SUBAREA I. REFLECTING ON AND CONSTRUCTING SCIENTIFIC KNOWLEDGE

COMPETENCY 1.0 UNDERSTAND THE PRINCIPLES AND PROCEDURES OF SCIENTIFIC INQUIRY

Skill 1.1 Formulating research questions and investigations in chemistry

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.

Skill 1.2 Developing valid experimental designs for collecting and analyzing data and testing hypotheses

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 predication, 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 increasingly 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 a logical set of steps that a scientist goes through to solve a problem. The main purpose of using the Scientific Method is to eliminate, as much as possible, preconceived ideas, prejudices and biases by presenting an objective way to study possible answers to a question. Only by designing a way to study one variable at a time can each possible answer be ruled out or accepted for further study. There are as many different scientific methods as there are scientists experimenting. However, there seems to be some pattern to their work.

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Observations

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Question

The observations and **data collection** lead to a question. In chemistry, observations almost always deal with the behavior of matter.

Information Gathering / Research

Having arrived at a question, a scientist usually researches the scientific literature to see what is known about the question. This research can be done by using scientific journals, by reading papers presented at conferences, by asking scientists at other institutions and in industry, and by researching the internet. 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 or some aspect of 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 observations and must be stated in positive terms and in such a way that 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. Designing an appropriate experiment can be challenging. Experiments need to have clearly defined controls (standards), variables, constants, and procedures that truly do test the variable in the question and hypothesis. 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 to which the rats respond. All other factors, such as time, temperature, age, water and other nutrients given to the rats would be held constant.
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When students are involved in designing experiments, they better understand what scientists are doing as well as the difficulty of designing appropriately controlled experiments. An ideal experiment at the high school level should not last more than 12-14 days.

Data Collection
In most experiments, scientists collect **quantitative data**, which are data that can be measured with instruments. Quantitative data involves numbers and measurements against a standard. Those measurements may be taken at specified time intervals. They also collect **qualitative data**, descriptive information from observations other than measurements. Qualitative data includes any observations made with the senses of hearing or seeing such as a popping sound or a color change.

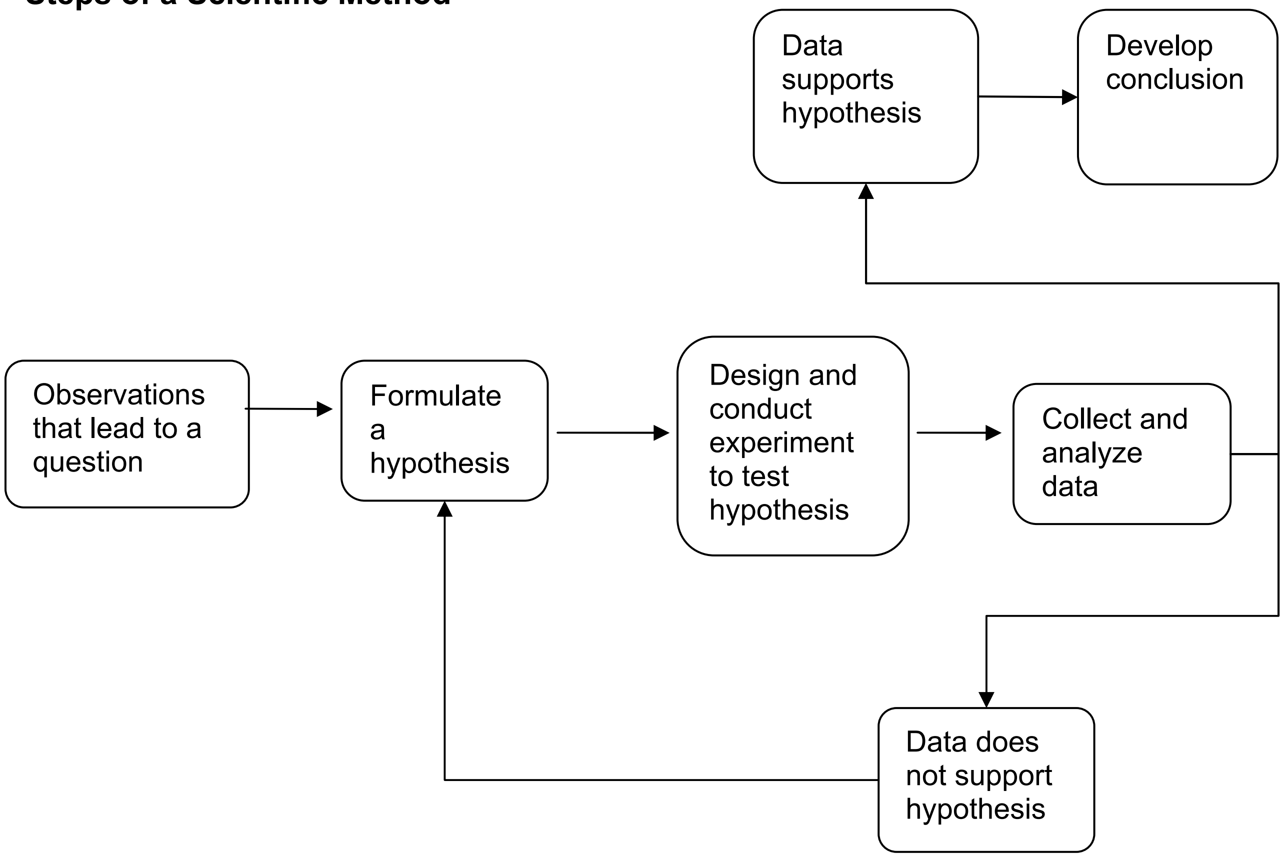
Data Analysis / Interpretation
Interpreting data and analyzing observations are important. If data are not organized in a logical manner, incorrect conclusions can be drawn. Also, other scientists may not be able to follow or reproduce the results. By placing data into charts and graphs, the scientist may see patterns or lack thereof. The scientist will also be able to understand if the experiment truly tested the hypothesis. Induction is drawing conclusions based on facts or observations. Deduction is drawing conclusions based on generalizations.

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 in writing 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.

Effective written communication is necessary to present the research to a teacher or to a scientific journal. Effective oral communication is needed to present the research to a group whether that group is a class or other scientists. Students must recognize that, in this age of communication, those who cannot communicate effectively will be left behind. Accordingly, the evaluation system of the use of the scientific method should make provision for communication skills and activities.

Defending results
Defending results is as important as conducting an experiment. One can honestly defend one's own results only if the results are reliable, and experiments must be well-controlled and repeated at least twice to be considered reliable. It must be emphasized to the students that *honesty and integrity are the foundation for any type of investigation.*

Steps of a Scientific Method



The Development of a Scientific Theory using the Scientific Method

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 that is required to prove a theory untrue is to show *one exception* to the theory.

Skill 1.3 Recognizing the need for control groups in experiments

Experimental **controls** prevent factors other than those under study from impacting the outcome of the experiment. A **test sample** in a controlled experiment is the unknown that is compared against one or more **control samples**. Control samples should be selected to be as identical to the test sample as possible in every way other than the one variable 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 or concentrations are often used to generate a **calibration curve** (also called a **standard curve**).

For example, a scientist may wish to measure the level of arsenic in drinking water in a former mining area. A negative control would consist of water similar to that being tested that does not contain arsenic. This insures that there has been no cross-contamination during the experiment, and that the instruments are recording properly. Positive controls are also prepared consisting of water samples with increasing known concentrations of arsenic. The curve of concentration responses obtained is called a calibration curve, and is compared to past curves to ensure that the instrument is recording accurate and precise measurements across a wide concentration range.

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. These standards are frequently used to evaluate potential bias in the results, which may be caused by poor instrument calibration, interference from other compounds, or loss of the substance during sample pre-processing.

Skill 1.4 Understanding procedures for collecting and interpreting data to minimize bias

Experimental bias occurs when a researcher favors one particular outcome over another in an experimental setup. In order to avoid bias, it is imperative to set up each experiment under exactly the same conditions, including a **control experiment**, an experiment with a known negative outcome. Additionally, in order to avoid experimental bias, a researcher must not “read” particular results into data.

An example of experimental bias can be seen in the example of the mouse in the maze experiment. In this example, a researcher is timing mice as they move through the maze towards a piece of cheese. The experiment relies on the mouse’s ability to smell the cheese as it approaches. If one mouse chases a piece of cheddar cheese, while another chases Limburger, or so called “stinky” cheese, clearly the Limburger mouse has a huge advantage over the mouse chasing cheddar. To remove the experimental bias from this experiment, the same cheese should be used in both tests.