting/forming intermolecular interactions.

- Although uncommon in General Chemistry texts and courses, the separation technique of distillation is introduced to connect this content to the chemical practice of analysis.
- Many General Chemistry courses and texts consider “solution chemistry” to be a stand-alone chapter or module. Here, phenomena related to solutions (dissolution and precipitation) are discussed with regard to the submicroscopic particle attractions involved in these phenomena, how they change, and how they relate to macroscopic energy flows.
### 4.1. Intermolecular Forces

Learners use the chemistry core concepts and models of molecular matter that incorporate intermolecular interactions to engage with phenomena like *How can two substances have similar molecular masses and three-dimensional shape but have very different boiling points?*

<table>
<thead>
<tr>
<th>forces-organization</th>
<th>structure-properties</th>
<th>energy-stability</th>
<th>sub-learning outcomes including potentially associated embedded abilities</th>
<th>example connections to UN Sustainability Goals</th>
</tr>
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| Certain molecules exhibit intermolecular interactions beyond London forces (dipole/dipole interactions, hydrogen bonding). | Different types of molecular structures lead to different collections of intermolecular forces; these differences can be used to separate mixtures of molecular substances. | Given that all intermolecular interactions are built from electrostatic forces, the strength of each general class of intermolecular interaction exhibits a different dependence on inter-particle separation; increased temperature will increase the kinetic energy of matter particles, which will disrupt intermolecular interactions | LO4.1.1. (A) Construct a model using Coulomb’s law, molecular structure representations, and the concepts of LDFs, dipole-dipole interactions, and/or hydrogen bonding (when appropriate) to explain or predict trends in physical properties among matter composed of molecules. *(developing and using models)*
- **embedded abilities:** determine molecular shape from a molecular formula or 2D Lewis structure, determine polarity of covalent bonds, determine polarity of molecules, pull information from electrostatic potential diagrams

LO4.1.2. (S, B) Construct a model using resonance structures, a resonance hybrid, valence bond theory, and electron delocalization to explain why the nitrogen atom of amide functional groups does not engage in hydrogen-bonding interactions. *(constructing explanations)*
- **embedded abilities:** draw resonance forms and hybrids, construct a valence-bond model of a bond or molecule

LO4.1.3. (A) Use Coulomb’s law, molecular structure representations, and the concepts of LDFs, dipole-dipole interactions, and/or hydrogen bonding (when appropriate) to explain how and why the physical state of matter composed of molecules changes when heated or cooled. *(developing and using models)*
- **embedded abilities:** construct 2D and 3D molecular representations

LO4.1.4. (B) Use molecular structure representations and the concepts of LDFs, dipole-dipole interactions, and/or hydrogen bonding (when appropriate) to explain the order of elution for a mixture of molecular substances when applied to a defined stationary... |

- SDG13: Climate Action. Discuss measures to remove CO₂ and greenhouse gasses from the atmosphere involving 3D molecular properties and IMFs.
Articulations of important ideas/thinking

- Phase change and distillation occur at different temperatures for different substances due to interactions between the molecules and not due to molecular mass.
- We use a molecule’s bond polarities and 3D shape to determine overall molecular polarity and whether a molecule has a dipole moment.
- We inspect electrostatic potential diagrams to visualize where the poles are located on a 3D molecular structure; we illustrate a molecular dipole moment on a 3D molecular structure using a dipole moment vector.
- Collections of molecules possessing dipole moments are attracted to each other via both London interactions and dipole-dipole interactions.
- Collections of molecules with polar E–H (where E is any element) bonds are attracted to one other via London and dipole-dipole interactions, as well as hydrogen bonding interactions; functionally, E = O and N, although HF molecules hydrogen bond with each other.
- The strength of each general class of intermolecular interaction (London interactions, dipole-dipole interactions, hydrogen bonding interactions) exhibits a different dependence on inter-particle separation.
- We use the intermolecular interactions among molecules collectively to explain trends in the physical properties of molecular substances.
- Intermolecular forces form the basis for a method that chemists use to separate mixtures of molecular substances: liquid chromatography.
4.2. Macromolecules and Their Behaviors. Learners use the chemistry core concepts and 3D models of macromolecular structure (including interactions between and within individual macromolecules) to engage with phenomena like *When does a molecule become a polymer?*

<table>
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<th>forces-organization</th>
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<th>example connections to UN Sustainability Goals</th>
</tr>
</thead>
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| Macromolecules present nearly all the force-structure concepts that have been discussed so far: covalent bonding, intermolecular interactions London forces (dipole/dipole, hydrogen bonding) | The extended 3-D structures of macromolecules give rise to extreme London dispersion forces. | Intermolecular forces have different strengths depending on the scenario; increased temperature will increase the kinetic energy of matter particles, which will disrupt intermolecular interactions. | LO4.2.1. (B) Use a viscosity vs. molecular weight graph to make a claim about the submicroscopic particle behavior that defines a “polymer.” *(analyzing and interpreting data)*  
- embedded abilities: pull information from graphs  
LO4.2.2. (A) Construct a model using Coulomb’s law, representations of polymer structure, and the density of specific intermolecular interactions to explain the properties (flexibility, density, strength) of polymer-based materials. *(developing and using models)*  
LO4.2.3. (S, B) Construct a model using resonance structures, a resonance hybrid, valence bond theory, and electron delocalization to explain how and why the peptide bond in the primary structure of a protein is largely planar, making it possible to form stable β-pleated sheet secondary structures utilizing intermolecular forces. *(constructing explanations)*  
LO4.2.4. (S, B) Construct a model using resonance structures, a resonance hybrid, valence bond theory, and electron delocalization to explain how and why the nucleobases of DNA are planar, making it possible for DNA to form a double helix structure. *(constructing explanations)*  
LO4.2.5. (D1) Construct a model using Coulomb’s law, representations of glycerolipid structures, and intermolecular interactions to explain observed melting points of saturated and unsaturated fats (and connect these properties to health risks associated with foods that contain lipids). *(developing and using models)*  
LO4.2.6. (B) Construct a model using intermolecular interactions to show how and why amphiphilic molecules arrange themselves into ordered macromolecular assemblies (e.g., lipid bilayers, soap bubbles, micelles, colloids, etc.). *(developing and using models)* | - SDG3: Good Health and Well-Being. Connecting physical properties of fats to coronary heart disease.  
- SDG9: Industry, Innovation, and Infrastructure. Green coatings like nanocellulose  
- SDG12: Responsible Consumption and Production. Corn-based plastics (poly lactic acids) |
Articulations of important ideas/thinking

- **polymers are macromolecules** with distinctive physical properties; we use *repeating units* to easily notate the structure of polymers
- we usually recognize three types of solid polymers: elastomers, thermoplastic polymers, and thermosetting polymers
- we inventory the density of intermolecular interactions between polymer chains to explain relative physical properties (like flexibility, “strength,” etc.)
- biological macromolecules (proteins, nucleic acids, lipids/triglycerides) tend to be built from functional groups with strong bonds: amides and esters; we can describe the structure and behavior of nucleic acids, proteins, and lipids using concepts we’ve already covered
- proteins (polypeptides) are built from amino acids and the planarity of the amide bond (and hydrogen bonding) gives rise to specific localized structure and properties in proteins
- nucleic acids are built from nucleobase-decorated ribose units connected with phosphodiester linkages; the planar nature of the nucleobases (and hydrogen bonding) make the famous double-helical structure of DNA possible
- lipids are carboxylic acids with long alkane chains—their physical and biological activity tends to be associated with the shape of the alkane chain
- in complex biological and synthetic macromolecules, we classify regions of the structure according to how intermolecular forces are compatible with those of water: *hydrophobic vs. hydrophilic*; this distinction can help to preliminary explain the tertiary structure of proteins and the self-assembly behavior of lipids.
- cellulose is a polymer of the sugar molecule glucose
4.3. Energy Flows Associated with Phase Changes. Learners use the chemistry core concepts and models of substances depicting submicroscopic particle interactions and energy flows to engage with phenomena like *Why does food cook faster in steam than in boiling water?*

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| Phase changes for molecular substances involve intermolecular interactions while those for ionic substances involve ionic interactions. | Phase changes for molecular substances involve breaking/forming intermolecular interactions while those for ionic substances involve ionic interactions. | Phase changes involve energy flows between a system and its surroundings as heat—this energy is associated with breaking/forming intermolecular or ionic interactions; differences in these energy flows can be used to separate mixtures of molecular substances. | LO4.3.1. (B) Using data (e.g., heat capacities, temperatures of phase changes), construct a graph that illustrates how the temperature of a substance changes as a constant source of heat is applied. (analyzing and interpreting data)  
   - **embedded abilities:** pull information from graphs  
LO4.3.2. (B) Develop a model using molecular representations to illustrate that the changing intermolecular attractions explain why a phase change is exothermic (release energy) or endothermic (absorb energy). (developing and using models)  
LO4.3.3. (A) Construct a model of matter particles, IMFs, and kinetic/potential energy to explain the shape of a substance’s heating or cooling curve, or to compare the heating or cooling curves of multiple substances. (developing and using models)  
LO4.3.4. (D1) Construct models using representations of protein secondary and tertiary structures, relevant IMFs, and energy flows to show why proteins become more stable and denatured when heated. (developing and using models)  
LO4.3.5. (B) Use molecular structure representations, relevant IMFs, and the relative energies associated with collections of intermolecular forces to explain the order of elution for a mixture of molecular substances when separated by distillation. (developing and using models) |

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</table>
| - SDG6: Clean Water and Sanitation.  
   Solar-assisted desalination. |
Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded

- energy exchange as heat occurs via particle contact/collisions
- the temperature at which a phase change occurs depends upon the molecular structure of the compound.
- as an ionic substance melts/boils, ionic interactions are overcome
- as a molecular substance melts/boils, intermolecular forces are overcome (not covalent bonds)—this idea can be applied unilaterally from the simplest molecules to the most complex macromolecules
- the breaking and forming of intermolecular interactions is accompanied by energy flows between the system and surroundings; under constant pressure conditions, we refer to these energy changes as changes in \textit{enthalpy}
- we specify enthalpy changes according to the associated phase changes (e.g., enthalpy of vaporization)
- how energy affects the temperature of a substance is governed by the substance’s \textit{heat capacity}
- intermolecular forces and the relative energies associated with collections of intermolecular forces form the basis for a method that chemists use to separate mixtures of molecular substances: \textit{distillation}
4.4. Energy Flows Associated with Dissolution and Precipitation. Learners use the chemistry core concepts and models of substances depicting submicroscopic particle interactions and energy flows to engage with phenomena like *How do instant ice packs work?*

<table>
<thead>
<tr>
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<th>sub-learning outcomes including potentially associated embedded abilities</th>
<th>example connections to UN Sustainability Goals</th>
</tr>
</thead>
</table>
| Dissolution and precipitation involve intermolecular/ionic interactions in both the solute and solvent. | Dissolution and precipitation involve breaking/forming ionic/intermolecular interactions in both the solute and solvent. | Dissolution and precipitation involve energy flows between a system and its surroundings as heat—this energy is associated with breaking/forming intermolecular or ionic interactions. | LO4.4.1. (A) Develop a model using ionic and/or molecular structures to illustrate that the release or absorption of energy from a dissolution or precipitation process depends on the changes in matter particle interactions; explain why the dissolution process is exothermic or endothermic. *(developing and using models)*  
LO4.4.2. (B) Using calorimetry data for dissolution or precipitation processes *(i.e., temperature changes)*, determine whether the process was exothermic or endothermic. *(analyzing and interpreting data)*  
*embedded abilities:* perform computations using heat capacities; perform computations using significant figures | – SDG2: Zero Hunger.  
Phosphate recovery (critical to wastewater treatment) can be facilitated using precipitation processes. |

**Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded**

- a rule of thumb for predicting solubility is “like dissolves like” but it does not tell us why
- a *solute* tends to be *soluble* in a *solvent* when the interactions between the matter particles of the substance are weaker than the interactions between the matter particles of the solvent and those of the substance
- an ionic substance is *insoluble* when the interactions between ions in the lattice are significantly stronger than the interactions between the component ions and the solvent
- two liquid or gaseous substances are *immiscible* when the interactions between matter particles of the pure substances are significantly stronger than the interactions between matter particles when the substances mix
• the opposite of a dissolution is a precipitation, where solute particles collect together and overcome interactions with the solvent to form a solid.
• we measure enthalpy changes for a process using calorimetry
• both endothermic and exothermic processes occur; thus, there is more to the story of how and why processes occur
MODULE 5: Physical Stability and Change

Chemists use energy concepts to explain the observed instability or stability of physical systems (i.e., its tendency to change or not) under specific conditions. Chemists define changes in these systems according to their starting and ending compositions. All systems tend toward equilibrium, a state where all change appears (visually) to have stopped but is still occurring without any net changes in composition. Chemists use energy concepts to describe two aspects of change toward equilibrium—the extent of the change and the rate of that change. This module introduces learners to the energy concepts needed to describe how the composition of a system changes on the way to equilibrium (i.e., enthalpy, entropy, and the Gibbs free energy) and the energy concepts needed to describe a system’s relative rate of change (i.e., activation energy). These ideas are used to explain and predict physical changes (e.g., physical state changes, dissolutions, protein folding, etc.). Topics in this Module include:

5.1. The Equilibrium State  
5.2. Entropy and Process Directionality  
5.3. Gibbs Free Energy and Equilibrium  
5.4. Submicroscopic Models of Phase Change  
5.5. Dissolution and Precipitation  
5.6. Submicroscopic Models of Dissolution and Precipitation

At the conclusion of Module 5, learners should be able to:

[LO5] Use models of structure and energy to describe how and why systems undergo physical changes to achieve equilibrium.

Module 5 Content Notes
- Many General Chemistry courses and texts separate discussions of equilibrium, kinetics, and thermodynamics, in varying topical order. Here, to support learners in reasoning with the chemistry core concepts, these ideas are
combined in a specific progression so that learners can engage with the energetics of physical change. First, equilibrium is introduced as the target of physical change. This is done to also undergird why energy changes at different scales are needed to describe systems as their compositions evolve toward an equilibrium state. Next, the extent to which change occurs is described using system-level energy changes and thermodynamics. Then, the rate at which change occurs is described using submicroscopic-level energy changes and collision theory. Lastly, these scales are united so that learners are supported in describing phase changes, dissolution, and precipitation processes—and especially how temperature affects change toward equilibrium. This is done to engage learners in the chemical practice of transformation.

- In many General Chemistry courses and texts, discussions of submicroscopic models of change (i.e., collision theory) and the methods to collect and analyze rate data are presented together in one chapter/module on “kinetics”. Here, these ideas are separated and only collision theory is presented in Module 5; rate data collection/analysis is presented in a later module so that this topic can be paired more easily with why chemists collect and analyze rate data—to inform reaction mechanisms.

- Often accompanying collision theory and/or Q vs. K reasoning is a discussion of the Le Châtelier’s principle heuristic. Even though Le Châtelier’s principle could be applied to physical equilibria, it is delayed until Module 6 to ground learners in energy-based reasoning first.

- Many General Chemistry courses and texts consider “solution chemistry” a stand-alone chapter or module. Here, solutions-related phenomena (dissolution and precipitation) continue to be discussed. Using the chemistry core concepts, learners are supported in engaging with the extent to which dissolution (i.e., solubility) and precipitation occur, the rate at which these processes occur, and how these processes occur (i.e., by the submicroscopic collisions of matter particles).
### 5.1. The Equilibrium State

Learners use the chemistry core concepts and models of system composition to reason about physical equilibria at a macroscopic scale and engage in phenomena like *Why doesn’t ten grams of calcium hydroxide completely dissolve in one liter of water?*

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</table>
| Intermolecular interactions, ionic interactions, and ion-dipole interactions are involved in phase changes, dissolutions, and precipitations. | The structure of a substance dictates the forces formed/overcome during a phase change, dissolution, or precipitation. | Energy changes related to molecules in bulk provide insight into the extent to which the composition of the system changes toward equilibrium, and energy changes at the scale of individual molecules provide insight into rates of change. | LO5.1.1. (B) Use data (e.g., a concentration/mass/partial pressure vs. time graph or data tables; experimental observations; molecular sketches or sequences, etc.) to evaluate whether a system has attained a low energy state (i.e., equilibrium). *(analyzing and interpreting data)*  
- **embedded abilities:** negotiate concentrations and partial pressures; pull information from concentration/mass/partial pressure vs. time graphs for phase changes and dissolutions  
LO5.1.2. (A) Using the starting composition of a system and its respective equilibrium constant, construct a concentration/mass/partial pressure vs. time graph to model how the system’s composition evolves as it approaches equilibrium. *(developing and using models)*  
- **embedded abilities:** construct equilibrium constant and reaction quotient expressions; perform equilibrium (“I-C-E”) computations using phase changes, dissolutions, and precipitations | - SDG6: Clean Water and Sanitation. Toxic heavy metals like lead and mercury can be removed from water using metal-organic frameworks (MOFs).  
- SDG6: Clean Water and Sanitation. Using florisil (magnesium silicate) to clean up oil spills should have a product-favored equilibrium. |

**Articulations of important ideas/thinking**

- Physical changes tend toward lower energy states; once a low energy state is achieved, no macroscopic changes are observed.
- The equilibrium condition is defined by a lack of macroscopic change among the components of a system (assessed using amounts/concentration/partial pressures); we consider a system at equilibrium to be stable (i.e., lower energy state).
• the composition of the equilibrium state is not only different for every system, but also dependent on the conditions at which the system exists
• we can describe the composition of a system using the reaction quotient Q (although only physical changes are considered here; chemical “reactions” are introduced in Module 6)
• as a reference point agreed to by scientists, we refer to Q = 1 as the standard composition
• the composition of the equilibrium state is described by a special case of Q: the equilibrium constant, K
• we describe an equilibrium state as “product-favored” when K > 1, while we describe an equilibrium state that is “reactant favored” when K < 1
• we can compute equilibrium concentrations or partial pressures using K and starting compositions
• we can qualitatively assess the direction in which a system’s composition will evolve to achieve equilibrium by comparing the starting composition Q to the equilibrium constant K.
• we can describe two aspects of change toward equilibrium: (1) the extent to which the composition of the system changes on the way to equilibrium (implied by the relative value of K) and (2) how quickly an equilibrium composition is obtained (rate); energy changes related to molecules in bulk provide insight into the extent to which the composition of the system changes toward equilibrium, and energy changes at the scale of individual molecules provide insight into rates of change
5.2. Entropy and Process Directionality. Learners use the chemistry core concepts and the Second Law of Thermodynamics to reason why phase changes occur and engage with phenomena like *Why do you feel colder when using hand sanitizer than when you wash your hands with water?*

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<td>LO5.2.1. (B) Develop a model using molecular structures that relates the ΔH° for a phase change to the breaking and forming of matter particle interactions; explain why a phase change is either endothermic or exothermic. <em>(developing and using models)</em></td>
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<td>– embedded abilities: compute ΔH° for a phase change using enthalpies of formation</td>
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<td>LO5.2.2. (A) Develop a model of how energy disperses among the various interactions between and motions of matter particles during a phase change and use the model to predict or explain the sign of the associated entropy change for that process. <em>(developing and using models)</em></td>
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<td>– embedded abilities: compute ΔS° using absolute entropy values</td>
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<td>LO5.2.3. (B) Develop a model for how a phase change affects the entropy of the universe; use this model to predict or explain how the system’s composition will evolve to obtain equilibrium. <em>(developing and using models)</em></td>
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<td>– embedded abilities: perform computations using ΔH° and ΔS°, with correct units and significant figures</td>
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<td>ionic interactions,</td>
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<td>LO5.2.4. (A) Explain, using arguments based on the signs of the enthalpy and entropy changes for a standard-state phase change, whether temperature conditions can affect the directionality of the process. <em>(constructing explanations)</em></td>
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<td>– embedded abilities: compute the temperature at which a physical change becomes product-favored</td>
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<td>SDG3: Good Health and Well Being. Exposure to volatile organic compounds (VOCs) is one of the main culprits behind Sick Building Syndrome. VOCs are present in many products such as paints, adhesives, personal care products, cleaning products, carpets, and furniture.</td>
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**Articulations of important ideas/thinking**

- it is essential to recognize that “standard” values are referenced to an agreed-upon “standard condition”—1 bar for partial pressure of gaseous components, and 1 M for dissolved components
• we use tabulated enthalpies of formation to compute $\Delta H^\circ$ for various processes like phase changes and dissolutions
• the quantity of energy transferred ($\Delta H^\circ$) doesn’t give us insight into how the composition of the system is changing toward equilibrium, as both exothermic and endothermic processes occur
• an additional aspect of energy is important in describing the tendency to change toward stability: *energy dispersal* (this is called *entropy*)
• given how energy can be dispersed in a collection of molecules in a particular phase, we can develop a qualitative understanding of entropy increases and decreases
• we can compute an entropy change ($\Delta S^\circ$) for a process using tabulated data: standard absolute entropies ($S^\circ$)
• H2O vaporization results in an entropy increase while H2O condensation results in an entropy decrease; since both processes occur (depending on temperature), $\Delta S^\circ$ isn’t a helpful guide
• the Second Law of Thermodynamics and the “entropy of the universe” is the ultimate model for describing a system’s tendency to evolve in a particular direction: a process will occur if it increases the total number of different spatial and energetic configurations available to the universe, either by increasing the energy configurations among the components of the chemical system ($\Delta S > 0$) or of the surroundings, which is achieved by having the system release energy ($\Delta H < 0$)
• these ideas can be applied to reason why proteins “fold” under biological conditions
5.3. Gibbs Free Energy and Equilibrium. Learners use the chemistry core concepts, models of system composition, and the Gibbs free energy to reason about phase changes and engage with phenomena like *Why does a puddle of water evaporate completely at temperatures less than 100 °C?*

<table>
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</table>
| Intermolecular interactions, ionic interactions, are involved in phase changes. | Energy transferred during a phase change is related to interactions formed or broken; energy dispersal increases with the number of different spatial and energetic configurations that the components of a system can adopt. | The Gibbs free energy \( \Delta G \) combines aspects of \( \Delta H \) and \( \Delta S \); when \( \Delta G = 0 \), there is no tendency to change (i.e., the system is at equilibrium); there is a relationship between \( \Delta G^\circ \) and \( K \). | **LO5.3.1. (A)** Using an equilibrium constant and representations of matter particles, develop a model to explain (beginning at any composition) how the energy and the composition of a two-phase system changes as it approaches equilibrium. (developing and using models)  
- **embedded abilities**: compute a reaction quotient, perform computations using \( \Delta H^\circ, \Delta S^\circ, \Delta G^\circ, K \) with correct units and significant figures | |

**Articulations of important ideas/thinking**

- the Gibbs free energy change for a process considers both enthalpy and entropy, as well as temperature: \( \Delta G = \Delta H - T\Delta S \); we can establish the temperature dependence of \( \Delta G \) using this relationship
- e.g., \( \text{H}_2\text{O}(\ell) \rightleftharpoons \text{H}_2\text{O}(g) \), when \( \Delta G < 0 \), the composition of the system will evolve from its starting composition to achieve stability that favors vaporization; when \( \Delta G > 0 \), the composition of the system will evolve from its starting composition to achieve stability that favors condensation
• using $\Delta G^\circ$ (i.e., beginning at the standard composition, $P_{\text{H}_2\text{O}} = 1$ bar) we see that at 25 °C, the composition of the $\text{H}_2\text{O}(\ell) \rightleftharpoons \text{H}_2\text{O}(g)$ system evolves to produce more $\text{H}_2\text{O}(\ell)$ and achieve stability; however, we can also see that this process becomes $\text{H}_2\text{O}(g)$-favored at $T > 100$ °C
• if processes at 25 °C are of interest, tabulated Gibbs energies of formation can be used to compute a $\Delta G^\circ$
• $\Delta G$ is also dependent on system composition: $\Delta G = \Delta G^\circ + RT \ln Q$, we can specify non-standard conditions (i.e., those that might be more applicable to situations we observe in real life) using the reaction quotient $Q$ and $\Delta G^\circ$
• the boiling point is the temperature at which the $\text{H}_2\text{O}(\ell) \rightleftharpoons \text{H}_2\text{O}(g)$ equilibrium composition changes from favoring $\text{H}_2\text{O}(\ell)$ to favoring $\text{H}_2\text{O}(g)$; for vaporizing liquids, this occurs at $Q = 1$ bar (i.e., when the partial pressure of the gas begins to overcome atmospheric pressure)
• under typical conditions ($P_{\text{H}_2\text{O}} \sim 3 \times 10^{-2}$ bar) at 25 °C, we see that the composition of the $\text{H}_2\text{O}(\ell) \rightleftharpoons \text{H}_2\text{O}(g)$ system will evolve in the forward direction to achieve an $\text{H}_2\text{O}(g)$-favored equilibrium composition (i.e., water can vaporize at temperatures below 100 °C).
• although $\Delta G$ allows us to make predictions about reaction directionality, the actual value tells us little about the final relative amounts of product to reactants at equilibrium
• using $\Delta G = \Delta G^\circ + RT \ln Q$ and the idea that when $Q = K$, the system is at equilibrium ($\Delta G = 0$), we see that the equilibrium composition (the extent to which the change occurs) is related to $\Delta G^\circ$ and the temperature: $\Delta G^\circ = -RT \ln K$
• since $\Delta G^\circ$ is dependent on temperature, so is $K$
5.4. Submicroscopic Models of Phase Change. Learners use the chemistry core concepts and matter particle-scale models of phase changes to engage with phenomena like *Why does water evaporate faster at higher temperatures?*

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| Intermolecular interactions, ionic interactions, are involved in phase changes. | The rate of physical change depends on matter particles colliding with each other. | Molecules in a sample exhibit a distribution of kinetic energies; activation energy is the minimum energy needed to overcome intermolecular forces; matter particle kinetic energies manifest in how quickly the equilibrium state is attained. | LO5.4.1. (D2) Using distributions of matter-particle kinetic energies, explain why entropy increases with increasing temperature. *(constructing explanations)*  
LO5.4.2. (B) Construct a model using distributions of kinetic energies and matter particle collisions to explain how substances can vaporize even when the system's temperature is less than the boiling point. *(developing and using models)*  
LO5.4.3. (B) Construct a model using distributions of kinetic energies and matter particle collisions to explain how and why temperature affects the rate at which a phase change occurs. *(developing and using models)*  
  - **embedded abilities**: perform computations using Arrhenius relationship  
LO5.4.4. (A) Construct and use models (molecular structures and reaction progress diagrams) to show how energy changes as intermolecular forces break and/or form during phase changes. *(developing and using models)*  
  - **embedded abilities**: draw and pull information from Gibbs free energy versus process progress diagrams  
LO5.4.5. (A) Develop a model using matter particle collisions and associated activation energies to explain for a phase change how the rates of the associated forward and reverse processes will change when conditions (amounts/concentrations/partial pressures/temperature) are changed; using this information, predict how the system will reestablish equilibrium following these changes. *(constructing explanations)*  
  - **embedded abilities**: draw and pull information from Gibbs free energy versus process progress diagrams |
| | | | | - SDG12: Responsible Consumption and Production. Mercury pollution from artisanal and small-scale gold mining does significant damage to ecosystems. |
Articulations of important ideas/thinking

- molecules at a particular temperature exhibit a range of kinetic energies, defined by distributions; the higher the temperature, the larger the fraction of molecules have the requisite energy (the activation energy) to overcome intermolecular forces and escape into the gas phase
- a few things will affect the rate of vaporization: the surface area available for molecules to escape and the fraction of molecules that have enough kinetic energy at a particular temperature to overcome the intermolecular forces in the liquid state (we'll call this the activation energy)
- rate \( \propto k \times \text{surface area} \), where \( k \) is the rate constant that describes the fraction of molecules that have enough kinetic energy at a particular temperature to overcome the intermolecular forces in the liquid state
- \( k \) is related to the activation energy via the Arrhenius relationship: \( k \propto e^{-E_a/RT} \); the higher the \( E_a \), the lower the \( k \) (and the slower the overall rate)
- increasing the temp will increase the rate of vaporization
- at the particle scale, there are competing processes: as \( \text{H}_2\text{O}(\ell) \) molecules gain enough kinetic energy to overcome intermolecular interactions and escape into the gas phase, \( \text{H}_2\text{O}(g) \) molecules can reform intermolecular interactions with molecules at the surface and condense back into the liquid phase: \( \text{H}_2\text{O}(\ell) \rightleftharpoons \text{H}_2\text{O}(g) \)
- the rate constant for the condensation process will be less dependent on activation energy and more on the probability of an \( \text{H}_2\text{O}(g) \) molecule colliding with the surface in the proper orientation to make an intermolecular interaction
- eventually, a steady state will be reached in which exactly as many molecules per unit time are leaving the surface of the liquid (vaporize) as colliding with it (condense); in a closed container, this leads to a dynamic equilibrium
- if a liquid is in an open container, most of the molecules that escape into the vapor phase will not collide with the surface of the liquid and return to the liquid phase; instead, they will diffuse through the gas phase away from the container, and equilibrium will never be established
5.5. Dissolution and Precipitation. Learners use the chemistry core concepts, models of system composition, and the Gibbs free energy to reason about dissolution and precipitation processes and with phenomena like Why are the solubilities of NaCl (360 g per 1 L of water) and MgCO3 (0.139 g per 1 L of water) so different?

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| Intermolecular interactions, ionic interactions, and ion-dipole interactions are involved in dissolution and precipitation processes. | Energy transferred during a dissolution is related to the interactions made/broken; Energy dispersal increases with the number of different spatial and energetic configurations that the components of a system can adopt. | Aspects of energies that undergird the tendency to change: ΔH, ΔS, and ΔG; relationship of K and ΔG°; how temperature affects the tendency to change: enthalpic effects become less relevant at high temperature, where entropic effects dominate. | LO5.5.1. (S, B) Develop a model using ionic and molecular structures that relate the ΔH° for a dissolution/precipitation to the breaking and forming of matter particle interactions; explain why the dissolution/precipitation is either endothermic or exothermic. (developing and using models)  
  - embedded abilities: compute ΔH° using enthalpies of formation |  |  |
|                     |                      |                  | LO5.5.2. (S, B) Develop a model of how energy can be dispersed among the matter particles involved in a dissolution/precipitation process and use the model to predict or explain the sign of the associated entropy change for that process. (developing and using models)  
  - embedded abilities: compute ΔS° using absolute entropies |  |  |
|                     |                      |                  | LO5.5.3. (S, B) Explain, using qualitative arguments based on the signs of the enthalpy and entropy changes for a standard-state dissolution process, whether the ionic solid will always be soluble, sparingly soluble, or soluble under certain temperature conditions. (constructing explanations)  
  - embedded abilities: compute ΔG° using ΔH°, ΔS°, and T |  |  |
|                     |                      |                  | LO5.5.4. (S, B) Explain, using qualitative arguments based on the signs of the enthalpy and entropy changes for a standard-state precipitation process, whether a solid will form under certain temperature conditions. (constructing explanations)  
  - embedded abilities: compute ΔG° using ΔH°, ΔS°, and T |  |  |
|                     |                      |                  | LO5.5.5. (S, B) Using an equilibrium constant and representations of matter particles, develop a model to explain why (beginning at any composition) the composition of a dissolution/precipitation system changes as it approaches equilibrium. (developing and using models)  
  - embedded abilities: compute a reaction quotient; complete computations using ΔH°, ΔS°, ΔG°, K with correct units and significant figures |  |  |
Articulations of important ideas/thinking

- dissolution isn’t just about breaking up solute inter-particle interactions and hydrogen-bonding among water molecules, but it also concerns forming interactions between the solvent molecules and solute matter particles—this gives rise to both exothermic (MgCO$_3$) and endothermic (NaCl) dissolution processes
- likewise, precipitation isn’t just about forming inter-particle interactions among solute particles and hydrogen-bonding among water molecules, but it also concerns breaking interactions between the solvent molecules and solute matter particles
- entropy changes ($\Delta S$) that accompany dissolution/precipitation processes can be net positive or net negative, depending on how ordered water molecules are around the ions; typically, the higher the ion charges, the more ordered H$_2$O molecules become around the solute ions
- the solubility of ionic substances and the tendency for precipitates to form become a balance of enthalpy, entropy, and system composition
- the *common ion effect* can be explored phenomenologically ($Q$ vs. $K$) and using energy concepts ($\Delta G$)
5.6. Microscopic Models of Dissolution and Precipitation. Learners use the chemistry core concepts and matter particle-scale models of dissolution/precipitation processes to engage with phenomena like *Why does increasing temperature make NaCl and MgCO3 dissolve more quickly, but decreases the solubility of MgCO3 while increasing the solubility of NaCl?*

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| Intermolecular interactions, ionic interactions, and ion-dipole interactions are involved in dissolutions and precipitations. | The rate of change depends on matter particles colliding with each other—the "productivity" of these collisions depends on the structures of the species colliding. | Molecules in a sample exhibit a distribution of kinetic energies; activation energy is the minimum energy needed to overcome intermolecular forces; matter particle kinetic energies manifest in how quickly the equilibrium state is attained. | LO5.6.1. (S, B) Construct a model using molecular representations and distributions of kinetic energies to explain how and why temperature affects the rate at which dissolution/precipitation occurs. *(developing and using models)*  
- **embedded abilities**: perform computations using Arrhenius relationship  
LO5.6.2. (S, B) Construct and use models (ionic/molecular structures and reaction progress diagrams) to show how energy changes as interparticle interactions break and/or form during a dissolution/precipitation process. *(developing and using models)*  
- **embedded abilities**: draw and pull information from Gibbs free energy versus process progress diagram  
LO5.6.3. (S, A) Develop a model using matter particle collisions and associated activation energies to explain for a dissolution/precipitation process how the rates of the associated forward and reverse processes will change when conditions (amounts/concentrations/partial pressures/temperature) are changed; using this information, predict how the system will reestablish equilibrium following these changes. *(constructing explanations)*  
- **embedded abilities**: draw and pull information from Gibbs free energy versus process progress diagrams  
LO5.6.4. (B) Using energy models of both the rate of change and the tendency to change, describe how temperature will affect these two aspects of a dissolution/precipitation. *(developing and using models)* | - SDG2: Zero Hunger.  
Soil testing for lead—because of differences in dissolution kinetics, a soil containing relatively small concentrations of Pb\(^{2+}\) may be assessed as a higher risk than a soil containing a high concentration of PbS.  
Phosphate is added to water supplies to protect us from lead poisoning. |
Articulations of important ideas/thinking

- we can understand dissolution at the matter particle level in terms of collisions: solvent molecules (e.g., water) need to collide with the solute with sufficient kinetic energy to break the inter-particle interactions within the solute structure (i.e., ionic interactions); this energy “requirement” is the activation energy
- rate $\propto k \times$ surface area of solute; $k \propto Ae^{-E_a/RT}$, but we can be a little more sophisticated by adding “A” to represent the fraction of productive collisions (i.e., in a proper orientation between solvent molecules and solute particles)
- the lower the activation energy, the faster the process proceeds, as the number of solvent molecules possessing the requisite kinetic energy is larger when the activation energy is low
- at the matter particle scale, there are competing processes: e.g., $\text{NaCl(s)} \rightleftharpoons \text{Na}^+(aq) + \text{Cl}^-(aq)$; a dynamic equilibrium is reached when the rates of the forward process and the reverse process become equal
- the rate constants for the forward and reverse process will be dependent on their respective activation energies—we can visualize this with an energy vs. progress diagram; for $K > 1$ (NaCl), the $k_{\text{forward}}$ will be larger; for $K < 1$ (MgCO$_3$), the $k_{\text{reverse}}$ will be larger
- given that $\Delta G^\circ < 0$ for dissolving NaCl, the activation energy for the reverse process is larger than the forward; increasing temperature will affect the rate of the forward process more than the reverse; however, given that $\Delta G^\circ > 0$ for dissolving MgCO$_3$, the activation energy for the forward process is larger than the reverse; increasing temperature will affect the rate of the reverse process more than the forward.
MODULE 6: Chemical Stability and Change

Chemists recognize that matter can not only change phase (liquid, solid, gas), but also transform in more profound ways—into different substances. These chemical changes are also both knowable and predictable. Chemists explain chemical changes mostly as rearrangements of atoms and redistributions of electron density based on interactions between positive and negative charge centers. Chemists understand that many chemical changes are in some ways reversible and/or incomplete. The proportion of reactant and product is governed by 1) the tendency of all things (including chemical systems) toward lower energy and 2) the time needed for the change to occur. This module introduces learners to the energy concepts needed to describe how the composition of a system changes on the way to equilibrium (i.e., enthalpy, entropy, and the Gibbs energy) and the energy concepts needed to describe a system’s relative rate of change (i.e., activation energy). These ideas are used to explain and predict chemical changes. Topics in this Module include:

6.1. Chemical Change
6.2. Chemical Equilibrium
6.3. Chemical Thermodynamics
6.4. Submicroscopic Models of Chemical Change
6.5. Kinetic and Thermodynamic Stability and Control

At the conclusion of Module 6, learners should be able to:

[LO6] Use models of structure and energy to describe how systems undergo chemical changes toward achieving equilibrium.

Module 6 Content Notes

- Many General Chemistry courses and texts introduce representations of chemical change early, without supporting learners in understanding the meaning of the symbols used or what change means in a chemical
context. Here, chemical change is delayed until Module 6 so learners have the opportunity to build an understanding of chemical structure and physical change. Both are critical to understand change in a chemical context and the overarching chemical practice of transformation.

- Two models of chemical change are introduced: acid-base and redox; applications of these two models are further expanded in Modules 8–10. Standard stoichiometry is introduced in the context of these chemical reaction models. Learners are expected to use their understanding of structure built from Modules 1–4 to rationalize stoichiometry, rather than learn stoichiometry in a rote fashion.

- The structure of Module 6 echoes that of Module 5, where ideas related to equilibrium, kinetics, and thermodynamics are combined in a specific progression so that learners can engage with both the extent to which and the rate at which change occurs as the composition of a chemical system evolves toward equilibrium. These ideas are united intentionally so that learners are supported in describing chemical changes—and especially how temperature affects change toward equilibrium.

- In many General Chemistry courses and texts, discussions of submicroscopic models of change (i.e., collision theory) and the methods to collect and analyze rate data are presented together in one chapter/module on “kinetics”. Here, these ideas are separated, and only collision theory is presented; rate data collection/analysis is presented in Module 7 so that this topic can be paired more easily with why chemists collect and analyze rate data: to inform reaction mechanisms.
6.1. Chemical Change. Learners use the chemistry core concepts and models of chemical change to engage in phenomena like *How are the shells of sea creatures created?*

<table>
<thead>
<tr>
<th>forces-organization</th>
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<th>sub-learning outcomes including potentially associated embedded abilities</th>
<th>example connections to UN Sustainability Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical change is driven by the interaction of positive and negative charge centers.</td>
<td>Chemical change is facilitated via collisions of matter particles, often such that negative and positive charge centers collide; the number and types of atoms do not change during a chemical reaction.</td>
<td>Although there is a focus on mass balance during chemical change, more fundamentally, it is energy that is being conserved ((E = mc^2)). During chemical changes, relatively little energy is exchanged with the surroundings and so the change in mass is often so small it can be ignored.</td>
<td>LO6.1.1. (B) Using mass data, make a claim as to whether a chemical reaction is balanced or not. <em>(analyzing and interpreting data)</em> &lt;br&gt;LO6.1.2. (B) Create a model of a chemical reaction (using molecular or ionic structures) to explain why reactant particles collide in a certain orientation to produce the desired products. <em>(developing and using models)</em></td>
<td>– SDG3: Good Health and Well-Being. Aspirin can be formed via a specific collision between salicylic acid (which has a negative charge center) and acetic anhydride (which has a positive charge center).</td>
</tr>
<tr>
<td>– embedded abilities: pull information from electrostatic potential diagrams</td>
<td></td>
<td>LO6.1.3. (D1) Create a model of a chemical reaction (using molecular or ionic structures) to explain that the act of “balancing” ensures the conservation of mass and matter. <em>(developing and using models)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– embedded abilities: balance chemical reaction representations</td>
<td></td>
<td>LO6.1.4. (A) Create a model of a chemical reaction (using molecular or ionic structures) to explain why reactants must combine in certain fixed ratios to produce the desired products. <em>(developing and using models)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– embedded abilities: balance chemical reaction representations; perform limiting reagent/percent yield computations</td>
<td></td>
<td>LO6.1.5. (B) Using macroscopic observations and a symbolic representation of a chemical change, make a claim as to the type of chemical change that is occurring. <em>(engaging in argument from evidence)</em></td>
<td></td>
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<tr>
<td>– embedded abilities: identify oxidation numbers</td>
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</tbody>
</table>
Articulations of important ideas/thinking

- most chemical change is driven by the interaction between positive and negative charge centers on different matter particles; chemical change often leads to charge redistribution
- these matter particle collisions must happen in ways that facilitate product formation, i.e., particles must collide in the correct orientation
- in chemical reactions, reactants combine in fixed ratios to achieve products; mass is neither created nor destroyed; it is merely transferred
- most chemical changes (i.e., matter particles colliding, resulting in the redistribution of electron density) can be described using two models (acid-base and redox) that describe how electron density is redistributed: acid-base reactions involve the redistribution of lone electron pairs and concomitant breaking/forming of covalent bonds while redox reactions similar electron redistributions with concomitant changes in oxidation number
6.2. **Chemical Equilibrium.** Learners use the chemistry core concepts and models of system composition to reason about chemical equilibria at a macroscopic scale and engage in phenomena like *A tube of brown NO\(_2\)(g) converts to colorless N\(_2\)O\(_4\)(g) over time—Why doesn't a tube of brown NO\(_2\)(g) eventually become completely colorless?*

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| Chemical change is driven by the interaction of positive and negative charges. | Chemical change is facilitated via collisions of matter particles, often such that negative and positive charge centers collide; the number and types of atoms do not change during a chemical reaction. | Energy changes related to molecules in bulk provide insight into the extent to which the composition of the system changes toward equilibrium, and energy changes at the scale of individual molecules provide insight into rates of change. | LO6.2.1. (S, B) Use concentration/mass/partial pressure vs. time data to evaluate whether a chemical system has attained a low energy state (i.e., equilibrium). *(analyzing and interpreting data)*  
- **embedded abilities:** negotiate concentrations and partial pressures; pull information from concentration/mass/partial pressure vs. time graphs | - **SDG2:** Zero Hunger. Haber-Bosch ammonia synthesis (N\(_2\) + 3H\(_2\) \rightleftharpoons 2NH\(_3\)), responsible for most of the world's fertilizer, achieves a reactant-favored equilibrium. |
|                      |                                             | LO6.2.2. (S, A) Using the starting composition of a chemical system and its respective equilibrium constant, construct a model (concentration/mass/partial pressure vs. time graph, sequence of molecular representations, etc.) that shows how the system's composition evolves as it approaches equilibrium. *(developing and using models)*  
- **embedded abilities:** construct equilibrium constant and reaction quotient expressions, perform equilibrium computations |                                             | SDG3: Good Health and Well Being. Calcium oxide is used to remove the pollutant SO\(_2\) from smokestack gas; the reaction 2CaO + 2SO\(_2\) + O\(_2\) \rightleftharpoons 2CaSO\(_4\) must achieve an extremely product-favored equilibrium to be effective (*K\(_P\) = 2.4 \times 10^{73})*. |

**Articulations of important ideas/thinking**

- chemical changes tend toward lower energy states; once a low energy state is achieved, no macroscopic changes are observed
- the equilibrium condition is defined by a lack of macroscopic change among the components of a system (assessed using masses/concentrations/partial pressures); we consider a system at equilibrium to be stable (i.e., lower energy state)
• we can describe the composition of a chemical system using the reaction quotient $Q$, as a reference point agreed to by scientists, we refer to $Q = 1$ as the *standard composition*
• the composition of the equilibrium state is described by a special case of $Q$: the equilibrium constant, $K$
• the composition of the equilibrium state is not only different for every system, but also dependent on the conditions at which the system exists
• chemical changes can be described by how the composition of the system changes from some starting composition toward an equilibrium composition
• we describe an equilibrium state as “product-favored” when $K > 1$, and “reactant favored” when $K < 1$
• we can compute equilibrium concentrations or partial pressures using $K$ and starting compositions
• we can qualitatively assess the direction in which a system’s composition will evolve to achieve equilibrium by comparing the starting composition $Q$ to the equilibrium constant $K$
• we can describe two aspects of change toward equilibrium: (1) the extent to which the composition of the system changes on the way to equilibrium (implied by the relative value of $K$) and (2) how quickly an equilibrium composition is obtained (rate); energy changes related to molecules in bulk provide insight into the extent to which the composition of the system changes toward equilibrium, and energy changes at the scale of individual molecules provide insight into rates of change
6.3. Chemical Thermodynamics. Learners use the chemistry core concepts, models of system composition, and ideas related to thermodynamics to engage with phenomena like *Why does the decomposition of cyclobutane to yield ethylene reach a product-favored equilibrium only at temperatures above 163 °C?*

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| Chemical change is driven by the interaction of positive and negative charges; breaking and forming covalent bonds tend to be involved in chemical changes. | Energy transferred during a chemical change is related to interactions formed/broken; energy dispersal increases with the number of different spatial and energetic configurations that the components of a system can adopt. | Aspects of energy that undergird the tendency to change: \( \Delta H \), \( \Delta S \), and \( \Delta G \); how temperature affects the tendency to change: enthalpic effects become less relevant at high temperature, where entropic effects dominate. | LO6.3.1. (A) Develop a model using molecular structures that relates the \( \Delta H^\circ \) for a process to the breaking and forming of matter-particle interactions and covalent bonds; explain why a chemical reaction is either endothermic or exothermic. *(developing and using models)*  
- **embedded abilities:** compute \( \Delta H^\circ \) using enthalpies of formation  
LO6.3.2. (A) Develop a model of how energy disperses among the bonds among and the motions of the reactants and products of a chemical reaction; then, use the model to predict or explain the sign of the associated entropy change for that reaction. *(developing and using models)*  
- **embedded abilities:** compute \( \Delta S^\circ \) using absolute entropies  
LO6.3.3. (S, B) Explain, using qualitative arguments based on the signs of the enthalpy and entropy changes for a chemical reaction starting at the standard composition, whether the equilibrium composition will always be product-favored, will always be reactant-favored, or be product-favored only under certain conditions of temperature. *(constructing explanations)*  
- **embedded abilities:** compute \( \Delta G^\circ \) using \( \Delta H^\circ \), \( \Delta S^\circ \), and \( T \)  
LO6.3.4. (S, B) Using an equilibrium constant or Gibbs free energy change and representations of matter particles, develop a model to explain (beginning at any reaction composition) why the energy and composition of a chemical system change as it approaches equilibrium. *(developing and using models)*  
- **embedded abilities:** compute a reaction quotient; perform computations using \( \Delta H^\circ \), \( \Delta S^\circ \), \( \Delta G^\circ \), \( K \) with correct units and significant figures  
SDG12: Responsible consumption and production. Globally, almost 50% of \( \text{H}_2 \) is produced via steam reforming of natural gas (\( \text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons 3 \text{H}_2 + \text{CO} \)), which attains a product-favored equilibrium only at high temperatures.  
SDG13: Climate Action. \( \text{CO}_2 \) sequestration in the ocean and the resulting formation of carbonic acid—this equilibrium for this process becomes more reactant-favored with increasing temperature; increasing ocean temperatures will result in more \( \text{CO}_2 \) in the atmosphere. | SDG12: Responsible consumption and production.  
SDG13: Climate Action. |
LO6.3.5. (A) Develop a model that illustrates how the Gibbs free energy change and $K$ for a chemical reaction varies as a function of temperature; use this model to explain the consequences of altering the temperature of a chemical change. (developing and using models)

- **embedded abilities**: compute a reaction quotient, perform computations using $\Delta H^\circ$, $\Delta S^\circ$, $\Delta G^\circ$, $T$ and $K$ with correct units and significant figures

**Articulations of important ideas/thinking**

- the tendency for a chemical system to change toward an energy minimum (i.e., an equilibrium) is controlled by the 2nd Law of Thermodynamics; but the complexity of chemical systems necessitates a more nuanced discussion of enthalpy and entropy
- for chemical reactions, we broaden the “breaking and forming interactions” model of enthalpy change to include the energy changes related to the breaking and forming of covalent bonds—breaking covalent bonds consumes energy, and forming covalent bonds liberates energy
- we can use tabulated enthalpies of formation to compute a standard $\Delta H^\circ$ for chemical reactions
- entropy increases as phase changes along $s \rightarrow l \rightarrow g$, but there are also distinct entropy trends related to mass, molecular complexity, and number of particles; given how energy can be dispersed in a collection of molecules in a particular phase, we can develop a qualitative understanding of entropy increases and decreases for chemical reactions
- we can compute a standard entropy change ($\Delta S^\circ$) for a process using tabulated data: standard absolute entropies ($S^\circ$)
- note that the ° symbol denotes that these parameters are computed with the chemical system beginning at the standard composition, $Q = 1$; thus, we must interpret their values as such
- the Gibbs free energy change for a process considers both enthalpy and entropy, as well as temperature: $\Delta G = \Delta H - T\Delta S$
• when $\Delta G^\circ < 0$, the composition of the system will evolve from the standard composition to achieve an equilibrium that favors products; when $\Delta G^\circ > 0$, the composition of the system will evolve from the standard composition to achieve an equilibrium that favors reactants; when $\Delta G^\circ = 0$, the system composition does not change: the equilibrium composition is coincidentally the same as the standard composition
• we can establish the temperature dependence of $\Delta G$ using the relationship $\Delta G = \Delta H - T\Delta S$; using the signs of $\Delta H$ and $\Delta S$, we can comment on the temperature conditions necessary to achieve equilibrium compositions that are product-favored
• if we’re interested in chemical reactions at 25 °C, we can use standard Gibbs energies of formation to compute $\Delta G^\circ$
• we can specify non-standard conditions (i.e., those that might be more applicable to situations we observe in real life) using the reaction quotient $Q$ and compute $\Delta G$ at these conditions using $\Delta G = \Delta G^\circ + RT\ln Q$
• when $\Delta G < 0$, the composition of the system will evolve from the starting composition, producing products to achieve equilibrium; when $\Delta G > 0$, the composition of the system will evolve from the starting composition, producing reactants to achieve equilibrium; when $\Delta G = 0$, the system composition does not change: the equilibrium composition is coincidentally the same as the starting composition
• when $\Delta G = 0$, the system is at equilibrium; thus, the equilibrium composition is related to $\Delta G^\circ$ and the temperature: $\Delta G^\circ = -RT\ln K$
• we see that the equilibrium composition is temperature dependent
### 6.4. Submicroscopic Models of Chemical Change

Learners use the chemistry core concepts and matter particle-scale models of chemical reactions to engage with phenomena like *Why do smog levels increase when temperature increases?*

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| Chemical change is driven by the interaction of positive and negative charges; breaking and forming covalent bonds tend to be involved in chemical changes. | Rate of change depends on matter particles colliding with each other—the “productivity” of these collisions depends on the structures of the species colliding. | Energy distributions of molecules; activation energy; matter-particle kinetic energies manifest in how quickly the equilibrium state is attained. | LO6.4.1. (A) Construct a model using representations of molecules and their potential interactions and collisions along with distributions of reactant kinetic energies to explain how and why temperature affects the rate at which a chemical reaction occurs. *(developing and using models)*  
  - **embedded abilities:** perform computations using the Arrhenius relationship | SDG3: Good Health and Well Being. Chiral compounds racemize (interconvert from one enantiomer to another); racemization rates can affect the efficacy of therapeutic compounds (thalidomide versus amino acids).  
  SDG12: Responsible consumption and production. Hydrocarbon-based polymers are often recycled via “cracking” into short-chain hydrocarbons; this occurs at extremely high temperatures due to the large activation energies. |
|                      |                     |                 | LO6.4.2. (A) Construct and use models *(molecular structures and reaction progress diagrams)* to show how energy changes over the course of a chemical reaction are determined by the interactions that break and form. *(developing and using models)*  
  - **embedded abilities:** draw and pull information from Gibbs free energy versus process progress diagram; complete computations using $\Delta H^\circ$, $\Delta S^\circ$, $\Delta G^\circ$, $K$ |                  | LO6.4.3. (S, B) Using a reaction progress diagram, predict for a chemical reaction how the rates of the associated forward and reverse processes will change when conditions (amounts/concentrations/partial pressures/temperature) are changed; justify this prediction based on the frequency of matter-particle collisions. *(constructing explanations)*  
  - **embedded abilities:** draw and pull information from Gibbs free energy versus process progress diagrams; apply Le Châtelier’s principle |  |
Articulations of important ideas/thinking

- The rate at which a chemical system changes toward an energy minimum (i.e., an equilibrium) is controlled by sub-microscopic collisions between molecules.
- To react, two molecules must collide with each other with sufficient kinetic energy to break bonds and in an effective orientation to achieve a transition state structure; this energy “requirement” is the activation energy.
- Rate $\propto k = A e^{-E_a/RT}$, “A” represents the fraction of productive collisions (i.e., in a proper orientation between solvent molecules and solute particles).
- The lower the activation energy, the faster the process proceeds, as the number of solvent molecules possessing the requisite kinetic energy is larger when the activation energy is low.
- At the matter particle scale, there are competing processes: the forward and reverse processes; a dynamic equilibrium is reached when the rates of the forward process and the reverse process become equal.
- The rate constants for the forward and reverse process will be dependent on their respective activation energies—we can visualize this with an energy vs. progress diagram.
- For $K > 1$, the $k_{\text{forward}}$ will be larger; for $K < 1$, the $k_{\text{reverse}}$ will be larger.
- Reasoning about how altering conditions will affect forward and reverse reaction rates (and thus how systems at equilibrium will respond to changes in condition) is quite common in chemistry—the outcomes of such reasoning are summarized by Le Châtelier’s principle.
6.5. Kinetic and Thermodynamic Stability and Control. Learners use the chemistry core concepts, and ideas related to both kinetics and thermodynamics to reason about stability and controlling chemical processes, and with phenomena like *Why does temperature affect which product predominates from the reaction of HBr and 1,3-butadiene?*

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| Chemical change is driven by the interaction of positive and negative charges; breaking and forming covalent bonds tend to be involved in chemical changes. | Chemical change is facilitated via collisions of matter particles, often such that negative and positive charge centers collide. | Whether a substance is stable or whether it changes depends on energy at both the system-level and submicroscopic scales | LO6.5.1. (B) Rationalize why a particular chemical system is "stable" under a given set of conditions (i.e., it does not seem to be changing) using activation energy and Gibbs energy data. (analyzing and interpreting data)  
- **embedded abilities:** draw and pull information from Gibbs free energy versus process progress diagrams | SDG2: Zero Hunger. 2% of the global energy output goes into synthesizing NH₃ for fertilizer via the Haber-Bosch process (N₂ + 3H₂ ⇌ 2NH₃) because of the reaction’s high activation energy; however, increasing temperature decreases the reaction’s equilibrium constant. |
| LO6.5.2. (B) Using energy ideas related to both the rate of change and the tendency to change, describe how temperature will affect these two aspects of a chemical reaction. (developing and using models)  
- **embedded abilities:** draw and pull information from Gibbs free energy versus process progress diagrams | LO6.5.3. (B) Using molecular representations, show how the collision of two molecules could form multiple products. (developing and using models) | LO6.5.4. (B) Given reaction progress diagrams with different reactivity pathways for a chemical reaction, determine which products will form quickly, which products may be more stable over time, and why these two products may not be the same. (developing and using models)  
- **embedded abilities:** draw and pull information from Gibbs free energy versus process progress diagrams | LO6.5.5. (A) For cases of chemical reactions that produce different products under different conditions, construct and use models (molecular structures and reaction progress diagrams) to explain why certain temperature conditions favor certain product formation. (developing and using models)  
- **embedded abilities:** draw and pull information from Gibbs free energy versus process progress diagrams |
Articulations of important ideas/thinking

- energy at both the submicroscopic and chemical system scales provides insight into how chemists use temperature to control chemical reactions
- we interpret *stability* as being dependent on conditions—a chemical substance might be stable under one set of conditions but be unstable (i.e., change to establish a new equilibrium) under other conditions
- we interpret stability as having only one of two main origins – kinetics or thermodynamics; we distinguish between *kinetic metastability* and *thermodynamic stability*
- something we refer to as a "fuel" should be kinetically metastable, but thermodynamically unstable under appropriate conditions
- some chemical reactions produce one product at one set of conditions, but produce a different product at another set of conditions
- we use reaction progress diagrams to explain the temperature conditions at which one product will be favored over another in cases where a reaction can produce two different products
MODULE 7: Determining How Chemical Change Occurs

Every process has a rate (fast or slow) and factors on which that rate depends. Chemists explain the rates of chemical and physical changes according to the necessary energy, orientation, pressure, and concentration of the involved particles. Chemists use measurements of reaction rate and associated data analysis procedures to draw conclusions about how chemical change happens at the submicroscopic scale. Topics in this Module include:

7.1. Reaction Mechanism
7.2. Measuring Reaction Rates
7.3. Reaction Rate Measurements Inform Mechanism Hypotheses
7.4. Catalysis
7.5. Predicting the Timing of Chemical and Physical Processes

At the conclusion of Module 7, learners should be able to:

[LO7] Use submicroscopic models of chemical reactions along with kinetic measurements to explain or predict how a chemical reaction occurs.

Module 7 Content Notes

- In many General Chemistry courses and texts, a “kinetics” chapter/module presents methods to collect and analyze chemical reaction rate data as well as discussions of submicroscopic models of change (i.e., collision theory). Here, these ideas are separated. Collision theory was presented in Modules 5 and 6. Rate data collection/analysis is presented in this Module so that this topic can be paired more intentionally with why chemists collect and analyze rate data—to inform submicroscopic models of change (i.e., reaction mechanism).

- Because reaction mechanisms are cascades of molecular collisions that “sum” to the net chemical change process, another aspect of summing reactions and associated parameters is presented here: Hess’s law. Introducing Hess’s law is delayed until learners have engaged with reaction progress diagrams, which are useful representations for
understanding the energy changes of a multi-step change process. Moreover, ideas regarding one process being used to thermodynamically “drive” another are presented.
7.1. Reaction Mechanism. Learners use the chemistry core concepts and models of submicroscopic particle collisions to engage in phenomena like It is very unlikely that two O2 molecules will collide simultaneously with a CH4 molecule—so how does natural gas combustion happen?

Articulations of important ideas/thinking
- chemical change doesn’t always occur according to the collisions dictated by the balanced chemical equation; we describe these step-by-step changes using reaction mechanisms
• some reactions require more than one reaction event (a multistep process). We interpret a reaction mechanism as a series of elementary reactions that propose how these reactions may occur

• catalysts and intermediates present themselves in different ways in a reaction mechanism

• if a multistep process best describes a reaction, the enthalpy, entropy, Gibbs energy, and equilibrium constant of the overall reaction are related to the individual steps via Hess’s Law

• we interpret Gibbs free energy changes for endergonic and exergonic processes in terms of direction (regarding the system and the surroundings) and use proper sign conventions in discussing the transfer of Gibbs free energy as work

• we interpret reaction coupling as a highly product-favored reaction sharing the Gibbs free energy it produces with a reactant-favored reaction that needs energy to become product-favored; reactions are coupled by a common intermediate
7.2. Measuring Reaction Rates. Learners use submicroscopic models of chemical reactions to reason about reaction rate data and engage in phenomena like *Why does the isomerization rate of cis-2-butene to trans-2-butene depend on the concentration of cis-2-butene?*

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| Chemical change is driven by the interaction of positive and negative charge centers; many chemical reactions involve the breaking and forming of interactions between matter particles (covalent bonds and/or ionic interactions). | The rate of a chemical reaction is related to the probability of productive collisions between molecules. | The rate of a chemical reaction is related to its activation energy. | LO7.2.1. (B) Determine the rate (average or instantaneous) of a chemical change from a graph of concentration versus time data and discuss what features of the graph were important in making these decisions. *(analyzing and interpreting data)*  
- **embedded abilities**: pull information from concentration vs. time graphs  
LO7.2.2. (B) Develop a model using representations of reaction components to explain why reaction rates can differ depending on which reactant or product concentration is being monitored. *(constructing explanations)*  
- **embedded abilities**: interpret balanced chemical reactions  
LO7.2.3. (B) Generate a representation that illustrates how concentrations change with time for all components of a chemical reaction. *(using mathematics and computational thinking)*  
- **embedded abilities**: interpret balanced chemical reactions; generate and pull information from concentration vs. time graphs; complete computations using relative rates  
LO7.2.4. (A) Analyze initial rate data for a reaction to determine the reaction order with respect to each reaction component, the rate constant, and/or the overall rate law; discuss what features of the data were important in making these decisions. *(analyzing and interpreting data)*  
- **embedded abilities**: complete computations using rate laws  
LO7.2.5. (B) Analyze rate constant data as a function of temperature for a chemical reaction to determine the activation energy of the process; discuss what features of the data were important in making these decisions. *(analyzing and interpreting data)*  
- **embedded abilities**: construct and pull information from graphs of ln(k) vs. 1/T |
| - SDG3: Good Health and Well Being.  
Acetaminophen (and other amide or ester-based pharmaceuticals) decomposes faster under humid conditions due to hydrolysis. |
LO7.2.6. (D1) For a reaction of type $A + B \rightarrow \text{products}$, design an experiment using the *flooding method* (pseudo first-order) to determine the reaction’s rate constant and the order with respect to each reactant; identify the experimental observations required to determine these quantities, how the experimental procedure permits making these observations, and how these observations can be used to draw conclusions. *(planning investigations)*

Articulations of important ideas/thinking

- in this sub-Module, reasoning is more centered on kinetics data analysis and interpretation than it is reasoning with the chemistry core concepts; thus, very few sub-LOs are color-coded to the core concepts
- In a reaction mechanism, one step is always the slowest; an entire process can only go as fast as its slowest step. So, it becomes important to understand the rates of reactions and what affects them (i.e., determining a rate law). How do we measure that?
- we describe the *rate* of a chemical reaction as the change in concentration of a reactant or a product per unit of time
- we use a reaction’s *stoichiometry* to justify the different reaction rates observed when tracking the concentrations of different reaction components.
- we interpret a *rate law* as a mathematical model for how the concentrations of reactants affect (or do not affect) the overall reaction rate.
- we can construct rate laws for elementary processes (unimolecular or bimolecular) using the stoichiometry of those processes
- we interpret a *rate constant* as a quantity that describes a reaction rate in a way that is independent of concentration; the rate constant, however, does depend on temperature
- we determine the *reaction order* with respect to individual reactants or the *overall reaction order* for a reaction from a rate law
- we predict the units of a rate constant based on the order of a reaction or *vice versa*
we can describe what features of a graph of concentration versus time data denote the initial rate, instantaneous rate, and order of a chemical reaction
7.3. Reaction Rate Measurements Inform Mechanism Hypotheses. Learners use the chemistry core concepts, multistep models of chemical reactions, and rate data to engage with phenomena like Why does the rate of the reaction between benzyl bromide and cyanide only depend on the concentration of benzyl bromide?

<table>
<thead>
<tr>
<th>forces-organization</th>
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<tbody>
<tr>
<td>Chemical change is driven by the interaction of positive and negative charge centers; many chemical reactions involve the breaking and forming of interactions between matter particles (covalent bonds and/or ionic interactions).</td>
<td>We hypothesize whether a reaction occurs as written by investigating molecular structures and whether a productive collision will yield desired products.</td>
<td>A reaction only proceeds as fast as its highest-energy step and the step with the largest activation energy is the rate-determining step.</td>
<td>LO7.3.1. (A) Given submicroscopic representations of proposed mechanisms for a chemical process, determine which mechanism is more appropriate based on the number of molecules (i.e., molecularity), intermolecular collisions, and expected enthalpy/entropy changes involved in each step. (engaging in argument from evidence) LO7.3.2. (B) Given a chemical reaction and a proposed mechanism for that reaction, infer the rate law and use representations of molecular collisions to predict how the rate of reaction may vary with the concentration of each reactant. (developing and using models) LO7.3.3. (A) Evaluate whether a reaction mechanism agrees with a reaction energy diagram and/or an experimentally determined stoichiometry, rate law, or other kinetic data. (evaluating information)</td>
<td>- SDG3: Good Health and Well Being. Photochemical smog is the result of a cascade of reactions that begins with oxygen atoms generated from nitrogen oxides.</td>
</tr>
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</table>

Articulations of important ideas/thinking

- we can use rate data to make claims about mechanism
- the slowest step of a reaction mechanism is referred to as the rate-determining step; thus, if rate of the first step matches the rate of the mechanism, the first step is the slow step
- we can use the equilibrium approximation to express reactant concentrations when the rate-determining step is not the first step of a reaction mechanism
- the rate-determining step can be illustrated in reaction energy diagrams—the step with the largest activation energy barrier is the rate-determining step
7.4. Catalysis. Learners use the chemistry core concepts and matter particle-scale models of chemical reactions to engage with phenomena like *Why are iron and ruthenium catalysts used in the production of ammonia?*

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| Catalysts (enzymes or surfaces) interact with their substrates via interparticle forces like LDFs or hydrogen bonding; enzyme specificity is rooted in specific intermolecular forces between substrate and active site. | Catalysts position and orient reactants in ways so that the fraction of productive collisions is increased. | Catalysts either directly lower the activation energy of a process or provide an alternate mechanism that overall has lower activation energy than the uncatalyzed mechanism. | LO7.4.1. (B) Given two reaction progress diagrams, determine which represents a catalyzed reaction; describe what aspects of the graphs allowed you to draw these conclusions. *(analyzing and interpreting data)*  
- **embedded abilities:** pull information from reaction progress diagrams  
LO7.4.2. (A) Construct a model using representations for enzyme- or surface-catalyzed reactions that highlight substrate catalyst interactions to explain how and why the reaction rate *saturates* at high substrate concentration. *(constructing explanations)*  
- **embedded abilities:** pull information from rate vs. [substrate] graphs for a catalyzed reaction  
LO7.4.3. (A) Construct a model using representations for substrates and an enzyme/surface as well as reaction progress diagrams to explain how an enzyme or surface can affect reaction rate; describe how the information provided by the enzyme or surface/substrate representation maps onto specific features of the reaction progress diagram. *(developing and using models)*  
- **embedded abilities:** pull information from reaction progress diagrams | - SDG3: Good Health and Well-Being. Catalytic converters in exhaust systems reduce emissions of NO by lowering $E_a$ for $2 \text{NO} \rightleftharpoons \text{N}_2 + \text{O}_2$.  
- SDG12: Responsible Consumption and Production. Enzymes can be engineered to convert biomass into "second generation biofuels" like ethanol.  
- SDG12: Responsible Consumption and Production. Enzymatic processes can convert cornstarch into polylactic acid–based plastic materials. |

**Articulations of important ideas/thinking**
- catalysts are substances that increase the rate of certain chemical reactions; they do this by reducing the activation energy, making productive collisions more probable, or by changing the reaction mechanism to accomplish either of the former points
- homogeneous catalysis involves the catalyst being in the same phase as the reaction; heterogeneous catalysis involves the catalyst being in a different phase (usually a solid) than the reaction
- substances that catalyze biological processes are called enzymes; many enzymes follow a Michaelis-Menten mechanism
- many reactions can be catalyzed on the surfaces of materials
7.5. Predicting the Timing of Chemical and Physical Processes. Learners use mathematical models of reaction rate to reason about the timing of chemical and physical processes, and with phenomena like Six main radioactive isotopes of iodine exist—why is iodine-131 specifically used to treat thyroid cancer?

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<tbody>
<tr>
<td>Chemical change is driven by the interaction of positive and negative charge centers; many chemical reactions involve the breaking and forming of interactions between matter particles (covalent bonds and/or ionic interactions).</td>
<td>The rate of a chemical reaction is related to the probability of productive collisions between molecules.</td>
<td>The rate of a chemical reaction is related to its activation energy.</td>
<td>LO7.5.1. (B) Given concentration versus time data plotted according to zero-, first-, and/or second-order integrated rate laws, determine the order of the reaction and discuss what features of the graphs were important in making these decisions. (analyzing and interpreting data) - embedded abilities: pull information from graphs of concentration vs. time data</td>
<td>- SDG3: Good Health and Well Being. Radioisotopes decay according to first-order kinetics and can be used very specifically in nuclear medicine applications. - SDG3: Good Health and Well Being. The half-life of a pharmaceutical can be a guide for how long a drug will take to reach a stable level in your body when you first start taking it.</td>
</tr>
<tr>
<td>LO7.5.2. (A) Given the half-life of a radioactive substance and particulate representations of radioactive atoms, construct a model to describe how the number of radioactive particles in a sample decrease over time. (developing and using models) - embedded abilities: complete integrated rate law computations</td>
<td>LO7.5.3. (D1) Use kinetic data to construct a model of the dosing needed to maintain a specific concentration of therapeutic agent. (using mathematics and computational thinking) - embedded abilities: complete integrated rate law computations</td>
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Articulations of important ideas/thinking

- in this sub-module, reasoning is more centered on kinetics data analysis and interpretation than it is reasoning with the chemistry core concepts; thus, very few sub-LOs are color-coded to the core concepts
- the integrated rate laws are mathematical transformations of rate laws; they describe functions that relate concentration and time for three different reaction types: zero-order, first-order, and second-order
- few uncatalyzed reactions are zero-order
● we apply the *integrated rate laws* to calculate a concentration at any given time during a reaction, or the time necessary to reach a certain concentration (e.g., 50% of initial concentration provides the half-life)
● we use concentration versus time data, plotted according to the first-, and second-order integrated rate laws, to determine the order of the reaction
MODULE 8: Harnessing Chemical Energy

Chemists explain how chemical changes are accompanied by electricity according to the observed stability/instability of the involved substances. Chemists explain the useful voltage, current, and work available in relatively unstable systems and the ability to store electricity by destabilizing a relatively stable system. Chemists use these explanations in a wide range of applications including batteries, photosynthesis, metallurgy, neurological function, corrosion, and chemical analysis. Chemists understand that all these electrical properties correspond qualitatively and quantitatively to the stability (thermodynamics) and composition (equilibrium) of all chemical systems—that the three (electrical potential, thermodynamics, and equilibrium) are inextricably interrelated. There are effectively three ways to describe the same behaviors. Topics in this Module include:

8.1. Electrochemical Cells
8.2. Controlling Electrical Current and Potential
8.3. Electrolysis

At the conclusion of Module 8, learners should be able to:

[LO8] Use submicroscopic redox reaction models and macroscopic electrochemical cell models to explain how energy is harnessed from chemical processes.

Module 8 Content Notes

- Given that electrical potential and current are direct manifestations of the topics presented in Modules 6–7 (thermodynamics and kinetics, as applied to redox reactions), electrochemistry is presented here in Module 8.
- In many General Chemistry courses and texts, an “electrochemistry” chapter/module concentrates only on the thermodynamic aspects of redox reactions (i.e., the connection between $\Delta G^\circ/K$ and electrical potential). Since learners were supported in considering both the kinetic and thermodynamic aspects of chemical change in
Modules 6–7, this Module also presents the kinetics aspects of redox reactions, as they relate to electric current and the overpotential needed to carry out nearly all electroplating procedures.
8.1. Electrochemical Cells. Learners use the chemistry core concepts and matter-particle models of redox reactions to engage in phenomena like *How does a battery generate an electric current?*

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| Chemical change is driven by the interaction of positive and negative charges; electrostatics controls the migration of ions to electrodes. | Oxidation numbers of atoms are related to the structure of the molecular compound containing the atoms. | Cell potential is a measure of energy per unit charge. | LO8.1.1. (B) Use oxidation numbers and molecular structures (when necessary) to show how charge is redistributed in an aqueous redox reaction. *(constructing explanations)*  
- **embedded abilities**: identify oxidation numbers; balance redox reactions  
LO8.1.2. (A) Using a balanced redox reaction, develop a model for a voltaic cell; use this model to explain the submicroscopic origin and direction of electric current for the redox reaction, the movement of ions across the salt bridge, and the change in mass of electrodes. *(developing and using models)*  
- **embedded abilities**: identify half-reactions and oxidizing/reducing agents; balance redox reactions | - SDG7: Affordable and Clean Energy. Not all communities have access to burnable fuels such as propane or wood. Electrochemical devices pair nicely with wind energy and solar energy by providing batteries for energy storage.  
- SDG7: Affordable and Clean Energy. Photovoltaic devices convert sunlight into electrical energy. |

**Articulations of important ideas/thinking**

- most chemical change is driven by the interaction between positive and negative charge centers on different matter particles; chemical change often leads to a redistribution of charge  
- in redox reactions, electrons tend to move from higher to lower potential energy states  
- the electron transfer that takes place during some redox reactions can be used to generate an electric current  
- electrochemical cells are systems designed to control the transformation of chemical energy into electrical energy  
- electrochemical devices that generate electrical energy (voltaic cells) are built from redox reactions that reach a product-favored equilibrium  
- voltaic cells often include three basic parts: (1) a chemical system that undergoes oxidation (anode); (2) a chemical system that undergoes reduction (cathode); and (3) a mechanism to allow and control charge transfer
8.2. Controlling Electrical Current and Potential. Learners use the chemistry core concepts, matter-particle models of redox reactions, and energy concepts to engage in phenomena like *How do rechargeable batteries like nickel-cadmium and lithium-ion cells work?*

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| Chemical change is driven by the interaction of positive and negative charges; electrostatics controls the migration of ions to electrodes. | Oxidation numbers of atoms are related to the structure of the molecular compound containing the atoms. | Cell potential is a measure of energy per unit charge; the electric current depends on the rate at which charge is transferred; we infer relative stability using cell potentials. | LO8.2.1. (B) Compare the *relative stability* of two aqueous species related by a charge transfer and/or the relative strength of oxidizing and reducing agents using experimental data (*standard half-cell potentials*). *(analyzing and interpreting data)*  
  - **embedded abilities**: assign oxidation numbers, identify half-reactions and oxidizing/reducing agents  
| © 2022 Center for Curriculum Redesign - All Rights Reserved | LO8.2.2. (B) Develop a model using *matter particles, collisions*, and *standard half-cell potentials* to explain how and why electrons are transferred during a redox reaction. *(developing and using models)*  
  - **embedded abilities**: complete computations using standard half-cell potentials, $\Delta G^\circ$, and $K$  
| SDG3: Good Health and Well Being. Battery lifetime and self-charging advances for implantable biomedical devices  
SDG7: Affordable and Clean Energy. Biobatteries are devices powered by bioorganic compounds, usually glucose, that mimic how living organisms use energy from metabolic reactions. |
| LO8.2.3. (A) Develop a model to predict or explain the effect of changing temperature, pressure, and/or electrode composition (electrodes, electrolytes, and electrolyte concentrations) on an *electrochemical device's directionality, extent, and energy cost/output*. *(developing and using models)*  
  - **embedded abilities**: complete computations using standard half-cell potentials, $\Delta G^\circ$, and $K$; complete computations using the Nernst relationship; generate or pull information from a graph of potential vs. temperature/pressure  
| LO8.2.4. (A) Develop a model to predict or explain the effect of changing temperature, pressure, and/or electrode composition (electrodes, electrolytes, and electrolyte concentrations) on the electric current generated by an electrochemical device. *(developing and using models)*  
  - **embedded abilities**: generate or pull information from a graph of current vs. temperature/pressure  
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LO8.2.5. (D1) Develop a model to illustrate (beginning with any electrochemical cell composition) how and why the electrode composition, electrical potential, or electric current of an electrochemical cell changes as it approaches equilibrium.
(developing and using models)
- **embedded abilities:** complete computations using the Nernst relationship

LO8.2.6. (D1) Design or analyze a battery that provides a specific potential or current; identify specific design elements that are important to the device’s function and describe how those design elements result in a device that can accomplish its function.
(planning investigations)
- **embedded abilities:** assign oxidation numbers, identify half-reactions and oxidizing/reducing agents, complete computations using standard half-cell potentials

**Articulations of important ideas/thinking**
- we interpret a cell potential as a measure of the *energy per unit charge* available from a redox reaction; the cell potential represents the difference in electrical potential between the two half cells of a voltaic cell
- cell potentials depend on the nature and concentration of reactants and products, but not on the quantity of each that reacts
- we interpret a standard reduction potential as the extent to which a substance transforms into a more stable substance upon gaining a negative charge
- cell potential is related to the Gibbs free energy for the redox process and thus can be used to assess the directionality and extent of a redox process
- we use the enthalpy and entropy changes for a redox process to analyze the energy cost and output of a redox process
- the Nernst relationship can be used to compute cell potentials under non-standard conditions (including concentration cells)
- *Faraday’s constant* can be useful in computing the total quantity of charge transferred per mole of a redox reaction
• the magnitude of the electric current is determined by the rate of the chemical reaction taking place in the cell.
• voltage can even be produced from a singular substance when it is present in two different concentrations (concentration cells)
• corrosion (rust and other forms of oxidation) is simply the observed product of naturally occurring (spontaneous) reactions
• considerable attention is devoted to corrosion control/prevention
8.3. Electrolysis. Learners use the chemistry core concepts, matter-particle models of redox reactions, and energy concepts to engage in phenomena like *Why must 14 volts be applied to recharge a 12 V car battery?*

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<tbody>
<tr>
<td>Chemical change is driven by the interaction of positive and negative charges; electrostatics controls the migration of ions to electrodes.</td>
<td>Oxidation numbers of atoms are related to the structure of the molecular compound containing the atoms.</td>
<td>Energy can be provided to a redox process to cause it to reverse direction; overpotentials are used to overcome the high activation energies of electrolytic processes.</td>
<td>LO8.3.1. (A) Design an electrolytic cell or electroplating procedure that consumes energy to accomplish a particular task (e.g., liberate a desired amount of product, etc.); identify specific design elements that are important to the device’s function and describe how those design elements result in a device that can accomplish its function. (planning investigations) - embedded abilities: identify oxidation numbers, complete computations using standard half-cell potentials, compute amount of material liberated during an electrolysis procedure</td>
<td>SDG6: Clean Water and Sanitation. Electrochemical disinfection in water and wastewater treatment generates oxidants in situ - SDG9: Industries, Innovation, and Infrastructure. Galvanization helps extend steel’s lifetime, especially when it is in contact with the ground or sea air, or in wet/humid areas. - SDG12: Responsible Consumption and Production. About 2% of the USA’s energy goes to electrochemical aluminum production, while aluminum recycling only requires 5% of that energy.</td>
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</table>

**Articulations of important ideas/thinking**

- *electrolysis* is a process where electrical energy is supplied to cause a redox reaction to occur in the reverse direction
- electricity can be used to plate one metal onto another via electrolysis; we examine this quantitatively using Faraday’s laws
- the amount of material liberated during electrolysis is proportional to the total charge transferred by the electrochemical cell (via the number of electrons transferred per mole of reaction)
- an *overpotential* represents the additional energy required to overcome barriers such as the large activation energies for some processes; overpotentials are needed in all electrolytic processes
MODULE 9: Acid-Base Chemistry and Chemical Synthesis

Regions of high and low electron density associated with molecules are uniquely important in chemical changes. The efforts of chemists to affect the movement, presence, absence, addition, and removal of electron density from those regions are paramount to an overwhelming number of chemical reactions. Chemists use reasoning related to the interaction of negative and positive charge centers on molecules, which are extremely important to the chemical practice of synthesis, to explain or predict all acid-base reactions. Topics in this Module include:

9.1. Aqueous Acids and Bases
9.2. Structure-Property Relationships in Aqueous Acids and Bases
9.3. Acid-Base Reactions
9.4. The Acidity of Aqueous Cations
9.5. Chemical Synthesis

At the conclusion of Module 9, learners should be able to:

[LO9] Use submicroscopic models of acid-base reactions to explain or predict the outcome of a chemical reaction or why certain conditions are chosen to optimize a chemical reaction.

Module 9 Content Notes

- Acid-base chemistry is expanded upon in Modules 9 and 10 and content is partitioned based on the connections of acid-base chemistry to two chemistry practices: synthesis (Module 9) and analysis (Module 10).
- In many General Chemistry courses and texts, an “acids and bases” chapter/module leads with a discussion of the macroscopic observations that define an acid and a base (i.e., the pH of aqueous solutions). Here, discussions of pH and its molecular origins are delayed until Module 10—until learners are supported in reasoning with a submicroscopic model of acid-base reactions.
• This Module supports learners in explaining/predicting relative acid-base reactivity by examining molecular structure. To achieve this, the Module is concerned with using structure to analyze (1) the charge distributions in acidic and basic molecules and (2) the charge redistribution that occurs in an acid-base reaction. Thus, the Lewis model of acid-base reactions (instead of Brønsted-Lowry and Arrhenius) and the associated curved arrow formalism are preferred here.

• The Module progresses from the interaction of acidic and basic molecules with water to the interaction of acids/bases with acids/bases other than water.

• Although they are not components of a traditional General Chemistry course, this Module introduces learners to the chemical practice of *synthesis* and the topic of Green Chemistry. The goal is for learners to analyze reactions thermodynamically and kinetically (using curved arrow mechanisms) and practically (using tenants of Green Chemistry) to explain or predict some observation of a phenomenon.
9.1. Aqueous Acids and Bases. Learners use the chemistry core concepts and matter-particle models of acid-base reactions to engage in phenomena like Why does Alka-Seltzer “fizz” when you drop the tablets into water?

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<tbody>
<tr>
<td>Most acid/base reactions are driven by electrostatic attractions (i.e., the interaction of positive and negative charges).</td>
<td>Electron-rich centers (like the N atom of amines) tend to act as bases, while electron-poor centers (like the H atom of carboxylic acids) tend to act as acids.</td>
<td>Aqueous strong acids are less stable than aqueous weak acids, based on $\Delta G^\circ$ and $K$.</td>
<td>LO9.1.1. (A) Using conductivity data, develop a model using molecular representations for why dissolving a carboxylic acid or amine gives rise to an increase in conductivity, but dissolving an alcohol or an amide does not. (analyzing and interpreting data) LO9.1.2. (B) Using a molecular structure and/or experimental data (e.g., $pK_a$), identify potential acidic and basic centers in a molecule and predict how those centers will interact with water. (developing and using models) ◦ embedded abilities: draw Lewis structures; pull information from electrostatic potential diagrams; interpret $K_a/K_b/pK_a/pK_b$ values LO9.1.3. (B) Illustrate using curved arrows and molecular representations the redistribution of electron density during the reaction of an acid or base with water. (developing and using models) ◦ embedded abilities: draw Lewis structures; show redistribution of electrons with curved arrows LO9.1.4. (A) Construct a model using $K_a/K_b/pK_a/pK_b$ values and molecular or particulate representations to illustrate the relative equilibrium concentrations of species present when an acid or base is introduced into an aqueous solution. (developing and using models) ◦ embedded abilities: draw Lewis structures; construct balanced chemical reactions of acids/bases with water; identify conjugate pairs; compute equilibrium concentrations using $K_a/K_b$</td>
<td>– SDG3: Good Health and Well Being. Most pharmaceuticals on the market have acid-base properties, which are crucial for their solubility and biological activity. – SDG12: Responsible Consumption and Production. Pollutants like $SO_2$ and $NO_x$ react with $H_2O$ in the atmosphere to produce acid rain. – SDG14: Life Below Water. Carbon dioxide reacts with ocean water to form carbonic acid, thus acidifying oceans.</td>
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</tbody>
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Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded

- acid-base reactions are driven by the interaction between positive and negative charge centers on different matter particles; acid-base reactions tend to lead to a redistribution of charge
- we model acid-base reactions as the electron-rich base donating electron density to an electron-poor acid; covalent bonds tend to be broken and formed during this process
- we illustrate the redistribution of electron density during an acid-base reaction using *curved arrows*
- many acid-base reactions that are central to industry and life involve H₂O; H₂O can act as either an acid or a base (depending on conditions) and can even undergo an acid-base reaction with itself (called autoionization)
- not all acids and bases react with water to the same extent; we can describe the reaction of an acid or base with water using an appropriate equilibrium constant (*Kₐ* or *Kₐ*; water ionization is described with *Kₐ*)
- like other equilibrium constants, *Kₐ*, *Kₐ*, and *Kₐ* are temperature dependent
- the extent to which an acid or base reacts with water (i.e., the value of *K*) determines its *strength*
- reactions of acids and bases with water tend to occur very quickly; but many do not achieve product-favored equilibria (*K > 1*)
- a common mathematical manipulation of a *Kₐ* or *Kₐ* is to generate p*Kₐ* and p*Kₐ*; this inverts the idea of “strength” being related to these values
9.2. Structure-Property Relationships in Aqueous Acids and Bases. Learners use the chemistry core concepts, matter-particle models of acid-base reactions, and energy concepts to engage in phenomena like *Why is the Ka of trifluoroacetic acid 55,000 times larger than the Ka for acetic acid?*

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| Analyses of charge distribution are of central importance in making predictions about acid or base strength. | Structure can affect the electron density distribution in a molecule and thus the relative reactivity of electron density centers toward water. | Stability is related to the \( \Delta G^\circ \) (K) of the reaction of the acid/base with water. | LO9.2.1. (B) Use thermodynamic data, molecular structures, and Coulomb's law to explain why the conjugates of polyprotic acids become progressively "weaker" after each deprotonation. (analyzing and interpreting data)  
- **embedded abilities:** draw Lewis structures; identify conjugate pairs; interpret thermodynamic parameters, compute \( \Delta G^\circ \) using \( \Delta S^\circ \), \( \Delta H^\circ \), and \( T \)  
| | | | LO9.2.2. (A) Construct a model using molecular representations, relative stabilities and energies (via \( K_a \), \( pK_a \), and/or \( \Delta G^\circ \)) of acids and their conjugate bases, and reaction progress diagrams to explain how and why the strengths of two acids differ. (developing and using models)  
- **embedded abilities:** draw Lewis structures; interpret \( K_a/K_b/pK_a/pK_b \) values; compute \( K_a/K_b \) or \( pK_a/pK_b \) values using conjugate pair relationships; construct and pull information from reaction progress diagrams  
| | | | LO9.2.3. (A) Construct a model using molecular representations, relative stabilities and energies (via \( K_b \), \( pK_b \), and/or \( \Delta G^\circ \)) of bases and their conjugate acids, and reaction progress diagrams to explain how and why the strengths of two bases differ. (developing and using models)  
- **embedded abilities:** draw Lewis structures; interpret \( K_a/K_b/pK_a/pK_b \) values; compute \( K_a/K_b \) or \( pK_a/pK_b \) values using conjugate pair relationships; construct and pull information from reaction progress diagrams  
| | | | LO9.2.4. (B) Using models of molecular structure, explain why proposed compositional/structural modifications would increase or decrease the strength of an acid or base. (constructing explanations)  
- **embedded abilities:** draw Lewis structures |
Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded

- there are enthalpy and entropy considerations when thinking about stability in terms of a reaction between an acid/base and water
- the conjugate of a polyprotic acid is usually a much weaker acid than was the original polyprotic acid; we can examine this using enthalpy and entropy
- in general, the more stable species have lower charge densities; analyses of charge distribution are of central importance in making predictions about acid-base reactivity
- the stability of charged species is affected by the size and electronegativity of the atoms that hold the charge
- negative charge can be stabilized if there is a way to delocalize electron density among different atoms; atoms or groups of atoms close to a center of charge can have a stabilizing or destabilizing effect depending on how they affect electron density
9.3. Acid-Base Reactions. Learners use the chemistry core concepts, matter-particle models of acid-base reactions, and energy concepts to engage in phenomena like *The acid-base reaction of cocaine and bicarbonate favors reactants—why is it used to produce crack?*

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Analyses of charge distribution are of central importance in making predictions about acid or base strength.</td>
<td>Structure can affect the electron density distribution in a molecule and thus the relative reactivity of electron density centers toward water.</td>
<td>Strong acids are less stable than weak acids, based on $\Delta G^\circ$ and $K$; acid-base equilibria will favor the more stable species.</td>
<td>LO9.3.1. (A) Explain/predict the extent to which a stoichiometric acid-base reaction occurs (i.e., the equilibrium constant) based on the relative strength of reactants and products. (constructing explanations) - embedded abilities: infer acid-base strength from Lewis structures or electrostatic potential diagrams; compute $K$ using $K_a/K_b$ expressions/values</td>
<td>SDG14: Life Below Water. Increased carbonic acid in the Earth’s oceans reacts with the calcium carbonate that comprises the shells of sea creatures.</td>
</tr>
</tbody>
</table>

Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded

- we can react acids and bases with acids/bases other than water
- stoichiometric acid-base reactions are likely to proceed in the direction in which the more stable species are formed (weaker acids and bases)
- we use Hess’s law to construct equilibrium constants for acid-base reaction reactions using $K_a$ and $K_b$ of reactants
9.4. The Acidity of Aqueous Cations. Learners use the chemistry core concepts, matter-particle models of aquated/hydrated cations, and energy concepts to engage in phenomena like *Why does a solution of FeCl₃(aq) react with a base, but a solution of NaCl(aq) does not?*

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</thead>
<tbody>
<tr>
<td>Water molecules interact electrostatically with metal cations.</td>
<td>When water molecules are bound to a metal cation, their acid-base properties are altered.</td>
<td>Stability is related to the $\Delta G^\circ$ ($K$) of the reaction of the aquated cations with solvent water molecules.</td>
<td>LO9.4.1. (A) Using $pK_a$ data for aqueous metal cations and molecular representations, develop a model for how the charge, electronegativity, and size of the cation affect $pK_a$. <em>(analyzing and interpreting data)</em></td>
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<td></td>
<td>LO9.4.2. (B) Construct a model to explain how and why the $pK_a$ of a water molecule changes when the water molecule is associated with a metal cation. <em>(developing and using models)</em></td>
<td></td>
</tr>
</tbody>
</table>

**Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded**

- aqueous solutions of metal cations can also be acidic
- when water molecules are bound to a metal cation (i.e., when the cation is aquated/hydrated), the cation's positive charge reduces the electron density within the O–H bonds, making the bound water molecules more susceptible to reaction with a base (a non-coordinated water molecule)
- metal cation acidity is related to its charge, electronegativity, and size
9.5. Chemical Synthesis. Learners use the chemistry core concepts, matter-particle models of acid-base reactions, and energy concepts to engage in phenomena like *How is the broadleaf herbicide 2,4-dichlorophenoxyacetic acid produced from chloroacetic acid and 2,4-dichlorophenol?*

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</tr>
</thead>
</table>
| **Covalent bonds breaking and forming; intermolecular interactions between reaction species and solvent.** | **Structure dictates centers of low and high electron density and thus the likely orientation with which the electrophile and nucleophile will collide.** | Δ\(G^\circ\) provides insight into the overall extent to which the reaction will occur and Δ\(H^\circ\) and Δ\(S^\circ\) provide insight into the energetic factors that drive the reaction; individual mechanistic steps and the relative stabilities of intermediates provide insight into the rate at which the reaction occur and what the rate-determining step is. | LO9.5.1. (B) Using molecular structures and or representations of electron density, explain why a compound is classified as an electrophile or nucleophile. *(constructing explanations)*
- **embedded abilities:** draw Lewis structures, infer acid-base reactivity from Lewis structures, interpret electrostatic potential diagrams
| - SDG3: Good Health and Well-Being. Soaps are made from the basic hydrolysis of triglyceride molecules. |
| - SDG7: Clean and Affordable Energy. Biodiesel production from triglycerides and methanol proceeds according to an acid-base mechanism. |
| - SDG9: Industries, Innovation, and Infrastructure. BHC company developed a green synthesis for ibuprofen that uses three steps (instead of six) and 99% atom economy (instead of 40%). |
| - SDG12: Responsible Consumption and Production. The biodegradable plastic, poly(lactic acid), is produced from the condensation of lactic acid monomers. |

**Δ\(G^\circ\)** provides insight into the overall extent to which the reaction will occur and **Δ\(H^\circ\)** and **Δ\(S^\circ\)** provide insight into the energetic factors that drive the reaction; individual mechanistic steps and the relative stabilities of intermediates provide insight into the rate at which the reaction occur and what the rate-determining step is.

LO9.5.2. (B) Draw curved arrows between molecular structures to represent the redistribution of electron density during an acid-base reaction; explain what the arrows represent in terms of covalent bond breaking and forming. *(developing and using models)*
- **embedded abilities:** draw Lewis structures, infer acid-base reactivity from Lewis structures, show redistribution of electrons with curved arrows

LO9.5.3. (A) Explain, using the curved arrow mechanism and thermodynamic data/reaction progress diagrams for a synthetic reaction, the effects of changing temperature, pressure, and solvent (where applicable). *(constructing explanations)*
- **embedded abilities:** interpret Δ\(H^\circ\), Δ\(S^\circ\), and Δ\(G^\circ\) values for reactions; interpret chemical reactions as collisions; pull information from a reaction progress diagram

LO9.5.4. (D1) Explain, using the curved arrow mechanism and thermodynamic data/reaction progress diagrams for a synthetic reaction, why certain conditions (temperature/ pressure/choice of solvent) and/or practices are used when the reaction is performed practically/industrially. *(constructing explanations)*
Articulations of important ideas/thinking; those that tend to be difficult for learners are bolded

- **embedded abilities**: interpret $\Delta H^\circ$, $\Delta S^\circ$, and $\Delta G^\circ$ values for reactions; interpret chemical reactions as collisions; pull information from a reaction progress diagram
- **LO9.5.5. (D1)** Using principles of green chemistry, explain why certain procedures are used for the synthesis of commodity compounds. (constructing explanations)

- acid-base reactions other than $H^+$ transfers can occur
- many reactions important to chemical synthesis are acid-base reactions, resulting from the interaction between electron-rich sites in a molecule (the nucleophile) and electron-poor sites in another molecule (the electrophile)
- we can illustrate the redistribution of electron density during an electrophile/nucleophile collision using *curved arrows*—the curved arrows are always drawn from the electron-rich side to the electron-poor site
- we can qualitatively infer a large amount of information from a curved arrow mechanism for a synthetic reaction, including the directionality of each step (and thus a reaction progress diagram), and the slowest step of the mechanism (and thus the rate law)
- we can analyze any synthetic reaction/processes thermodynamically and kinetically
- synthetic chemistry often focuses on transforming one functional group into another (e.g., converting an alkene into an alcohol; converting an alkyl halide into an alkene; converting alcohols/acyl groups into esters; converting amines/acyl groups into amides)
- synthetic chemistry also focuses on specific structural changes (e.g., addition, elimination, rearrangement, or substitution)
- substitutions must have a group of atoms on the electrophile (a leaving group) that is capable of both separating from the molecule and directing the molecule’s interaction with the nucleophile
- the structures of the electrophile and nucleophile and choice of solvent can influence the types of structural changes that occur in a synthetic reaction
• solvents can affect the rates of individual synthetic steps
• in recent years, chemists have focused efforts on synthetic strategies that minimize hazards and maximize reaction efficiency (i.e., the principles of green chemistry)
• polymers can also be made from synthetic acid-base interactions (step growth vs. chain growth)
**MODULE 10: Acid-Base Chemistry and Chemical Analysis**

In addition to making new chemical compounds (the chemical practice of synthesis), acid-base chemistry is also essential for understanding chemical analysis and measurement. One of these measurements is the “pH” of acid-base solutions. However, chemists aren’t interested in only measuring the pH of various substances. Chemists use the concept of pH to think about how the structure of acid-base molecules changes as the concentration of H3O+ in solution changes—this type of reasoning is crucial for understanding how, for example, the structure and biological activity of therapeutic molecules are altered by the changing pH environments of the human body. Moreover, pH forms the basis of methods used to separate and analyze the purity of substances to be appropriate for human consumption. Topics in this Module include:

10.1. Measuring pH  
10.2. Controlling Molecular Structure with pH  
10.3. Controlling Properties with pH  
10.4. Buffer Systems  
10.5. Acid-Base Titrations

At the conclusion of Module 10, learners should be able to:

[LO10] **Use submicroscopic models of acid-base equilibria to explain chemical measurements, separation methods, and structural analyses based on pH.**

**Module 10 Content Notes**

- Acid-base chemistry is expanded upon in Modules 9 and 10 and content is partitioned based on the connections of acid-base chemistry to two chemistry practices: *synthesis* (Module 9) and *analysis* (Module 10).
Because learners were supported in reasoning with a submicroscopic model of acid-base reactions in Module 9, discussions of the macroscopic observations that define an acid and a base (i.e., the pH of aqueous solutions) and the molecular origins of pH can be presented from a submicroscopic perspective. This Module supports learners in explaining/predicting how molecular structure and properties can be controlled using acid-base chemistry, using the experimental handle of pH. To achieve this, Module 10 first discusses how the structures of acidic/basic molecules (and consequently, their properties) change when pH is changed. Then, these ideas are leveraged to discuss their application to the chemical practice of analysis (buffers, separation techniques, and titrations).
### 10.1. Measuring pH

Learners use chemistry core concepts and matter-particle models of acid-base reactions to engage in phenomena like *How does a pH meter determine the concentration of H₃O⁺?*

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<th>forces-organization</th>
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| Electrostatics      | Structure is related to aqueous acid-base reactivity. | We can infer relative stability of acid/base species using $\Delta G^\circ$, $K$, and $E^\circ$. | LO10.1.1. (A) Construct a model using $K_a/K_b$ values and molecular/particulate representations to explain why the aqueous solution of an acid or base has a certain pH. *(developing and using models)*  
  - *embedded abilities*: perform computations using $K_a/K_b$ (*I-C-E*); compute pH or $pOH$ from $[H_3O^+]$ or $[OH^-]$ | SDG15: Life on Land. The pH of soil and water sources affects forests and land restoration efforts worldwide. |
|                     |                      |                  | LO10.1.2. (D1) Construct a model using $K_a/K_b$ values and molecular/particulate representations to explain why the aqueous solution of a salt has a certain pH. *(developing and using models)*  
  - *embedded abilities*: perform computations using $K_a/K_b$ (*I-C-E*); compute pH or $pOH$ from $[H_3O^+]$ or $[OH^-]$ | |
|                     |                      |                  | LO10.1.3. (B) Explain trends in pH vs. temperature data for an acid or base species using $K_a$, $K_b$, $K_w$, $\Delta H^\circ$, and $\Delta S^\circ$. *(constructing explanations)*  
  - *embedded abilities*: pull information from pH vs. temperature graphs | |

### Articulations of important ideas/thinking

- pH is one of the most common measurements in chemistry
- We measure pH with a “pH meter,” which is an electrochemical cell
- We predict the pH of a solution of an acid, base, or salt solution by computing the $[H_3O^+]$ at equilibrium
- pH and $pOH$ are related to $K_w$ ($\text{pH} + \text{pOH} = \text{p}K_w$)
- pH is affected by temperature as $K_a$, $K_b$, $K_w$ change with temperature
- The $\Delta H^\circ$ and $\Delta S^\circ$ of acid/base equilibria in water can explain the observed changes in pH due to temperature
10.2. Controlling Molecular Structure with pH. Learners use chemistry core concepts and matter-particle models of acid-base reactions to engage in phenomena like *Why are opioids like morphine more quickly absorbed in the mouth than if swallowed?* and *How do we separate proteins?*

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</table>
| Intermolecular interactions/ionic interactions influence the biological activity of molecules; electrostatics controls the migration of charged species to electrodes. | The structure of weakly acidic or basic molecules can change with pH, and thus their properties and behaviors can change with pH. | We infer relative stability of acid/base species using $pK_a$, which represents the $\Delta G^\circ$ for the reaction of the acid/base with water. | LO10.2.1. (A) Using a speciation diagram, construct a representation for the predominating form of a molecule with acid-base properties (e.g., an amino acid) at a specific pH; identify the $pK_a$ values for the molecule and the pH where the molecule is isoelectric. *(analyzing and interpreting data)*
- **embedded abilities**: draw Lewis structures; infer acid-base reactivity from Lewis structures; interpret $pK_a$ values; pull information from a pH speciation diagram |

LO10.2.2. (A) Construct a model using $pK_a$ values and molecular representations to explain how and why the structure of an aqueous molecule changes as the pH is raised or lowered. *(developing and using models)*
- **embedded abilities**: draw Lewis structures; infer acid-base reactivity from Lewis structures; interpret $pK_a$ values; perform computations with the Henderson-Hasselbalch relationship |

LO10.2.3. (B) Using $pK_a$ values and molecular representations, explain or predict biological activity (solubility, membrane permeability) for molecules in different pH regions of the body. *(developing and using models)*
- **embedded abilities**: draw Lewis structures; infer acid-base reactivity from Lewis structures; interpret $pK_a$ values; perform computations with the Henderson-Hasselbalch relationship |

LO10.2.4. (D2) Given isoelectric focusing data and representations of short peptides, explain how the structure of the peptide changes during the experiment and why the peptide “stops” at a particular pH along the gradient. *(constructing explanations)* |

- SDG3: Good Health and Well-Being. How pH varies depending on the region of the body impacts drug uptake and biological activity, as most pharmaceuticals are weak acids and bases.
Articulations of important ideas/thinking

- the pH of a solution can affect the structure of a dissolved substance
- the Henderson-Hasselbalch relationship helps us rationalize how molecular structure is affected by the pH of the solution
- we interpret a $pK_a$ as the pH at which a weak acid is 50% neutralized (i.e., when the weak acid is in solution with an equivalent amount of its conjugate base)
- the structures of amino acids and some therapeutics vary across pH—this is important for understanding biological speciation
- amino acids possess different charged molecular structures (i.e., cations, zwitterions, anions) depending on the pH of the solution
- isoelectric focusing is a technique that separates charged molecules, usually proteins or peptides, based on their isoelectric point
- the isoelectric point is the pH at which a molecule has no overall charge
- in an isoelectric focusing experiment, a mixture of proteins is loaded onto a gel with a fixed pH gradient, and after an electric field is applied, the proteins migrate until they reach the pH at which they are electrically neutral
### 10.3. Controlling Properties with pH

Learners use chemistry core concepts and matter-particle models of acid-base reactions to engage in phenomena like *Why are antihistamines like diphenhydramine sold as the “hydrochloride salt”?*

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<tbody>
<tr>
<td>The intermolecular forces between solvent and solute contribute to the solubility of a substance in a particular solvent.</td>
<td>The structure of weakly acidic or basic molecules can change with pH; structural changes result in property changes.</td>
<td>We infer relative stability of acid/base species using ( pK_a ), which represents the ( \Delta G^\circ ) for the reaction of the acid/base with water.</td>
<td><strong>LO10.3.1.</strong> (B) Using ( pK_a ) values, molecular representations, and intermolecular interactions, explain how pH-dependent changes in structure affect the solubility of substances in polar and nonpolar solvents. <em>(developing and using models)</em></td>
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<td><strong>embedded abilities:</strong> draw Lewis structures, infer acid-base reactivity from Lewis structures, interpret ( pK_a ) values</td>
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<td><strong>LO10.3.2.</strong> (A) Using ( pK_a ) values, molecular representations, and intermolecular interactions, explain why liquid-liquid extraction is often used to separate pH-active molecules in a mixture. <em>(developing and using models)</em></td>
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<tr>
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<td></td>
<td><strong>embedded abilities:</strong> draw Lewis structures, infer acid-base reactivity from Lewis structures, interpret ( pK_a ) values</td>
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<td>– SDG3: Good Health and Well-Being/SDG9: Industry, Innovation, and Infrastructure. Many alkaloid pharmaceuticals are isolated as the hydrochloride salt to capitalize on crystallization and avoid the use of harmful solvents during purification; these are fundamentally green techniques.</td>
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#### Articulations of important ideas/thinking

- Solubility isn’t just about breaking up solute inter-particle interactions, but it also concerns forming interactions between the solvent molecules and solute matter particles.
- The solubility of weakly acidic or basic substances is a balance between the pH of the solution, what molecular species predominates at that pH, and what the structure of those species affords in terms of intermolecular forces.
10.4. Buffer Systems. Learners use chemistry core concepts and matter-particle models of acid-base reactions to engage in phenomena like *The artificial sweetener aspartame is most stable at low pH—how is the pH maintained in a can of soda to ensure that aspartame doesn’t decompose?*

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</thead>
</table>
| Chemical change is driven by the interaction of positive and negative charges; intermolecular and ionic interactions are examples of this. | The structure of weakly acidic or basic molecules can change with pH; structural changes result in property changes. | We can infer relative stability of acid/base species using $pK_a$, which represents the $\Delta G^\circ$ for the reaction of the acid/base with water. | LO10.4.1. (B) Given a graph of pH versus added volume of acid/base solution, make a claim as to whether the data are indicative of buffer formation; support your claim with a particulate model of the process that the graph represents and reasoning that connects your model to the data and your claim. (analyzing and interpreting data)  
  - **embedded abilities:** pull information from graphs of added volume of acid/base solution versus pH data | - SDG2: Zero Hunger. Crops vary in their ability to grow in soil at very high and very low pH; adding CaCO₃ (“liming”) raises the pH and increases the buffering capacity of depleted soil. |
|                     |                      |                  | LO10.4.2. (A) Using molecular representations of the major species of a buffer, develop a model to illustrate (beginning at equilibrium) how and why a buffer solution can resist changes to pH when acid or base is added. (developing and using models)  
  - **embedded abilities:** draw Lewis structures; infer acid-base reactivity from Lewis structures, perform computations with the Henderson-Hasselbalch relationship | - SDG14. Life Below Water. The buffering capacity of lakes helps guard against acid rain’s harmful effects. |
|                     |                      |                  | LO10.4.3. (B) Given a list of chemical species, make a claim as to whether, when combined, the species will form a buffer solution; support your claim using your knowledge of buffers and reasoning that connects your knowledge to the claim of buffer formation. (constructing explanations)  
  - **embedded abilities:** infer information from acid-base reactions |                     |
|                     |                      |                  | LO10.4.4. (A) Given buffer capacity vs. pH data, use molecular representations to explain the regions of the highest buffer capacity for acid-base species in a mixture, and how changing the concentration of the chemicals modifies the buffer capacity of the solution. (constructing explanations) |                     |
| embedded abilities: perform computations with buffer capacity and the Henderson-Hasselbalch relationship |
| LO10.4.5. (A) Select a proper buffer, with an appropriate pH and concentrations of major species, for use in a particular experiment; describe how you would go about making that buffer in the laboratory; identify the procedural steps required to make the buffer and describe how those steps result in a solution that acts as a buffer. (planning investigations) |
| embedded abilities: infer information from acid-base reactions, perform computations with buffer capacity and the Henderson-Hasselbalch relationship |

**Articulations of important ideas/thinking**

- in this sub-module, reasoning is more centered on pH data analysis/interpretation and chemical analysis design than it is reasoning with the chemistry core concepts; thus, very few sub-LOs are color-coded to the core concepts
- buffers solutions are used to hold samples at a constant pH
- a buffer solution is one that resists changes in pH when small amounts of acid or base are added.
- the Henderson-Hasselbalch relationship can be used to compute or reason about the properties of a buffer system
- we can create a buffer solution by partially reacting a weak acid/base species with a strong base/acid species
- the buffer capacity is the amount of acid or base that can be added to a given volume of buffer solution before the pH changes by ±1 unit from the p$K_a$ of the weak acid
10.5. Acid-Base Titrations. Learners use the chemistry core concepts and matter-particle models of acid-base reactions to engage in phenomena like *How do we know when a lactic acid fermentation (to produce pickles, kimchi, sour beers, etc.) is fit for human consumption?*

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| The reaction of a weak acid/base with a strong acid/base will reach a strongly product-favored equilibrium (i.e., have a strongly negative $\Delta G^\circ$). | Chemical change is driven by the interaction of positive and negative charges; intermolecular and ionic interactions are examples of this. | LO10.5.1. (B) Given speciation diagrams, **use molecular representations** to model the solution composition at any point along a titration curve. (analyzing and interpreting data)  
- **embedded abilities**: pull information from speciation diagrams and graphs of added volume of acid/base solution versus pH data; draw Lewis structures  
LO10.5.2. (B) Use speciation diagrams and **molecular representations** of acid-base species that model solution composition to explain the observed shape of the titration curve. (constructing explanations)  
- **embedded abilities**: pull information from speciation diagrams and graphs of added volume of acid/base solution versus pH data; draw Lewis structures, perform computations using pH and the Henderson-Hasselbalch relationship  
LO10.5.3. (A) Using **molecular representations** for the species involved, model the solution composition at any point along a titration curve; use these models of solution composition to explain the observed differences between two titration curves. (developing and using models)  
- **embedded abilities**: pull information from graphs of added volume of acid/base solution versus pH data; draw Lewis structures  
LO10.5.4. (D1) Compute pH values for various points (mL of added titrant) during a titration experiment; use these computations to construct a titration curve for the acid-base system in question. (using mathematics and computational thinking) | - SDG2: Zero Hunger. Titrations are used in the food industry to determine the quantity of a substance (salt, vitamins, etc.) in a food sample.  
- SDG3: Good Health and Well Being. Pharmaceuticals like ephedrine (commonly found in many cough syrups) can be tested for purity using titration.  
- SDG6: Clean Water and Sanitation. SDG12: Responsible Consumption and Production. While most contaminants from industry are well accounted for, some may slip through and contaminate ground water—this is why it is tested by titrations.  
- SDG12: Responsible Consumption and Production. Whether an...
Articulations of important ideas/thinking

- in this sub-module, reasoning is more centered on pH data analysis/interpretation and chemical analysis design than it is reasoning with the chemistry core concepts; thus, very few sub-LOs are color-coded to the core concepts
- an acid-base titration can be used to determine the concentration of an unknown acid or base
- the equivalence point occurs when just enough titrant has been added to complete the reaction with the solution being titrated; the chemical species in solution at the equivalence point of an acid/base titration is a salt
- one can compute the concentration of a volume of an unknown acid or base solution using data obtained from a titration (i.e., volume and concentration of titrant added).
- a graph of added volume of titrant versus pH data (often called a titration curve) documents a process (an acid-base reaction between the titrant and solution being titrated) and can look different depending on the reaction; this graph does not describe a relationship between volume and pH.
- the equivalence point of a strong acid-strong base titration will most often occur at pH = 7, because the resulting salt solution components do not have detectable acid-base properties
- a buffer is produced during the titration of a strong acid/base and a weak acid/base
- there is a conceptual relationship between the midpoint of a titration and the Henderson-Hasselbalch equation for strong acid/weak base and strong base/weak acid titrations.
• an *indicator* is a substance added to the solution being titrated to provide a color change at or very near the equivalence point
Recommended Resource Material

This LO framework supports a view of chemistry learning that values engagement with science practices to understand phenomena. Thus, developers and instructors should construct learning materials and environments that foreground and embed appropriate epistemic messages to support this view.

10. Stowe, R. L.; Scharlott, L. J.; Ralph, V. R.; Becker, N. M.; Cooper, M. M. You are what you assess: The case for emphasizing chemistry on chemistry assessments. *Journal of Chemical Education 2021, 98*(8), 2490–2495.


Further Recommendations

American Chemical Society General Chemistry Performance Expectations Project


Core Ideas/Concepts


Science and Chemistry Practices


Assessment

• Stowe, R. L., Cooper, M. M. Assessment in Chemistry Education. Israel Journal of Chemistry 2019, 59(6), 598–607, DOI: 10.1002/ijch.201900024
• Stowe, R. L., Scharlott, L. J., Ralph, V. R., Becker, N. M., Cooper, M. M. You are what you assess: The case for emphasizing chemistry on chemistry assessments. Journal of Chemical Education 2021, 98(8), 2490–2495.

Related Curricula
• CLUE: Cooper, M., Klymkowsky, M. Chemistry, Life, the Universe, and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform. Journal of Chemical Education 2013, 90(9), 1116–1122, DOI: 10.1021/ed300456y

**United Nations Sustainable Development Goals**
- Chemistry Sustainable Development Goals: https://www.acs.org/content/acs/en/sustainability/chemistry-sustainable-development-goals.html

**Other Works Informing Curriculum Design**
- Crandell, O. M., Kouyoumdjian, H., Underwood, S. M., Cooper, M. Reasoning about Reactions in Organic Chemistry: Starting It in General Chemistry. Journal of Chemical Education 2019, 96(2), 213-226, DOI: 10.1021/acs.jchemed.8b00784