*"There are and can be only two ways (inductive and deductive methods) of searching into and discovering truth. The one (deductive) flies from the senses and the particulars to the most general axioms and from these (principles); the truth it takes as fore settled and immovable proceeds to judgment and to the discovery of middle axioms and this way is now in fashion. The other (inductive) derives axioms from the senses and particulars rising by a gradual and unbroken assent, that it arrives at the most general axiom last of all. This is the true way."*

Sir Francis Bacon

## COMPETENCY 0001 UNDERSTAND THE NATURE OF SCIENTIFIC INQUIRY, SCIENTIFIC PROGRESSES, AND THE ROLE OF OBSERVATION AND EXPERIMENTATION IN SCIENCE.

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 with an intellectual and enquiring mind.

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 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 mass neither lost nor 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. In other words, a dependent variable is the factor that is measured in an experiment and independent variables are things that are changed or manipulated in an experiment.

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 ability of rats to see in dim light and this could be measured by placing food at different distances.

All other factors, such as time, temperature, age, water , and 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.

The design of chemical experiments must include every step to obtain the desired data. In other words, the design must be **complete** and it must include all required **controls**

**Complete design**
Familiarity with individual experiments and equipment will help you evaluate if anything is missing from the design. For data requiring a difference between two values, the experiment **must determine both values**. For data utilizing the ideal gas law, the experiment **must determine three values of *P*, *V*, *n*, or *T*** in order to determine the fourth or one value and a ratio of the other two in order to determine the fourth.

Example: In a mercury manometer, the level of mercury in contact with a reaction vessel is 70.0 mm lower than the level exposed to the atmosphere. Use the following conversion factors:

760 mm Hg=1 atm=101.325 kPa.

What additional information is required to determine the pressure in the vessel in Pa?

Solution: The barometric pressure is needed to determine vessel pressure from an open-ended manometer. A manometer reading is always a **difference** between two pressures. See **0005**. One standard atmosphere is 760 mm mercury, but on a given day at a given location, the actual ambient pressure may vary. If the barometric pressure on the day of the experiment is 104 kPa, the pressure of the vessel is:

$$104\ \text{kPa} + 70.0\ \text{mm Hg} \times \frac{101.325\ \text{kPa}}{760\ \text{mm Hg}} = 113\ \text{kPa}.$$

<u>Controls</u>
Experimental **controls** prevent factors other than those under study from impacting the outcome of the experiment. An **experimental sample** in a controlled experiment is the unknown to be compared against one or more **control samples**. These should be nearly identical to the experimental sample except for the one aspect whose effect is being tested.

A **negative control** is a control sample that is known to lack the effect. A **positive control** is known to contain the effect.

Positive controls of varying strengths are often used to generate a **calibration curve** (also called a **standard curve**).

When determining the concentration of a component in a mixture, an **internal standard** is a known concentration of a different substance that is added to the experimental sample. An **external standard** is a known concentration of the substance of interest. External standards are more commonly used. They are not added to the experimental sample; they are analyzed separately

**Replicate samples** decrease the impact of random error. A mean is taken of the results from replicate samples to obtain a best value. If one replicate is obviously inconsistent with the results from other samples, it may be discarded as an **outlier** and not counted as an observation when determining the mean. Discarding an outlier is equivalent to assuming the presence of a systematic error for that particular observation. In research, this must be done with great caution because some real-world behavior generates sporadically unusual results.

Example: A pure chemical in aqueous solution is known to absorb light at 615 nm. What controls would best be used with a spectrophotometer to determine the concentration of this chemical when it is present in a mixture with other solutes in an aqueous solution?

Solution: The other solutes may also absorb light at 615 nm. The best negative control would be an identical mixture with the chemical of interest entirely absent. Known concentrations of the chemical could then be added to the negative control to create positive controls (external standards) and develop a calibration curve of the spectrophotometer absorbance reading at 615 nm as a function of concentration. Replicate samples of each standard and of the unknown should be read.

Example: Ethanol is separated from a mixture of organic compounds by gas chromatography. The concentration of each component is proportional to its peak area. However, the chromatograph detector has a variable sensitivity from one run to the next. Is an internal standard required to determine the concentration of ethanol?

Solution: Yes. The variable detector sensitivity may only be accounted for by adding a known concentration of a chemical not found in the mixture as an internal standard to the experimental sample and control samples. The variable sensitivity of the detector will be accounted for by determining the ratio of the peak area for ethanol to the peak area of the added internal standard.

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.

**Analysis of data:**
It is very important to analyze the data, to see if there are variations and patterns.

**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, a mathematical model 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.

The test of the hypothesis may be observations of phenomena or a model may be built to examine its behavior under certain circumstances.

A theory is open and is subject to experimentation. Experiments may establish a theory or may reject it.

**Theories** provide a framework to explain the **known** information of the time, but are subject to constant evaluation and updating. There is always the possibility that new evidence will conflict with a current theory.

Some examples of theories that have been rejected because they are now better explained by current knowledge:

Theory of Spontaneous Generation
Inheritance of Acquired Characteristics
The Blending Hypothesis

Some examples of theories that were initially rejected because they fell outside of the accepted knowledge of the time, but are well-accepted today due to increased knowledge and data include:

The sun-centered solar system
Warm-bloodedness in dinosaurs
The germ-theory of disease
Continental drift

A Law is a naturally occurring phenomenon like the law of gravity .

**Law is defined as:** a statement of an order or relation of phenomena that so far as is known is invariable under the given conditions. Everything we observe in the universe operates according to known natural laws.

- If the truth of a statement is verified repeatedly in a reproducible way then it can reach the level of a natural law.
- Some well know and accepted natural laws of science are:

1. The First Law of Thermodynamics

2. The Second Law of Thermodynamics

3. The Law of Cause and Effect

4. The Law of Biogenesis

5. The Law of Gravity

**Steps of a Scientific Method**