Physics in the Universe: Unit 2

Forces at a Distance

Background for Teachers and Instructional Suggestions

Instructional segment 1 introduces the concept of force as an influence that tends to change the motion of a body or produce motion or stress within a stationary body. While forces govern a wide range of interactions, the design challenge and many of the simplest applications from instructional segment 1 primarily involved interactions between objects that appeared to be physically touching. Instructional segment 2 builds upon this foundation by examining gravity and electromagnetism, forces that can be modeled as fields that span space. Despite the fact that we cannot see them, we interact with these fields on a daily basis and students are already familiar with their pushes and pulls.

At the middle grade level, students laid out a firm groundwork for studying these forces. They gathered **evidence** that fields exist between objects and exert forces (*MS-PS2-5*), **asked questions** about what causes the strength of electric and magnetic forces to vary (*MS-PS2-3*), and determined one factor that affects the strength of the gravitational force (*MS-PS2-4*). This high school instructional segment extends those skills by providing mathematical **models** of these forces. Though students' everyday experience with electric forces, magnetic forces, and gravity all seem to be independent of one another, these mathematical models will reveal some important connections between them.

Science and Engineering Practices and the History of Gravity

Although scientists have studied gravity and electromagnetism intensely for centuries, many mysteries remain concerning the nature of these forces. The *CA NGSS* learning progression mirrors the historical development of our understanding of gravity and orbital motion. In 1576, Danish scientist Tycho Brahe set up the world's most sophisticated astronomical observatory of its time. He methodically ***investigated*** and recorded the motion of celestial objects across the sky. Just before he died, Brahe took on Johannes Kepler as a student who **analyzed the data** to develop a simple descriptive **model**. Even though his model did a superb job of predicting the motion of objects in the sky, it was incomplete because it could not explain the fundamental forces driving the motions. In late 1600's, Isaac Newton extended Kepler's model by describing the nature of gravitational forces. From his fundamental equations of gravity, Newton was able to derive Kepler's geometric laws and match the observations of Brahe. Despite the fact that Newton's work was revolutionary, he became so well-known because his book, *Principia Mathematica*, did such a good job of ***communicating information***. In NGSS, elementary students mirror the work of Brahe, recognizing ***patterns*** in the sky (*1-ESS1-1*, *5-ESS1-2*). At the middle grade level, students mirror the work of Kepler by making simple ***models*** that describe how galaxies and the solar system are shaped (*MS-ESS1-2*). In high school, students add ***mathematical thinking*** to their descriptive model (using Kepler's laws, *HS-ESS1-4*) and then finally extend their model to a full explanation with the equations of the force of gravity from Newton's model (*HS-PS2-4*).

Equations of Gravitational Force

Newton's Law of Gravitation is a mathematical expression to describe and predict the gravitational attraction between two objects. Newton's Law is expressed as $F=Gm_1m_2/r^2$, where F represents the gravitational force, m_1 and m_2 represent the masses of two interacting objects, r represents the distance (radius) between the centers of mass of these two objects, and G is the universal gravitational constant.

Common Core Connection: Rearranging Formulas

The Common Core Mathematics standard *MATH.HAS.CED.A.4* states that students should be able to "rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations." Thus, given G and any three of the variables, students should be able to apply basic algebra to calculate the value of the remaining variable. Students are expected to make quantitative predictions using this equation, and they must also be able to understand it qualitatively (*HS-PS2-4*).

Mathematical **models**, such as expressed in Newton's Law of Gravitation, provide the opportunity for students to conceptualize complex physical principles using elegant equations. To assess understanding of such models, teachers can ask students such **questions** as, "What happens to the force of gravity if one doubles the mass?", or "What happens to the force of gravity if the distance between the centers of mass of the two objects is doubled?" All mathematical **models** in science are based on physical principles of relationships between ***scale, proportion, and quantity***. While students may be mathematically adept at calculating quantities, instructors can probe for understanding of the physical principles by asking questions about the equations such as "Why does this equation have an "r^2" value in the denominator?" or "Why does this equation resemble equations for radiation intensity, sound intensity, illumination, magnetism, and electrostatic forces?" This last question allows us to transition into the discussion of electromagnetism.

Equations of Electrostatic Force

Working together, electricity and magnetism are a constant presence in daily life: electric motors, generators, loudspeakers, microwave ovens, computers, telephone systems, static cling, the warm glow of the Sun, maglev trains, and electric cars, to name a few.

Asking students to identify the core ideas of science that are used by engineers to design and improve such technologies provides opportunities to review prior learning, and recognize the value of science in everyday life. It also opens the door to understanding the interdependence of science, engineering, and technology, in which scientists aid engineers through discoveries that can be incorporated into new devices, while engineers develop new instruments for observing and measuring phenomena that help further scientific research.

While students may readily see the application of electromagnetism to machines, they may have difficulty realizing that electromagnetic forces are also essential for life and govern every biochemical process in their bodies. Positively charged protons hold negatively charged electrons in orbit around the nucleus, and electrons of one atom are attracted to protons of neighboring atoms to form a residual electromagnetic force that holds molecules together, governs biochemical reactions, and ultimately prevents you from falling through the floor. All chemical reactions are driven by electromagnetic forces, and all chemical bonds are held together by electrochemical forces. These tiny electrical interactions can add up to some very large effects. For example, our sense of touch is mislabeled because we never actually "touch" anything. Instead, the electrons in our hand repel the electrons from other objects and we feel this electrostatic force as a sensation that objects are solid. In fact all interactions between objects in contact with one another are, at their essence, electrostatic interactions.

Well known physicist Michio Kaku said, "You may think that I am sitting on this chair, but actually that's not true. I'm actually hovering 10^{-8} cm over this chair because the electrons of my body are repelling the electrons of this chair (PonderAbout 2008)." How does he know? He calculates this value using Coulomb's Law, the equation that describes the force of electrically charged objects as directly proportional to the magnitudes of the charges and inversely related to the square of the distances between them: $F=k(q_1q_2)/r^2$, where F is the electrostatic force, k is the Coulomb's constant, q_1 and q_2 are the magnitudes of the charges, and r is the distance between the charges. Given k and any three of the variables, students should be able to calculate the value of the remaining variable. (Calculating the delicate balance between gravity and electrostatic forces for an entire human body and an entire chair's worth of electrons is unfortunately too complex a challenge for most students, but students can calculate the force between two electrons at 10^{-8} cm distance apart.).

Students should notice that Coulomb's Law is strikingly similar to Newton's Universal Law of Gravitation. Both forces apparently have an infinite range and are directly proportional to the magnitude of the component parts (the two masses or the two charges), and inversely proportional to the square of the distance between them. With guidance, students apply **computational and mathematical thinking** to conclude that gravitational and electrostatic forces share a common geometry, radiating out as spherical shapes from their point of origin (See snapshot below).

Snapshot: Coulomb's Law, Newton's Gravitation, and CA CCSSM Geometry

Imagine throwing a rock into a glassy-smooth pond. Waves emanate in all directions from the point where the rock hits the surface of the pond. As a wave moves from the point of impact, the same ***energy*** is spread over an increasingly large area.

Initially the waves are tall, but as the waves get farther from the source, they become more diffuse. What is true of the water wave along the surface of the pond is similar to what happens to any point source that spreads its influence equally in all directions. Although the water waves are confined to the surface of the water, point sources, such as radiation, sound, seismic waves, illumination, magnetism, electrostatics and gravity display a similar attenuation with distance (Figure 3).

Students can model this effect mathematically with just a simple understanding of the surface area of a sphere (*CA CCSSM G-GMD.1*). The ***energy*** from a point source radiates out as a sphere so that energy initially concentrated at the source is distributed over an imaginary spherical surface. To determine the intensity of the energy at a given radius (r), we need to divide the source energy (S) by the surface area of the sphere to which the energy is distributed. Since the surface area of a sphere can be calculated as $A=4\pi r^2$, the intensity at one radius (r) can be calculated as $I_{1r} = \frac{S}{4\pi r^2}$, where S is the initial ***energy*** of the source, and I is the intensity at any radius (r) to which the energy has been dispersed. As the energy continues to radiate, the intensity will decrease as a function of the inverse square ($1/r^2$) of the radius, even though the amount of energy (S) remains constant. If the intensity of the energy at $r=1$ is defined as I_{1r}, then the intensity at $r=2$ will be $I_{2r} = \frac{1}{4} I_{1r}$, and the intensity at $r=3$ will be $I_{3r} = \frac{1}{9} I_{1r}$. The intensity falls off as the inverse square of the distance from the source simply because the surface area of the spherical front increases as a function of the radius squared.

Understanding of the geometric foundations of the inverse square principle is an important tool for understanding the mathematical representations of Newton’s Law of Gravitation and Coulomb’s Law (*HS-PS2-4*).

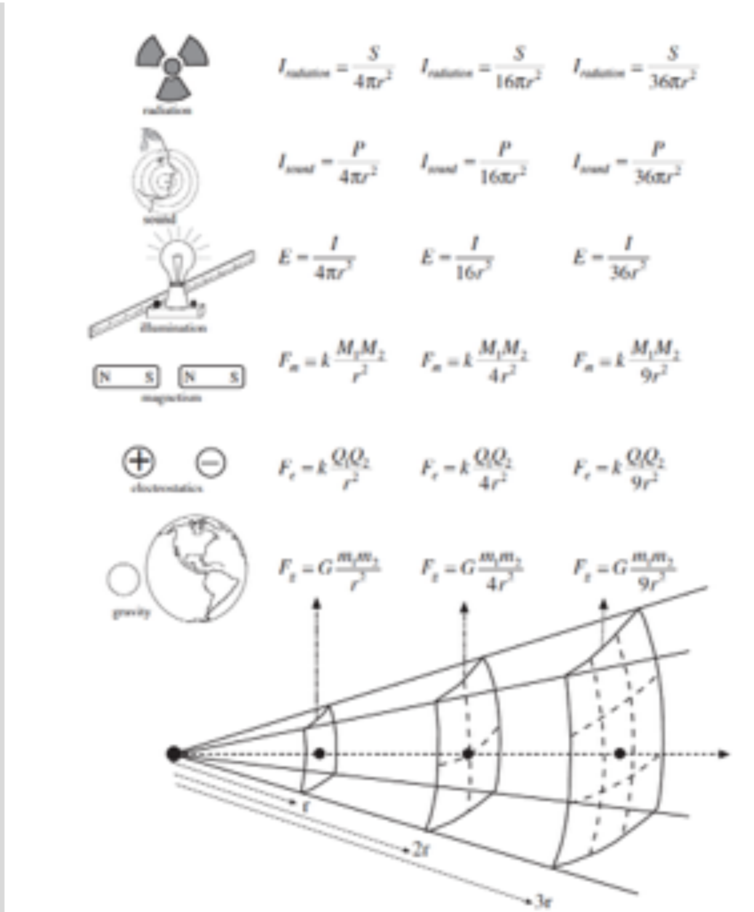

Figure 4. Equations representing how different phenomena all obey the inverse square law. (Herr 2008, 285)

Applications of Gravitational Force: Planetary motions

In order to verify that his mathematical model of gravitation was correct, Newton compared his results to observations of planetary orbits. If gravity was holding the planets in their orbits, Newton should be able to show it. He rearranged his equation in order to compare its prediction to the previous work of Johannes Kepler who used geometry to describe planetary motion. Indeed, Newton's equation simplified to match Kepler's. The focus of this section is not on deriving Kepler's Laws for elliptical orbits directly from the gravitational force, but instead on interpreting the evidence of the orbital period of different bodies in our solar system, including planets and comets. These laws form an excellent illustration of the crosscutting concept of ***scale,***

proportion, and quantity. By comparing the distance of objects away from the Sun and the time it takes them to complete one orbit, students recognize a ***pattern***.
Table 2 shows that the ratio determined by Kepler (orbital period squared divided by orbital distance cubed) is nearly constant for objects in our solar system. Students can calculate this ratio for Earth and other planets and then make measurements of the orbital path of comets to try estimate how often they will return. The ratio is only true for objects orbiting the same body (illustrated by the dramatically different ratio for the Moon in
Table 2), but students can use measurements of the Moon to predict the height of satellites in geosynchronous orbit (they have an orbital period of exactly one day, which allows them to always be in the same position in the sky. Satellite Television receives signals from these satellites), or the orbital period of the International Space Station from its height above Earth. Students can also the more complete form of Kepler's laws to calculate the mass of distant stars using only the orbital period of newly discovered planets that orbit them.

Table 2. Objects far away from the Sun take longer to orbit it, but ratios using Kepler's Laws are nearly the same for all bodies in our solar system.

Planet	Period (yr)	Average Distance (AU)	Kepler's ratio: T (yr^2
Mercury	0.241	0.39	0.98
Venus	0.615	0.72	1.01
Earth	1	1	1.00
Mars	1.88	1.52	1.01
Jupiter	11.8	5.2	0.99
Saturn	29.5	9.54	1.00
Uranus	84	19.18	1.00
Neptune	165	30.06	1.00
Pluto	248	39.44	1.00

Halley’s comet	75.3	17.8	1.00
Comet Hale Bopp	2,521	186	0.99
Moon (relative to Earth)*	0.0766	0.00257	345667*

* Kepler’s ratio only works for objects orbiting around the same body. Since Moon orbits Earth, its ratio should be much different.

Engineering Connection: Computational models of orbits

When a company spends millions of dollars to launch a communications satellite or the government launches a new weather satellite, they employ computer models of orbital motion to make sure these investments will stay in orbit. These **models** are based on the exact equations introduced in the *CA NGSS* high school courses. In fact, students can gain a deeper understanding of the orbital relationships and develop **computational thinking** skills by interacting directly with computer models of simple two body ***systems***. Even with minimal computer programming background, students could learn to interpret an existing computer program of a two-body gravitational system. They could start by being challenged to identify an error in the implementation of the gravity equations in sample code given to them. Next, students modify the code to correctly reflect the mass of the Earth and a small artificial communications satellite orbiting around it. They can vary different parameters in the code such as the distance from Earth or initial speed and see how those parameters affect the path of the satellite. At what initial launch speeds will the satellite stay in orbit versus spiral back into Earth’s atmosphere?

While Kepler’s laws present a simple view of orbital shapes and periods, the *NRC Framework* pushes teachers to emphasize the importance of ***changes*** in orbits, as these changes have large impacts on Earth’s internal systems:

> *Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. Cyclical changes in the shape of Earth’s orbit around*

the sun, together with changes in the orientation of the planet's axis of rotation, both occurring over tens to hundreds of thousands of years, have altered the intensity and distribution of sunlight falling on Earth. These phenomena cause cycles of ice ages and other gradual climate changes. (National Research Council 2012, 176)

Using realistic computer simulations of Earth's orbit, students can **investigate** the ***effects*** collisions (such as the impact that led to the creation of the Moon) or explore the variation in the Earth-Sun distance to look for **evidence** of cyclic ***patterns***. They would discover some cyclic ***patterns*** called Milankovitch cycles, which have strong influence on Earth's ice age ***cycles***.

Applications of Electrical and Magnetic Forces

The instructional segment then moves on to examining electromagnetic effects in solid matter. In this part of the instructional segment, connections should also be made to the electromagnetic interactions within and between molecules and the idea of chemical bonds. At the middle grade level, students were asked to develop conceptual **models** of the ***structure*** of solids, liquids and gases (*MS-PS1-4*). Here they work to develop and refine those models, and to understand that the ***stability*** and properties of solids depend on the electromagnetic forces between atoms, and thus on the types and ***patterns*** of atoms within the material. Key to this step is an understanding of the substructure of an atom, and of how the mass of the atom is determined by its nucleus, but its electronic structure extends far outside the region where the nucleus sits. An important idea here is that the geometric size of more massive atoms is not very different from that of a hydrogen atom, and an explanation for this is the fact that the higher charge of the nucleus pulls the electrons more strongly, so though there are more electrons, and their patterns are more complex, there is a roughly common size scale for all atoms. **Models** for materials help make the importance of this fact visible, as students see that you can fit many different combinations of atoms together in space, and thus make a great variety of molecules and materials. Once again, at this level the understanding expected is qualitative, not quantitative, but students should experience and consider a wide range of different types of materials, including some biological examples, to build an idea of the power of understanding forces in materials and the variety of consequences that can arise from their electromagnetic substructure.

Most collegiate STEM education is highly departmentalized, with students majoring in biology, chemistry, geology, astronomy, physics, engineering, mathematics or related fields. Students may inadvertently assume that particular topics belong to one domain or another and may fail to see the elegance and power of crosscutting concepts that have applications in a variety of fields. Teachers and students of physics may therefore have difficulty understanding the relevance of such performance expectations as *HS-PS2-6*, which states that students shall “communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.” This performance expectation sounds like it belongs in a chemistry course because it deals with “molecular-level structure”, or perhaps in engineering since it deals with the “functioning of designed materials”. In reality, this performance expectation, like many, can be equally valuable in the study of chemistry, engineering and/or physics. After studying electromagnetic interactions, students are better prepared to study the attractive and repulsive forces that determine the properties of matter.

HS-PS2-6 requires students to **obtain, evaluate, and communicate information** related to the properties of various materials and their consequent usefulness in particular applications. As stated in Appendix-M (Connections to the Common Core State Standards for Literacy in Science and Technical Subjects) of the *NGSS*, “reading in science requires an appreciation of the norms and conventions of the discipline of science, including understanding the nature of evidence used, an attention to precision and detail, and the capacity to make and assess intricate arguments, synthesize complex information, and follow detailed procedures and accounts of events and concepts.” Students “need to be able to gain knowledge from elaborate diagrams and data that convey **information** and illustrate scientific concepts. Likewise, writing and presenting information orally are key means for students to assert and defend claims in science, demonstrate what they know about a concept, and convey what they have experienced, imagined, thought, and learned.” *HS-PS2-6* emphasizes these skills.

Students may study the molecular-level interactions of various conductors, semiconductors and insulators to **explain** why their unique properties make them indispensable in the design of integrated circuits or urban power grids. For example, if students understand that the fundamental ***structure*** of metals, such as copper, aluminum, silver, and gold, can be described as a myriad of nuclei immersed in a “sea of mobile electrons”, they can then **explain** that these materials make good conductors because the electrons are free to migrate between nuclei under applied electromagnetic forces. By contrast, when students investigate the molecular level properties of covalent compounds, such as plastics and ceramics, they should note that they behave as electrical insulators because their electrons are locked in bonds and therefore resistant to the movement that is necessary for electric currents. As students learn to communicate such information, they obtain a better appreciation of ***cause and effect.*** For example, students should be able to explain that electromagnetic interactions at the molecular level (***causes***) result in properties (***effects***) at the macro-level, and that these properties make certain materials good candidates for specific technical applications.

The role of engineering in this instructional segment is not to make a design, but to use engineering thinking to analyze and explain a designed or natural material, and to **communicate** conclusions about how the substructure relates to the macroscopic properties of the material.