Competency 1.0 Understand the historical and contemporary contexts of the study of chemistry

Development of Modern Chemistry

Chemistry emerged from two ancient roots: craft traditions and philosophy. The oldest ceramic crafts (i.e., pottery) known are from roughly 10,000 BC in Japan. Metallurgical crafts in Eurasia and Africa began to develop by trial and error around 4000-2500 BC resulting in the production of copper, bronze, iron, and steel tools. Other craft traditions in brewing, tanning, and dyeing led to many useful empirical ways to manipulate matter.

Ancient philosophers in Greece, India, China, and Japan speculated that all matter was composed of four or five elements. The Greeks thought that these were: fire, air, earth, and water. Indian philosophers and the Greek Aristotle also thought a fifth element—"aether" or "quintessence"—filled all of empty space. The Greek philosopher Democritus thought that matter was composed of indivisible and indestructible atoms. These concepts are now known as classical elements and classical atomic theory.

Before the emergence of the scientific method, attempts to understand matter relied on alchemy: a mixture of mysticism, best guesses, and supernatural explanations. Goals of alchemy were the transmutation of other metals into gold and the synthesis of an elixir to cure all diseases. Ancient Egyptian alchemists developed cement and glass. Chinese alchemists developed gunpowder in the 800s AD.

During the height of European alchemy in the 1300s, the philosopher William of Occam proposed the idea that when trying to explain a process or develop a theory, the simplest explanation with the fewest variables is best. This is known as Occam's Razor. European alchemy slowly developed into modern chemistry during the 1600s and 1700s. This began to occur after Francis Bacon and René Descartes described the scientific method in the early 1600s.

Robert Boyle was educated in alchemy in the mid-1600s, but he published a book called *The Skeptical Chemist* that attacked alchemy and advocated using the scientific method. He is sometimes called the founder of modern chemistry because of his emphasis on proving a theory before accepting it, but the birth of modern chemistry is usually attributed to Lavoisier. Boyle rejected the 4 classical elements and proposed the modern definition of an element. Boyle's law states that gas volume is proportional to the reciprocal of pressure.

Blaise Pascal in the mid-1600s determined the relationship between pressure and the height of a liquid in a barometer. He also helped to establish the scientific method. The SI unit of pressure is named after him.

Isaac Newton studied the nature of light, the laws of gravity, and the laws of motion around 1700. The SI unit of force is named after him.

Daniel Bernoulli proposed the kinetic molecular theory for gases in the early 1700s to explain the nature of heat and Boyle's Law. At that time, heat was thought to be related to the release of a substance called *phlogiston* from combustible material.

James Watt created an efficient steam engine in the 1760s-1780s. Later chemists and physicists would develop the theory behind this empirical engineering accomplishment. The SI unit of power is named after him.

Joseph Priestley studied various gases in the 1770s. He was the first to produce and drink carbonated water, and he was the first to isolate oxygen from air. Priestley thought oxygen was air with its normal phlogiston removed so it could burn more fuel and accept more phlogiston than natural air.

Antoine Lavoisier is called the father of modern chemistry because he performed quantitative, controlled experiments. He carefully weighed material before and after combustion to determine that burning objects gain weight. Lavoisier formulated the rule that chemical reactions do not alter total mass after finding that reactions in a closed container do not change weight. This disproved the plogiston theory, and he named Priestley's substance oxygen. He demonstrated that air and water were not elements. He defined an element as a substance that could not be broken down further. He published the first modern chemistry textbook, *Elementary Treatise of Chemistry*. Lavoisier was executed in the Reign of Terror at the height of the French Revolution.

<u>Additional Gas Laws in the 1700s and 1800s</u>

These contributions built on the foundation developed by Boyle in the 1600s.

Jacque Charles developed Charles's law in the late 1700s. This states that gas volume is proportional to absolute temperature.

William Henry developed the law stating that gas solubility in a liquid is proportional to the pressure of gas over the liquid. This is known as Henry's Law.

Joseph Louis Gay-Lussac developed the gas law stating that gas pressure is directly proportional to absolute temperature. He also determined that 2 volumes of hydrogen react with one of oxygen to produce water and that other reactions occurred with similar simple ratios. These observations led him to develop the Law of Combining Volumes.

Amedeo Avogadro developed the hypothesis that equal volumes of different gases contain an equal numbers of molecules if the gases are at the same temperature and pressure. The proportionality between volume and number of moles is called Avagadro's Law and the number of molecules in a mole is called Avagadro's Number. Both were posthumously named in his honor.

Thomas Graham developed Graham's Law of effusion and diffusion in the 1830s. He is called the father of colloid chemistry.

Electricity and Magnetism in the 1700s and 1800s

Benjamin Franklin studied electricity in the mid-1700s. He developed the concept of positive and negative electrical charges. His most famous experiment showed that lightning is an electrical process.

Luigi Galvani discovered bioelectricity. In the late 1700s, he noticed that the legs of dead frogs twitched when they came into contact with an electrical source.

In the late 1700s, Charles Augustin Coulomb derived mathematical equations for **attraction and repulsion** between electrically charged objects.

Alessandro **Volta** built the first **battery** in 1800, permitting future research and applications to have a source of continuous electrical current available. The SI unit of electric potential difference is named after him.

André-Marie **Ampère** created a mathematical theory in the 1820s for magnetic fields and electric currents. The SI unit of electrical current is named after him.

Michael **Faraday** is best known for work in the 1820s and 1830s establishing that a moving magnetic field induces an electric potential. He built the first **dynamo** for electricity generation. He also discovered benzene, invented oxidation numbers, and popularized the terms *electrode*, *anode*, and *cathode*. The SI unit of electrical capacitance is named in his honor.

James Clerk **Maxwell** derived the **Maxwell Equations** in 1864. These expressions completely describe **electric and magnetic fields** and their interaction with matter. Also see Ludwig Boltzmann below for Maxwell's contribution to thermodynamics.

Nineteenth Century Chemistry: Caloric Theory and Thermodynamics

Lavoisier proposed in the late 18^{th} century that the heat generated by combustion was due to a weightless material substance called **caloric** that flowed from one place to another and was never destroyed.

In 1798, **Benjamin Thomson**, also known as **Count Rumford** measured the heat produced when cannons were bored underwater and concluded that caloric was not a conserved substance because heat could continue to be generated indefinitely by this process.

Sadi **Carnot** in the 1820s used caloric theory in developing theories for the **heat engine** to explain the engine already developed by Watt. Heat engines perform mechanical work by expanding and contracting a piston at two different temperatures.

In the 1820s, Robert **Brown** observed dust particles and particles in pollen grains moving in a random motion. This was later called **Brownian motion**.

Germain Henri **Hess** developed **Hess's Law** in 1840 after studying the heat required or emitted from reactions composed of several steps.

James Prescott **Joule** determined the equivalence of heat energy to mechanical work in the 1840s by carefully measuring the heat produced by friction. Joule attacked the caloric theory and played a major role in the acceptance of **kinetic molecular theory**. The SI unit of energy is named after him.

William Thomson, 1^{st} Baron of Kelvin also called **Lord Kelvin** recognized the existence of **absolute temperature** in the 1840s and proposed the temperature scale named after him. He failed in an attempt to reconcile caloric theory with Joule's discovery and caloric theory began to fall out of favor.

Hermann von **Helmholtz** in the 1840s proposed that **energy is conserved** during physical and chemical processes, not heat as proposed in caloric theory.

Rudolf **Clausius** in the 1860s introduced the concept of **entropy**.

In the 1870s, Ludwig **Boltzmann** generalized earlier work by Maxwell solving the **velocity or energy distribution among gas molecules**.

Johannes **van der Waals** in the 1870s was the first to consider **intermolecular attractive forces** in modeling the behavior of liquids and non-ideal gases.

Francois Marie **Raoult** studied colligative properties in the 1870s. He developed **Raoult's Law** relating solute and solvent mole fraction to vapor pressure lowering.

Jacobus **van't Hoff** was the first to fully describe **stereoisomerism** in the 1870s. He later studied **colligative properties** and the impact of temperature on equilibria.

Josiah Willard **Gibbs** studied thermodynamics and statistical mechanics in the 1870s. He formulated the concept now called **Gibbs free energy** that will determine whether or not a chemical process at constant pressure will spontaneously occur.

Henri Louis **Le Chatelier** described chemical **equilibrium** in the 1880s using **Le Chatelier's Principle**.

In the 1880s, Svante **Arrhenius** developed the idea of **activation energy.** He also described the dissociation of salts—including **acids and bases**—into ions. Before then, salts in solution were thought to exist as intact molecules and ions were mostly thought to exist as electrolysis products. Arrhenius also predicted that CO_2 emissions would lead to global warming .

In 1905, **Albert Einstein** created a **mathematical model of Brownian motion** based on the impact of water molecules on suspended particles. Kinetic molecular theory could now be observed under the microscope. Einstein's more famous later work in physics on **relativity** may be applied to chemistry by correlating the energy change of a chemical reaction with extremely small changes in the total mass of reactants and products.

<u>Nineteenth and Twentieth Century: Atomic Theory</u>

See section 0008 for the contributions to atomic theory of John **Dalton**, **J. J. Thomson,** Max **Planck,** Ernest **Rutherford,** Niels **Bohr,** Louis **de Broglie,** Werner **Heisenberg, and** Erwin **Schrödinger**.

Wolfgang **Pauli** helped to develop quantum mechanics in the 1920s by forming the concept of spin and the **exclusion principle**.

Friedrich **Hund** determined a set of **rules to determine the ground state** of a multi-electron atom in the 1920s. One particular rule is called **Hund's Rule** in introductory chemistry courses.

<u>Discovery and Synthesis: Nineteenth Century:</u>

Humphry **Davy** used Volta's battery in the early 1800s for **electrolysis of salt solutions**. He synthesized several pure elements using electrolysis to generate non-spontaneous reactions.

Jöns Jakob **Berzelius** isolated several elements, but he is best known for inventing modern **chemical notation** by using one or two letters to represent elements in the early 1800s.

Friedrich **Wöhler** isolated several elements, but he is best known for the chemical **synthesis of an organic compound** in 1828 using the carbon in silver cyanide. Before Wöhler, many had believed that a transcendent "life-force" was needed to make the molecules of life.

Justus **von Liebig** studied the chemicals involved in agriculture in the 1840s. He has been called the **father of agricultural chemistry**.

Louis **Pasteur** studied **chirality** in the 1840s by separating a mixture of two chiral molecules. His greater contribution was in biology for discovering the germ theory of disease.

Henry **Bessemer** in the 1850s developed the **Bessemer Process** for mass producing steel by blowing air through molten iron to oxidize impurities.

Friedrich August **Kekulé** von Stradonitz studied the chemistry of carbon in the 1850s and 1860s. He proposed the **ring structure of benzene** and that carbon was tetravalent.

Anders Jonas **Ångström** was one of the founders of the science of spectroscopy. In the 1860s, he found hydrogen and other **elements in the spectrum of the sun**. A non-SI unit of length equal to 0.1 nm is named for him.

Alfred **Nobel** invented the explosive **dynamite** in the 1860s and continued to develop other explosives. In his will he used his fortune to establish the **Nobel Prizes**.

Dmitri **Mendeleev** developed the first modern **periodic table** in 1869.

Discovery and Synthesis: Turn of the 20th Century

William **Ramsay** and Lord **Rayleigh (**John William Strutt) isolated the **noble gases**.

Wilhelm Konrad **Röntgen** discovered **X-rays**.

Antoine Henri **Becquerel discovered radioactivity** using uranium salts.

Marie **Curie** named the property radioactivity and determined that it was **a property of atoms** that did not depend on which molecule contained the element.

Pierre and Marie **Curie** utilized the properties of radioactivity to **isolate radium** and other radioactive elements. Marie Curie was the first woman to receive a Nobel Prize and the first person to receive two. Her story continues to inspire. See http://nobelprize.org/physics/articles/curie/index.html for a biography.

Frederick **Soddy** and William **Ramsay** discovered that **radioactive decay can produce helium** (alpha particles).

Fritz **Haber** developed the **Haber Process** for synthesizing ammonia from hydrogen and nitrogen using an iron **catalyst**. Ammonia is still produced by this method to make fertilizers, textiles, and other products.

Robert Andrew **Millikan** determined the **charge of an electron** using an oil-drop experiment.

Discovery and Synthesis: 20th Century

Gilbert Newton **Lewis** described **covalent bonds** as sharing electrons in the 1910s and the **electron pair donor/acceptor theory of acids and bases** in the 1920s. Lewis dot structures and Lewis acids are named after him.

Johannes Nicolaus **Brønsted** and Thomas Martin **Lowry** simultaneously developed the **proton donor/acceptor theory of acids and bases** in the 1920s.

Irving **Langmuir** in the 1920s developed the science of **surface chemistry** to describe interactions at the interface of two phases. This field is important to heterogeneous catalysis.

Fritz **London** studied the electrical nature of chemical bonding in the 1920s. The weak intermolecular **London dispersion forces** are named after him.

Hans Wilhelm **Geiger** developed the **Geiger counter** for measuring ionizing radiation in the 1930s.

Wallace **Carothers** and his team first synthesized **organic polymers** (including neoprene, polyester and nylon) in the 1930s.

In the 1930s, Linus **Pauling** published his results on **the nature of the covalent bond.** Pauling electronegativity is named after him. In the 1950s, Pauling determined the α-helical structure of proteins.

Lise **Meitner** and Otto **Hahn** discovered **nuclear fission** in the 1930s.
Glenn Theodore **Seaborg** created and isolated several **elements larger than uranium** in the 1940s. Seaborg reorganized the periodic table to its current form.

James **Watson** and Francis **Crick** determined the double helix structure of DNA in the 1950s.

Neil **Bartlett** produced **compounds containing noble gases** in the 1960s, proving that they are not completely chemically inert.

Harold Kroto, Richard Smalley, and Robert Curl discovered the **buckyball C_{60}** in the 1980s.

Competency 2.0 Understand the nature of science and scientific inquiry

Characteristics and components of scientific inquiry.
Modern science began around the late 16th century with a new way of thinking about the world. Few scientists will disagree with Carl Sagan's assertion that "science is a way of thinking much more than it is a body of knowledge" (Broca's Brain, 1979). Thus science is a process of inquiry and investigation. It is a way of thinking and acting, not just a body of knowledge to be acquired by memorizing facts and principles. This way of thinking, the scientific method, is based on the idea that scientists begin their investigations with observations. From these observations they develop a hypothesis, which is extended in the form of a prediction, and challenge the hypothesis through experimentation and thus further observations. Science has progressed in its understanding of nature through careful observation, a lively imagination, and increasing sophisticated instrumentation. Science is distinguished from other fields of study in that it provides guidelines or methods for conducting research, and the research findings must be reproducible by other scientists for those findings to be valid. It is important to recognize that scientific practice is not always this systematic. Discoveries have been made that are serendipitous and others have not started with the observation of data. Einstein's theory of relativity started not with the observation of data but with a kind of intellectual puzzle.

The Scientific method is just a logical set of steps that a scientist goes through to solve a problem. There are as many different scientific methods as there are scientists experimenting. However, there seems to be some pattern to their work.

While an inquiry may start at any point in this method and may not involve all of the steps, here is the pattern.

Observations
Scientific questions result from observations of events in nature or events observed in the laboratory. An **observation** is not just a look at what happens. It also includes measurements and careful records of the event. Records could include photos, drawings, or written descriptions. The observations and data collection lead to a question. In chemistry, observations almost always deal with the behavior of matter. Having arrived at a question, a scientist usually researches the scientific literature to see what is known about the question. Maybe the question has already been answered. The scientist then may want to test the answer found in the literature. Or, maybe the research will lead to a new question.

Sometimes the same observations are made over and over again and are always the same. For example, you can observe that daylight lasts longer in summer than in winter. This observation never varies. Such observations are called **laws** of nature. Probably the most important law in chemistry was discovered in the late 1700s. Chemists observed that no mass was ever lost or gained in chemical reactions. This law became known as the law of conservation of mass. Explaining this law was a major topic of chemistry in the early 19th century.

Hypothesis
If the question has not been answered, the scientist may prepare for an experiment by making a hypothesis. A **hypothesis** is a statement of a possible answer to the question. It is a tentative explanation for a set of facts and can be tested by experiments. Although hypotheses are usually based on observations, they may also be based on a sudden idea or intuition.

Experiment
An **experiment** tests the hypothesis to determine whether it may be a correct answer to the question or a solution to the problem. Some experiments may test the effect of one thing on another under controlled conditions. Such experiments have two variables. The experimenter controls one variable, called the *independent variable*. The other variable, the *dependent variable*, is the change caused by changing the independent variable.

For example, suppose a researcher wanted to test the effect of vitamin A on the ability of rats to see in dim light. The independent variable would be the dose of Vitamin A added to the rats' diet. The dependent variable would be the intensity of light that causes the rats to react. All other factors, such as time, temperature, age, water given to the rats, the other nutrients given to the rats, and similar factors, are held constant. Chemists sometimes do short experiments "just to see what happens" or to see what products a certain reaction produces. Often, these are not formal experiments. Rather they are ways of making additional observations about the behavior of matter.

In most experiments, scientists collect quantitative data, which is data that can be measured with instruments. They also collect qualitative data, descriptive information from observations other than measurements. Interpreting data and analyzing observations are important. If data is not organized in a logical manner, wrong conclusions can be drawn. Also, other scientists may not be able to follow your work or repeat your results.

Conclusion
Finally, a scientist must draw conclusions from the experiment. A conclusion must address the hypothesis on which the experiment was based. The conclusion states whether or not the data supports the hypothesis. If it does not, the conclusion should state what the experiment *did* show. If the hypothesis is not supported, the scientist uses the observations from the experiment to make a new or revised hypothesis., Then, new experiments are planned.

Theory
When a hypothesis survives many experimental tests to determine its validity, the hypothesis may evolve into a **theory**. A theory explains a body of facts and laws that are based on the facts. A theory also reliably predicts the outcome of related events in nature. For example, the law of conservation of matter and many other experimental observations led to a theory proposed early in the 19th century. This theory explained the conservation law by proposing that all matter is made up of atoms which are never created or destroyed in chemical reactions, only rearranged. This atomic theory also successfully predicted the behavior of matter in chemical reactions that had not been studied at the time. As a result, the atomic theory has stood for 200 years with only small modifications.

A theory also serves as a scientific **model**. A model can be a physical model made of wood or plastic, a computer program that simulates events in nature, or simply a mental picture of an idea. A model illustrates a theory and explains nature. In your chemistry course, you will develop a mental (and maybe a physical) model of the atom and its behavior. Outside of science, the word theory is often used to describe someone's unproven notion about something. In science, theory means much more. It is a thoroughly tested explanation of things and events observed in nature.

A theory can never be proven true, but it can be proven untrue. All it takes to prove a theory untrue is to show an exception to the theory. The test of the hypothesis may be observations of phenomena or a model may be built to examine its behavior under certain circumstances.