

Periodic Table of the Sciences®

The Periodic Table of the Sciences is a graphical description of Falling Apple's vision for science education. Within each column, the table shows the stages of development (from bottom to top) of the five major theories that are essential to a basic education in science. The order of the columns (from left to right) reflects the fact that each theory is a prerequisite for the next.

The concepts of science have a necessary order. Kepler's laws of planetary motion must come before Newton's law of universal gravitation, electric charge before atomic theory, and atomic theory before modern biology. This logical order is shown in the table—vertically in the development of each theory and horizontally in the progression from one theory to the next. Thus, the Periodic Table of the Sciences captures the integration and the hierarchy of scientific knowledge.

For students and teachers, the table serves as a reference that demands an answer to two crucial questions: what previous knowledge does an idea rest on, and where does the new knowledge lead?

Click on any cell for more information	Astronomy Heliocentric Theory	Physics I Newtonian Mechanics	Physics II Electromagnetism	Chemistry Atomic Theory	Biology Theory of Evolution
Stage 4 Culmination of Theories	Galileo: The Telescope and the Relativity of Motion	Newton's Law of Universal Gravitation	Maxwell's Equations and Light	The Structure of Atoms	Modern Genetics and Immunology
Stage 3 Mature Theories	The Copernican Revolution and Kepler's Laws	Newton's Universal Laws of Motion	Electric Current and Electromagnetism	Kinetic Theory and the Periodic Table	Darwin's Theory of Evolution
Stage 2 Beginning Theories	The Geocentric Theory	Galileo's Laws of Terrestrial Motion	Static Electricity	Early Evidence for Atoms	Linnaeus and Classification
Stage 1 Early Experiments and Measurements	Early Mathematical Astronomy	Statics: Measurement of Force	Properties of Light: Newton's Optics	Quantitative Analysis and Elements	Geology and Early Microbiology
Stage 0 Observations and Simple Concepts	Astronomical Observations and Time	Simple Machines, Force and Friction	Magnets and Electrics	Materials: Observed Properties and Changes	Survey of Life, Survival Mechanisms, Anatomy

Astronomy –

Stage 0 – Observations and Simple Concepts

The first stage is pre-scientific; it provides the student with the foundation of observable facts that are later integrated and explained by scientific theory. Every theory begins with observation and understanding simple concepts. Science is the process of discovering the causes of what we observe. *What must precede why.*

The importance of this stage is often overlooked in trying to learn or teach a subject. A common mistake in teaching is to introduce a theory first, and then show its application. This cuts the theory off from its roots in reality, leaving it a floating abstraction. At every stage of learning the student should arrive at the abstractions from the observed facts. Learning entails the capacity to answer the question: “How do I know?” The student does not understand if his only answer is: “Because the teacher told me so.”

Observations are not only the starting point of science, they are the key to advancing scientific knowledge at every level.

We call this stage *zero* to highlight the fact that this level of material does not yet have a necessary order or scope. In contrast to the goal of stages 1 through 4, which is building to a solid understanding of a major theory, the goal of stage zero is simply to become aware of the vast array of things and phenomena in our world.

The guiding principle for selecting and teaching this level of material is to make it interesting and fun for the kids, and don't try to smuggle in overly complex explanations. For example, if a four-year-old asks where babies come from, he is satisfied with being told they come from the mother's tummy. A detailed, cause and effect explanation of mating and egg fertilization would be confusing, would not satisfy his curiosity, and would not advance his knowledge, even if he could memorize and recite the explanation on cue.

Stage 1 – Early Experiments and Measurements

It is the progression from qualitative observation to quantitative measurement that makes scientific theory possible. At the earliest and simplest levels of knowledge, causes can be grasped in a qualitative way. At the more abstract level of scientific theory, however, causes can be identified only by relating numerical measurements. Every natural science, from astronomy to physics to chemistry to biology, is crucially dependent on mathematics, the science of relating quantities.

“Experiment” is the method of establishing causal relationships by means of controlling variables. In the 17th century, the discovery of the fundamental role of experiment made possible the modern scientific era. The numerical measurements of the experimenter are the prerequisite for the application of mathematics and the discovery of theories that identify fundamental causes.

This stage introduces some of the quantitative data and narrow laws that are eventually integrated by the broad theory.

Stage 2 – Beginning Theories

After what and how much, scientists raise the question: Why? The beginning theories of a subject are first attempts at answering this question. First theories are often deeply flawed, but they are still useful in advancing a science if they are attempts to integrate and explain observations, rather than merely empty speculations.

To the extent they are correct, initial theories confirm cause and effect relationships and serve to reduce the units of data that the scientist must deal with. To the extent they are wrong, their flaws are highlighted by the refusal of observations to conform to their predictions. By attacking the discrepancies, scientists can find leads to the truth. Kepler started by trying to find the best circular orbit of Mars—and then the failure of his model played an essential role in his discovery that planetary orbits are ellipses.

For teachers and students, tracing the early attempts to explain phenomena highlights the logic and necessity of the correct theory that scientists eventually discover. The student sees the contrast between the thinking that led to errors and the thinking that led to valid discoveries, and he thereby gains insight into proper scientific method.

Stage 3 – Mature Theories

The payoff of scientific research comes when a mature theory is established. A theory reaches this stage when it identifies the basic causes that explain a large body of observed phenomena. At this point the scientist can predict future outcomes based on the forces at work. Although scientific understanding is often initially pursued for the sake of curiosity or the knowledge itself, the mature theory is extraordinarily practical: e.g., the study of heat and electromagnetism led to generators, motors, and electric light; the atomic theory of matter led to new materials, computers, and advances in medicine.

Unfortunately, it is precisely this supreme power of theories that leads many educators to dive right into teaching students the theory and its applications, without covering how the theory was discovered. Understanding how we know a theory is true—and how we know competing theories are false—is the essence of scientific knowledge.

Stage 4 – Culmination of Theories

In science, one breakthrough paves the way for the next. The theories covered in our curriculum had implications that opened up new frontiers of research and led to the integration of subjects that had previously been regarded as separate. Thus the heliocentric astronomy led to a new physics, culminating in Newton's discovery of universal gravitation; Maxwell's theory led to a new understanding of light, thereby integrating the fields of electricity, magnetism, and optics; the atomic theory of matter culminated in an understanding of atomic structure, completing the integration of physics and chemistry; and finally, the combination of all this knowledge with Darwin's theory of evolution gave rise to modern biology and its extraordinary life-saving technology.

Physics I

Stage 0 – Simple Machines, Force, Friction, Work, Buoyancy

Man has used mechanical devices since prehistoric times. The leverage of a swinging club creates a potent weapon; a wheel can be used to spin pottery or assist in moving a load. Boats, too, come to us from the earliest times.

No scientific knowledge is required to intuitively understand these devices. A student can grasp the workings of simple machines such as levers, screws, wheel & axles, inclined planes, and wedges simply by manipulating them and watching for examples of their application, which are all around us. The fact that some objects sink and others float is known to every toddler, as is the idea that water on the floor can cause you to slip and fall. The first step of understanding mechanics is simply to focus on and name these basic phenomena, thereby stocking your mind with a myriad of examples.

Here we introduce the concept “work “(force x distance), which is a prerequisite for the more advanced concept “energy.”

Stage 1 – Statics

Archimedes introduced mathematical rigor to machines with his law of levers and principle of buoyancy. He then demonstrated the practical nature of his discoveries in the battle of Syracuse, where his machines held off a Roman attack for more than a year.

The understanding of statics (i.e., the study of forces in equilibrium) is the basis for much of mechanical engineering, and this subject was further advanced by Leonardo da Vinci and Galileo. Da Vinci invented complex machines involving gears, drills, cranes, and hydraulic jacks. He also designed a paddle wheel boat, a water pump, and a prototype of a flying machine. Galileo contributed to the subject by investigating the relative strength of beams and other structures. Furthermore, his collaboration with Torricelli led to the discovery of air pressure and the invention of the mercury barometer. It was then recognized that Archimedes’ principle of buoyancy applies to gases as well as fluids.

Throughout this development, forces were measured by balances and steelyards. In the later 17th century, Robert Hooke discovered another way to measure forces: the amount a spring is stretched or compressed is proportional to the force pulling or pushing on it. Now, the spring-scale is a standard device for measuring forces in classroom demonstrations.

Stage 2 – Galileo's Laws of Terrestrial Motion

Galileo was the first great physicist. His experimental investigation of motion provided the foundation for all that followed (in regard to method and content).

Galileo performed relatively simple experiments that have profoundly important (and often surprising) results. When properly presented, the student grasps the entire sequence of experiments as a logical chain of reasoning, with each discovery leading to the next. He sees that Galileo’s law of pendulums played a crucial role in his investigation of free fall, that free fall experiments led to the study of inclined planes, and that the results of inclined plane experiments led to the discovery of parabolic trajectories.

For the teacher and the student, this material is a gold mine. It is passed over far too quickly in most physics classes; in contrast, we treat it with the respect and the depth that it deserves.

The students will also learn that Galileo was more than a physicist; he led a courageous battle to defend independent thought against the coercive authority of the Church. This battle was one of the great turning points in intellectual history and every student should learn about it. Galileo paved the way for the Age of Reason.

Stage 3 – Newton's Universal Laws of Motion

Prior to Newton, nobody had conceived the possibility of fundamental laws that apply to all bodies in the universe. We lead the student step by step through the reasoning by which Newton discovered these laws. As a result, the student views $F = mA$ not as dogma to be memorized but as a brilliant answer to intriguing questions that had been raised across centuries.

Newton's laws of motion appear deceptively simple, which is one reason so many teachers believe they can be presented at the outset with little preamble or explanation. However, the concepts necessary to arrive at the laws – concepts such as “acceleration,” “limit,” “gravity,” “mass” and “momentum” -- are complex integrations of an extraordinary range of facts. Newton needed all the laws discovered by Galileo and Kepler, plus additional astronomical data, further experiments, and new mathematical techniques.

The student emerges from this study with a deep admiration for Newton's magnificent achievement

Stage 4 – Newton's Law of Universal Gravitation

Contrary to the way this topic is usually presented, Newton did not leap to the law of universal gravitation and then search for confirming instances. He started by using his understanding of motion to identify the nature of the sun's force on the planets. He then showed that a similar force is exerted by Jupiter and Saturn on their moons – and he therefore had a law pertaining to planets and moons. He next showed that a similar force is exerted by Earth on both terrestrial bodies and our moon – and he therefore had a law that applied to all bodies on Earth's surface as well as planets and moons. He then showed that the attractive force is not merely exerted by Earth as a whole, but it is exerted independently by every bit of matter making up Earth (his analysis of Earth's shape and precession, and the ocean tides, provided important evidence for this conclusion). Finally, he showed that the law applies even to comets, the celestial bodies that were legendary for their mysterious behavior and appearance. This was the genesis of Newton's discovery that all bodies have the property “mass” and thus attract in accordance with his law of gravitation.

Just as with Galileo, Newton's legacy transcends his specific discoveries in physics. He made enormous contributions to identifying the proper method of science. We discuss his famous statement that he “frames no hypotheses,” and contrast his approach to that of his predecessors. His rejection of arbitrary speculation was essential to his success.

By following the inductive method, Newton was able to discover a thoroughly causal, integrated universe for the first time. When taught correctly, the message is not lost on students – and they find the subject fascinating.

Physics II

Stage 0 – Magnets and Electrics

It was the Greeks who first wrote about the phenomena of magnetism and electricity. Thales commented on the power of lodestone (a magnet) and on the fact that amber (“elektron” in Greek) rubbed with wool attracts bits of straw.

In 1600, William Gilbert wrote a book (On Magnets) that summarized the existing knowledge about magnets and “electrics” (substances that were discovered to have the “amber effect”), and announced his discovery that Earth is a magnet. Unlike some of his predecessors, Gilbert carefully distinguished the properties of magnets and electrics. He pointed out that magnets attract only iron, whereas electrics attract many light objects. Magnets have “poles,” whereas electrics do not. The effect of electrics is easily shielded by interposing another body such as paper, but the attraction of magnets is unaffected by such shielding. The electrics attract only after rubbing with another material, but magnets do not require rubbing.

In this section of the course, the student learns some of the basic facts that are essential to the later development of a theory.

Stage 1 – Properties of Light: Newton's Optics

The study of light has a long history. Euclid knew the law of reflection from mirrors, Ptolemy studied refraction, and eyeglasses were invented in the Middle Ages.

But optics did not become a science until the 17th century, when telescopes and microscopes were invented and put to use as scientific instruments. In 1621 Snell discovered the law of refraction, and soon thereafter scientists began to use prisms and lenses to investigate colors. In the 1660s, Newton developed the correct theory of colors by means of a brilliant series of experiments. He then used his theory to explain the properties of rainbows and chromatic aberration in refracting telescopes. Most of Newton's experiments are relatively easy to perform in class, and they provide a great lesson in scientific method.

In addition, a Dutch astronomer (Olaus Roemer) used data on the eclipses of Jupiter's moons to calculate the speed of light for the first time.

Stage 2 – Static Electricity

Electricity became a science in the 18th century. It was discovered that some materials conduct electricity and others do not; that electric charge exists in two varieties, called positive and negative; that charge can be stored in “Leyden jars,” which can be discharged through a conductor; that lightning is an atmospheric discharge; and that opposite charges attract and like charges repel with a force that varies as the inverse square of the distance. Our students also learn how Benjamin Franklin developed the first theory of electricity, and how the theory was later modified and improved.

The early experiments in electricity can be performed in class, with results that are enlightening and occasionally shocking. The student comes to see the scientist as a detective, investigating the mysteries of nature and making them intelligible.

Stage 3 – Electric Current and Electromagnetism

It was a landmark achievement when scientists learned how to generate electric currents. The invention of the battery (by Volta in 1800) made it possible to discover the connection between electricity and magnetism.

Many of the experimental discoveries that followed—made by Oersted, Ampere, Faraday, and others—can be demonstrated in class. For example, students can see that electric currents deflect the needle of a magnetic compass and that a moving magnet can generate an electric current. Here we explain the facts that gave rise to the concepts of electric and magnetic “fields.” The basic relationships can be understood without higher mathematics, which is how Faraday understood them (since he was not a mathematician).

Stage 4 – Maxwell's Equations and Light

It was Maxwell who completed the theory of electromagnetism and formulated it in terms of a few fundamental equations. He discovered that a changing electric field gives rise to a magnetic field (the reverse relationship had been discovered by Faraday decades earlier). The result is that moving charges can generate electromagnetic waves, and Maxwell was able to show that such waves move at the speed of light. He concluded that light is an electromagnetic wave. Thus the science of optics was integrated with electromagnetism.

Chemistry

Stage 0 – Early Chemistry and Applications

We observe a variety of chemical changes all around us—metals rust, wood burns, bread stales and milk sours. In the early history of chemistry, our students will see how people learned to cause chemical changes that were beneficial to their lives. They learned how to extract metals and make alloys for tools; they learned how to make glass and shape it to their purposes; they learned about dyes and used them to color their clothes; and they discovered explosives that could be used as weapons.

A great deal of practical knowledge about the properties and transformations of materials was necessary before chemistry could be developed into a science. Young students find the early discoveries fascinating, and it prepares them for the later study of chemistry.

Stage 1 – Quantitative Analysis and Elements

To understand chemistry we must know how to distinguish substances from mixtures and elements from compounds. In the 18th century, when investigators finally learned to make these crucial distinctions, chemistry began to develop into an integrated science (rather than a collection of disparate facts).

The principle of mass conservation and the method of quantitative analysis enabled chemists to identify the basic elements composing materials. They discovered that air is a mixture of oxygen and nitrogen, water is a compound of hydrogen and oxygen, and carbon dioxide is essential to plant growth. By the end of the 18th century, chemists had arrived at the law of constant composition, i.e., they discovered that different samples of a compound always contain the same elements in the same proportions by mass.

In this section of the course, we also discuss the measurement of temperature, the heat capacities of materials, and the basic law of gases (i.e., the product of pressure and volume is proportional to temperature).

Stage 2 – Early Evidence for Atoms

In the early decades of the 19th century, a series of discoveries provided strong evidence for the atomic theory. Dalton discovered the law of multiple proportions, implying that elements combine in discrete units of mass; Gay-Lussac discovered that gases combine in integer units of volume; Dulong and Petit discovered that the specific heats of elements could be explained by supposing that each atom absorbs the same amount of heat; and Faraday discovered that the results of electrolysis experiments could be

explained if each atomic ion carries the same electric charge.

At this stage, however, there were doubts about how to determine the correct atomic weights and about the validity of Avogadro's hypothesis (which was necessary to explain the law of combining gas volumes). Our students see how the story unfolds—the questions, the initial answers, the problems that arose, and finally the ingenious way the problems were resolved.

Stage 3 – Kinetic Theory and the Periodic Table

It was the study of heat and gases that led physicists to the atomic theory. In a brilliant experiment, Joule discovered the relationship between heat and motion. Waterston then identified temperature with the average kinetic energy of molecules and used the atomic theory to derive the basic law of gases. He showed that Avogadro's hypothesis could be inferred from his simple atomic model of gases.

Expanding on this work, Maxwell used the atomic theory to derive laws of gaseous diffusion, heat conduction, and viscosity. It was a great triumph for the atomic theory when experiments confirmed these laws. The theory was leading to breakthrough discoveries in physics as well as chemistry.

The atomic theory of gases enabled chemists to resolve earlier ambiguities regarding atomic weights and to develop the concept of atomic "valence." This led to Mendeleev's periodic table and to the discovery of many molecular structures. Chemists were finally able to explain the properties of compounds in terms of the spatial distribution of atoms. At this stage, the atomic composition of matter was proven.

Stage 4 – The Structure of Atoms

A fascinating series of further discoveries eventually led to the understanding of atomic structure. Physicists discovered the electron, radioactivity, the nucleus, the discrete electron states within the atom, and finally the processes of nuclear fission and fusion. As a result, they came to a much deeper understanding of chemical bonding and understood for the first time the source of the sun's energy.

The course ends by examining the crucial applications of this knowledge, which has been used to benefit our lives in so many ways

Biology

Stage 0 - Survey of Life, Survival Mechanisms, Anatomy

Stage 1 - Geology and Early Microbiology

Stage 2 - Linnaeus and Classification

Stage 3 - Darwin's Theory of Evolution

Stage 4 - Modern Genetics and Immunology