## COMPETENCY 1.0 UNDERSTANDS THE HISTORICAL AND CONTEMPORARY CONTEXTS OF THE STUDY OF PHYSICS AND THE APPLICATIONS OF PHYSICS TO EVERYDAY LIFE

### Skill 1.1 Explain the significance of key individuals and their theories in the history of physics

**Archimedes**
Archimedes was a Greek mathematician, physicist, engineer, astronomer, and philosopher. He is credited with many inventions and discoveries some of which are still in use today such as the Archimedes screw. He designed the compound pulley, a system of pulleys used to lift heavy loads such as ships.

Although Archimedes did not invent the lever, he gave the first rigorous explanation of the principles involved which are the transmission of force through a fulcrum and moving the effort applied through a greater distance than the object to be moved. His Law of the Lever states that magnitudes are in equilibrium at distances reciprocally proportional to their weights.

He also laid down the laws of flotation and described Archimedes' principle which states that a body immersed in a fluid experiences a buoyant force equal to the weight of the displaced fluid.

**Niels Bohr**
Bohr was a Danish physicist who made fundamental contributions to understanding atomic structure and quantum mechanics. Bohr is widely considered one of the greatest physicists of the twentieth century.
Bohr's model of the atom was the first to place electrons in discrete quantized orbits around the nucleus.

Bohr also helped determine that the chemical properties of an element are largely determined by the number of electrons in the outer orbits of the atom. The idea that an electron could drop from a higher-energy orbit to a lower one emitting a photon of discrete energy originated with Bohr and became the basis for future quantum theory.

He also contributed significantly to the Copenhagen interpretation of quantum mechanics. He received the Nobel Prize for Physics for this work in 1922.

**Marie Curie**
Curie was as a Polish-French physicist and chemist. She was a pioneer in radioactivity and the winner of two Nobel Prizes, one in Physics and the other in Chemistry. She was also the first woman to win the Nobel Prize.

Curie studied radioactive materials, particularly pitchblende, the ore from which uranium was extracted. The ore was more radioactive than the uranium extracted from it which led the Curies (Marie and her husband Pierre) to discover a substance far more radioactive then uranium. Over several years of laboratory work the Curies eventually isolated and identified two new radioactive chemical elements, polonium and radium. Curie refined the radium isolation process and continued intensive study of the nature of radioactivity.

**Albert Einstein**
Einstein was a German-born theoretical physicist who is widely considered one of the greatest physicists of all time. While best known for the theory of relativity, and specifically mass-energy equivalence, $E = mc^2$, he was awarded the 1921 Nobel Prize in Physics for his explanation of the photoelectric effect and "for his services to Theoretical Physics". In his paper on the photoelectric effect, Einstein extended Planck's hypothesis ($E = h\nu$) of discrete energy elements to his own hypothesis that electromagnetic energy is absorbed or emitted by matter in quanta and proposed a new law $E_{\max} = h\nu - P$ to account for the photoelectric effect.

He was known for many scientific investigations including the special theory of relativity which stemmed from an attempt to reconcile the laws of mechanics with the laws of the electromagnetic field. His general theory of relativity considered all observers to be equivalent, not only those moving at a uniform speed. In general relativity, gravity is no longer a force, as it is in Newton's law of gravity, but is a consequence of the curvature of space-time.

Other areas of physics in which Einstein made significant contributions, achievements or breakthroughs include relativistic cosmology, capillary action, critical opalescence, classical problems of statistical mechanics and problems in which they were merged with quantum theory (leading to an explanation of the Brownian movement of molecules), atomic transition probabilities, the quantum theory of a monatomic gas, the concept of the photon, the theory of radiation (including stimulated emission), and the geometrization of physics.

Einstein's research efforts after developing the theory of general relativity consisted primarily of attempts to generalize his theory of gravitation in order to unify and simplify the fundamental laws of physics, particularly gravitation and electromagnetism, which he referred to as the Unified Field Theory.

**Michael Faraday**
Faraday was an English chemist and physicist who contributed significantly to the fields of electromagnetism and electrochemistry. He established that magnetism could affect rays of light and that the two phenomena were linked. It was largely due to his efforts that electricity became viable for use in technology. The unit for capacitance, the farad, is named after him as is the Faraday constant, the charge on a mole of electrons (about 96,485 coulombs). Faraday's law of induction states that a magnetic field changing in time creates a proportional electromotive force.

**J. Robert Oppenheimer**
Oppenheimer was an American physicist best known for his role as the scientific director of the Manhattan Project, the effort to develop the first nuclear weapons. Sometimes called "the father of the atomic bomb", Oppenheimer later lamented the use of atomic weapons. He became a chief advisor to the United States Atomic Energy Commission and lobbied for international control of atomic energy. Oppenheimer was one of the founders of the American school of theoretical physics at the University of California, Berkeley. He did important research in theoretical astrophysics, nuclear physics, spectroscopy, and quantum field theory.

**Sir Isaac Newton**
Newton was an English physicist, mathematician, astronomer, alchemist, and natural philosopher in the late 17$^{th}$ and early 18$^{th}$ centuries. He described universal gravitation and the three laws of motion laying the groundwork for classical mechanics. He was the first to show that the motion of objects on earth and in space is governed by the same set of mechanical laws. These laws became central to the scientific revolution that took place during this period of history. Newton’s three laws of motion are:

> I. Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.
> II. The relationship between an object's mass m, its acceleration a, and the applied force F is F = ma.
> III. For every action there is an equal and opposite reaction.

In mechanics, Newton developed the basic principles of conservation of momentum. In optics, he invented the reflecting telescope and discovered that the spectrum of colors seen when white light passes through a prism is inherent in the white light and not added by the prism as previous scientists had claimed. Newton notably argued that light is composed of particles. He also formulated an experimental law of cooling, studied the speed of sound, and proposed a theory of the origin of stars.

**Erwin Schrödinger**
Schrödinger was a Nobel Prize winning Austrian physicist who is best remembered for his contributions to quantum mechanics. Chief among his findings was the Schrödinger equation which describes the space and time-dependence of quantum systems. This equation predicts behavior of microscopic particles in much the same way that Newton's second law predicts the behavior of macroscopic matter. Much of solid state physics was built upon the Schrödinger (wave) equation. Schrödinger also devised the "cat in a box" thought experiment to illustrate a paradox of quantum mechanics.

**Enrico Fermi**
Fermi was an extremely gifted Italian physicist and Nobel Prize winner. His work focused on radioactivity, quantum theory, and statistical mechanics and he helped develop the first nuclear reactor. He also participated in the Manhattan Project after fleeing to America prior to the Second World War. Fermi's Golden Rule is an important equation in quantum mechanics and is used to calculate the transition rates of quantum systems. Much of Fermi's work in quantum mechanics (Fermi holes, Fermi levels, Fermi-Dirac statistics) ultimately led to our modern understanding of semiconductors.

**James Clerk Maxwell**
Maxwell was a Scottish theoretical physicist and mathematician whose work was especially important to our understanding of electromagnetism. His famous Maxwell's equations were the first to unify and simply express the laws of electricity and magnetism. Maxwell was also important in the development of the kinetic theory; the Maxwell-Boltzman distribution is a probability distribution used in statistical mechanics and to predict the behavior of gases. His work paved the way for much of the progress in physics during the 20$^{th}$ century (special relativity, quantum mechanics, etc) and ultimately led to all modern electrical and communications technology.

**Daniel Bernoulli**
Bernoulli was a Swiss mathematician who developed many equations important in physics. His work was especially focused on the behavior of fluids and the Bernoulli equation governs all steady, inviscid, incompressible flow. The resultant Bernoulli principle is especially useful in aerodynamics. The Euler-Bernoulli beam theory, which allows calculation of the loading characteristics of a beam, was of key importance during the Industrial Revolution and remains an important equation for engineers today. Bernoulli was also the first scientist to suggest the principles of the kinetic theory of gases.

**Skill 1.2 Explain the societal implications of developments in physics (e.g., nuclear technology, solid state technology)**

Nearly all advances in science and technology have some effect on society. However, some are especially important in changing the way we think about the natural world or how we lead our day to day lives. Several examples drawn from physics are briefly explored below.

**Heliocentric theory**
While we largely take for granted that the planets in our solar system orbit around the sun, during the 16$^{th}$ and 17$^{th}$ centuries it was a controversial notion in the western world. Most religious authorities, at least publicly, condemned the writings of Galileo and Copernicus which postulated a heliocentric model of the solar system. Both scientists and theologians argued over how new scientific evidence could be brought into agreement with scripture. This provides a famous historical example of how organized religion can interact with, and at times impede, scientific progress. Today, we still see this playing out in debates over such theories as the Big Bang and evolution.

**Nuclear physics and the atomic bomb**
Advances in nuclear physics in the first half of the 20$^{th}$ century led to the realization that tremendous amounts of power could be generated for fuel or weaponry through atomic fission and fusion. During World War II, the United State and its allies (through the Manhattan Project) were the first to succeed in the creation of atomic bombs which were subsequently dropped on Hiroshima and Nagasaki in 1945. The long term and exceedingly devastating effect of these weapons cannot be overstated. Nuclear proliferation (especially by the US and the USSR) in the following 50 years contributed to the Cold War and created an imminent threat of vast worldwide destruction. While the Cold War has since ended, the continued testing and possession of nuclear weaponry by an ever growing number of countries remains an important socio-political problem.

Nuclear power is currently use but remains controversial. On one hand, the extreme short and long term dangers of nuclear accidents have been demonstrated by incidents such as those at Three Mile Island and Chernobyl. On the other hand, society is highly in need of a cleaner, more sustainable source of energy and nuclear power might be able to fill this role.

**Semiconductors, the transistor, and digital devices**

The discovery that the electrical conductive properties of semiconductors can be either permanently or temporarily manipulated has been an important one. Most importantly, it led to the creation of solid state electrical devices such as transistors. In electrical circuits, these elements replaced the previously used vacuum tubes and mechanical relays which were highly susceptible to wear and physical stressors. Transistors, however, are small, fast, accurate, reliable, and can be produced quickly and cheaply. Thus, transistors have paved for the way for the vast array of affordable electrical devices. They have been particularly important in advancing computers and digital technology. We are well aware of how digital devices and information technology, made possible in part by transistors, touch every part of our modern lives.

**MEMS and nanotechnology**

Many people speculate that nanotechnology is poised to make significant changes in our lives. Microelectromechanical Systems (MEMS), or micromachines are made possible by modern materials and technologies (such as lasers and micro-etching) that allow manufacture and manipulation of devices on the micrometer scale. Developments in these technologies are already being used in the automotive, biomedical, chemical, cosmetic, telecommunications, and manufacturing industries.

## COMPETENCY 2.0 UNDERSTAND THE NATURE OF SCIENTIFIC INQUIRY, SCIENTIFIC PROCESSES, AND THE ROLE OF OBSERVATION AND EXPERIMENTATION IN SCIENCE

### Skill 2.1 Outline the processes by which new scientific knowledge and hypotheses are generated

The scientific method is 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. The scientific method is the process by which data is collected, interpreted and validated. While an inquiry may start at any point in this method and may not involve all of the steps here is the general pattern.

**Formulating problems**

Although many discoveries happen by chance, the standard thought process of a scientist begins with forming a question to research. The more limited and clearly defined the question, the easier it is to set up an experiment to answer it. 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 physics, 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. One of the most important scientific laws 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 scientific research in the early 19th century.

**Forming a hypothesis**
Once the question is formulated, take an educated guess about the answer to the problem or question. This 'best guess' is your 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. Scientists sometimes do short experiments "just to see what happens". Often, these are not formal experiments. Rather they are ways of making additional observations about the behavior of matter. A good test will try to manipulate as few variables as possible so as to see which variable is responsible for the result. This requires a second example of a **control**.  A control is an extra setup in which all the conditions are the same except for the variable being tested.

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. For instance, in your science class you may 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.

**Steps of a Scientific Method**