IS2

Physics in the Universe Instructional Segment 2: Forces at a Distance

Instructional segment 1 introduced 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 IS1 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.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 2: FORCES AT A DISTANCE

Guiding Questions

- How can different objects interact when they are not even touching?
- How do interactions between matter at the microscopic scale affect the macroscopic properties of matter that we observe?
- How do satellites stay in orbit?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. [Clarification Statement: Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] *[Assessment Boundary: Assessment is limited to systems with two objects.]*

HS-PS2-6. Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.* [Clarification Statement: Emphasis is on the attractive and repulsive forces that determine the functioning of the material. Examples could include why electrically conductive materials are often made of metal, flexible but durable materials are made up of long chained molecules, and pharmaceuticals are designed to interact with specific receptors.] *[Assessment Boundary: Assessment is limited to provided molecular structures of specific designed materials.]*

HS-ESS1-4. Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. [Clarification Statement: Emphasis is on Newtonian gravitational laws governing orbital motions, which apply to human-made satellites as well as planets and moons.] *[Assessment Boundary: Mathematical representations for the gravitational attraction of bodies and Kepler's Laws of orbital motions should not deal with more than two bodies, nor involve calculus.]*

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a practice or disciplinary core idea.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 2: FORCES AT A DISTANCE

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-5] Using Mathematics and Computational Thinking [SEP-8] Obtaining, Evaluating, and Communicating Information	PS2.B: Types of Interactions ESS1.B: Earth and the Solar System	[CCC-1] Patterns [CCC-2] Cause and Effect: Mechanism and Explanation [CCC-3] Scale, Proportion, and Quantity [CCC-6] Structure and Function

CA CCSS Math Connections: N-Q.1–3; A-SSE.1a–b, 3a–c; A-CDE.2, 4; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: RST.11–12.1, WHST.9–12.2.a–e

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

At the middle grades level, students established a firm groundwork for studying gravitational and electromagnetic forces. They gathered **evidence [SEP-7]** that fields exist between objects and exert forces (MS-PS2-5), **asked questions [SEP-1]** 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 [SEP-2]** of these forces. Though students' everyday experiences 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 [SEP-3]** 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 [SEP-4]** to develop a simple descriptive **model [SEP-2]**.

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 the late 1600s 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. Newton is known not only for his innovative thinking, but for his ability to **communicate [SEP-8]** clearly; many twenty-first century physics classes still read his book *Principia Mathematica* to learn about his ideas. In the CA NGSS, elementary students mirror the work of Brahe, recognizing **patterns [CCC-1]** in the sky (1-ESS1-1, 5-ESS1-2). In the middle grades, students mirror the work of Kepler by making simple **models [SEP-2]** that describe how galaxies and the solar system are shaped (MS-ESS1-2). In high school, students add **mathematical thinking [SEP-5]** 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

Students should be able to use Newton's Law of Gravitation to describe and predict the gravitational attraction between two objects (HS-PS2-4). 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.

Opportunities for Mathematics Connections

Students should be able to "rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations" (CA CCSSM A-CED.4). Thus, given G and any three of the variables, students should be able to apply basic algebra to **calculate [SEP-5]** 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).

CA CCSS Math Standards: A-CDE.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. All mathematical **models [SEP-2]** in science are based on physical principles of relationships between **scale, proportion, and quantity [CCC-3]**. To assess understanding of such models, teachers can ask questions like, "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?” In the middle grades, students argued that gravity always attracts objects together, but they only had empirical evidence and could not describe any mechanism for this behavior. Students can **explain [SEP-6]** why gravity is always attractive by referring to Newton’s Law of Gravitation (noting that mass can never be negative, so all terms are positive).

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.

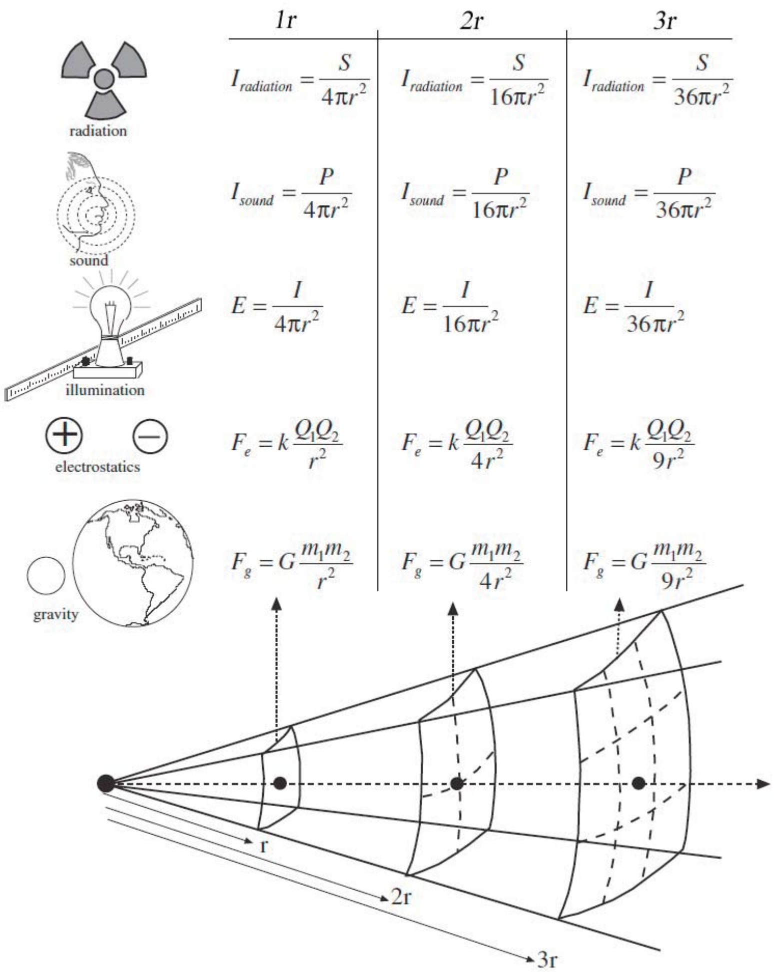
Asking students to identify the scientific principles that engineers apply to design and improve such technologies provides opportunities to review prior learning and recognize the value of science in everyday life. It also opens the door to understanding the **interdependence of science, engineering, and technology [CCC about nature of science]** 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. In the high school chemistry course, students create a model describing how electromagnetic forces are ultimately responsible for holding atoms together in chemical bonds.

Students likely have experience with magnetic latches and are aware of static electricity, but they will need firsthand experiences with electrostatic forces. Are they always attractive like gravity? Students can explore conceptual hands-on tutorials (see the University of Maryland Physics Education Research Group Tutorials in Physics Sense-Making at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link45) and interactive simulations (see the Concord Consortium Electrostatics at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link46).

Students should be able to use the simple equation in Coulomb’s Law to predict electrostatic forces between two electrically charged objects (HS-PS2-4). Coulomb’s Law states: $F = k(q_1q_2)/r^2$, 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.

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 [SEP-5]** to conclude that gravitational and electrostatic forces share a common geometry, radiating out as spherical shapes from their point of origin (figure 7.50).

Figure 7.50. Many Physical Processes Follow the Inverse Square Law



The intensity of radiation, sound, illumination, electrostatic interaction, and gravity vary as a function of distance (radius, *r*) from the source. *Source*: Herr 2008, 285

Physics in the Universe Snapshot 7.12: Coulomb's Law, Newton's Gravitation, and CA CCSSM Geometry

Everyday phenomenon: Waves spread out in all directions when a rock falls into a pond.

Ms. C asked her students to imagine throwing a rock into a glassy-smooth pond. Waves would 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 [CCC-5]** is spread over an increasingly large area. Initially the waves are tall, but as the waves get further 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, electrostatics, and gravity display a similar attenuation with distance (figure 7.50).

Investigative phenomenon: Waves get weaker as you move farther from their source.

Ms. C provided students access to all the equipment in the lab and asked them to develop a **model [SEP-2]** that illustrated how intensity varies with distance. Tom and Min used a marker to color a square on a balloon and proceeded to inflate the balloon to observe how the color of the square got lighter as the balloon was inflated. As Joshua and Maria observed Tom and Min, they got the idea to do the same, but used their cell phones to video their balloon as it is inflated so that they would have a permanent record to share with the class. Julia and Tae realized that Joshua and Maria had a good idea, but were lacking a scale, and improved upon their design by including a ruler in the background. Ms. C subsequently asked all three teams to share their ideas, and then asked Julia and Tae to wirelessly send their movie to the data projector so the class could observe the model (CA CCSS for ELA/Literacy SL.11–12.5). Students then estimated the surface area of the balloon at three different radii (CA CCSSM G-GMD.1) and noted how the intensity of the marker color decreased significantly with increasing radius (CA CCSSM G-GMD.5).

Applications of Gravitational Force: Planetary Motions

To verify that his mathematical model of gravitation was correct, Newton compared his results to observations of planetary orbits. If gravity were holding the planets in their orbits, Newton should be able to show it. He rearranged his equation to compare its prediction to the previous work of Johannes Kepler, who had 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 to interpret the evidence of the orbital period of different bodies in our solar system, including planets and comets. These laws form an excellent illustration of **scale, proportion, and quantity [CCC-3]**. By comparing the distance of objects away from the Sun and the time it takes them to complete one orbit, students recognize a **pattern [CCC-1]** and then use this pattern to predict orbital parameters using Kepler's Laws (HS-ESS1-4). Table 7.8 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 to 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, also in table 7.8). But students can use measurements of the Moon to predict the height of satellites in geosynchronous orbit, which have an orbital period of exactly one day, allowing them to always be in the same position in the sky. Satellite television receives signals from these satellites. Alternatively, students can use the orbital period of the International Space Station from its height above Earth. Students can also use 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 7.8. Observations of Planetary Distance and Orbital Period

PLANET	PERIOD (yr)	AVERAGE DISTANCE (AU)	KEPLER'S RATIO: T^2/R^3 (yr^2/AU^3)
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 (dwarf planet)	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 the Moon orbits Earth, its ratio should be much different.

Engineering Connection: Computational Models of Orbit

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 satellites will stay in orbit and the investment is not lost. These **models [SEP-2]** 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 [SEP-5]** skills by interacting directly with computer models of simple two-body **systems [CCC-4]**. 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 (HS-ESS1-4). At what initial launch speeds will the satellite stay in orbit? What is the tradeoff between the cost of fuel and the payload mass?

(Note: Appendix 3 in this framework provides guidance about teaching computer coding aligned with the CA NGSS.)

While Kepler's laws present a simple view of orbital shapes and periods, the *NRC Framework* pushes teachers to emphasize the importance of **changes [CCC-7]** in orbits, as these changes have large impacts on Earth's internal **systems [CCC-4]**:

> 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 [S]un, 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 (HS-ESS1-4), students can **investigate [SEP-3]** the **effects [CCC-2]** 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 [SEP-7]** of cyclic **patterns [CCC-1]**. They would discover some cyclic **patterns [CCC-1]** called Milankovitch cycles, which have a strong influence on Earth's ice age **cycles [CCC-5]**.

Applications of Electromagnetic Forces

Up to this point, this instructional segment has focused on interactions *between* different objects via electrostatic, electromagnetic, and gravitational forces. Now, students look at how forces work *within* materials at the microscopic level to explain macroscopic properties. In the middle grades, students developed conceptual models of atoms and molecules making up the **structure [CCC-6]** of solids, liquids, and gases. Here they **develop and refine those models [SEP-2]**, and understand that the **stability [CCC-7]** and properties of solids depend on the electromagnetic forces between atoms, and thus on the **types and patterns [CCC-1]** of atoms and molecules within the material.

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 discipline 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 HS-PS2-6 which focuses on how 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 because it deals with the functioning of designed materials. In reality, this performance expectation, like many, can be equally valuable in many different disciplines of science and engineering. An emphasis on material strength allows this content to flow well from the previous material in this course.

Students can begin by **investigating [SEP-3]** materials with macroscopic structure such as rope, yarn, knitted fabrics, individual clay bricks, clumps of soil, wood, or handmade paper. Students can sort the objects based on common **patterns [CCC-1]** in their structures. Rope, yarn, and wood all have fibers that run dominantly in one direction while knitted fabrics and paper both have fibers going in multiple directions. Clay bricks and clumps of soil have tiny particles in a three-dimensional matrix. All materials also have structure at the atomic level. These structures are held together by attractions caused by electromagnetic forces that can be different strengths (just as a clump of soil is weaker than a brick that has a similar internal structure because the forces holding the soil particles together are weak). Hence, different materials have different properties that are determined by features at the molecular level.

To develop a model of molecular level structure, students must first refine their model of the substructure of an atom. 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. 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 [CCC-1]** are more complex, there is a roughly common size **scale [CCC-3]** 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. For HS-PS2-6, students need only a qualitative, not quantitative understanding.

HS-PS2-6 requires students to **obtain, evaluate, and communicate information [SEP-8]** related to the properties of various materials and their consequent usefulness in particular applications. The role of engineering in this activity is not to make a design, but to use engineering thinking to **explain [SEP-6]** how the substructure relates to the macroscopic properties of the material and then **communicate [SEP-8]** that understanding. Performance expectation HS-PS2-6 emphasizes the skills 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. (NGSS Lead States 2013b)

Students may **obtain information [SEP-8]** about the molecular-level interactions of various electrical 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 these compounds 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 [CCC-2]**. 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.

IS3 Physics in the Universe Instructional Segment 3: Energy Conversion and Renewable Energy

We use **energy [CCC-5]** every moment of every day, but where does it all come from? Our body uses energy stored in the chemical potential energy of bonds between the atoms of our food, which were rearranged within plants using energy from the Sun. The light energy shining from our computer was converted from the electric potential energy of electrons from the wall socket that flowed through wires that may trace back to a wind turbine, which did work harnessing the movement of air masses, which absorbed thermal energy from the solid Earth, which originally absorbed the energy from the Sun. Each of these examples represents the **flow of energy [CCC-5]** within different components of the Earth **system [CCC-4]**. With each interaction, energy can change from one form to another. These ideas comprise perhaps the most unifying crosscutting concept in physics and all other science, **conservation of energy [CCC-5]**.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 3: ENERGY CONVERSION AND RENEWABLE ENERGY

Guiding Questions

- How do power plants generate electricity?
- What engineering designs can help increase the efficiency of our electricity production and reduce the negative impacts of using fossil fuels?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS2-5. Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current. *[Assessment Boundary: Assessment is limited to designing and conducting investigations with provided materials and tools.]*

HS-PS3-1. Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known. [Clarification Statement: Emphasis is on explaining the meaning of mathematical expressions used in the model.] *[Assessment Boundary: Assessment is limited to*