College Guild
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SCIENCE SAMPLER
~ Physics ~
Unit 2 of 5

Physics is the study of the rules that govern all types of matter and energy. It is the most fundamental of the sciences. A physicist studies how things move, how they interact with each other, how energy and heat work, what light and sound are, and so forth.

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Part 1. Physics: The Most Fundamental Science

Before science, people relied on traditional stories to explain their world. Gods and spirits could be found in all things: rocks and trees and clouds and bodies of water. When there was bad weather, a flood, or anything else unfortunate, people thought that the gods must be angry or that the spirits of their ancestors must be feeling neglected.

Around the beginning of the sixth century B.C. (roughly 2,600 years ago), the Greek philosopher Thales, an engineer by trade, was among the first to try to explain the world without involving gods or spirits. Thales said earthquakes were not the result of angry gods, but rather that the Earth floated on water and it was the rocking of the solid Earth on the water that caused earthquakes.

1. **We now know that the Earth does not float on water. But was Thales on the right track with this theory? Why or why not?**

2. **Thales could be superstitious. He thought that magnets had a soul, since they pulled metals to them. Explain how the old way of thinking — that everything, even rocks, might have a spirit — was hard to let go.**

After Thales came many other Greek thinkers. They liked *speculating* (guessing) about the *fundamental essence* of things, the stuff that all things come from. The following list summarizes their thoughts.

1. Thales said that water was the fundamental essence.
2. Anaximenes said that air was the most fundamental.
3. Anaxagoras said there was no fundamental essence.
4. Parmenides said that change was impossible, an illusion. Zeno, his student, said that motion was impossible.
5. Heraclitus disagreed. He said that change was the fundamental essence of the universe.
6. Democritus said that everything is composed of atoms, which cannot be broken down and are in constant motion, and that between the atoms was the void — nothingness.

3. **Which Greek thinker do you think got it mostly right? Explain.**

Sometime in the fourth century B.C. (roughly 2,350 years ago), the Greek *polymath* (someone with expertise in many fields) Aristotle wrote a work he called *Physics*. This great work included many of the concepts we now consider part of modern physics: how things move and interact with each other. Aristotle commented on the ideas of Greek thinkers of the past and added his own thoughts.

What Aristotle and the Greeks lacked was a means to test their ideas. They were careful observers of nature: they discovered the reason for eclipses; they understood that air particles bubble up through water because air is lighter than water. But, by and large, they did not (and often could not) test their theories. As a consequence, significant parts of Aristotle's physics are simply wrong.

Part 2. Classical Mechanics

In 1687, the great English polymath Isaac Newton published his *Mathematical Principles of Natural Philosophy*, which outlined his *theory of gravity*, and his *three laws of motion*, which describe how objects move and interact with each other. Together, these form the foundation of what we call *classical mechanics*.

Newton's Three Laws of Motion

Newton's first law of motion is often translated: *"An object at rest stays at rest and an object in motion stays in motion until acted upon by an external force."*

In late 2017, an interstellar asteroid, Oumuamua (oh-moo-ah-moo-ah), passed close to our sun. Before it got close to the sun, it was traveling in a straight line, at a constant *velocity* of 16–17 miles per second through the vacuum of space. When it approached the sun, it *accelerated* due to the sun's gravity and bent around the sun. As it moved away, it *decelerated* back to its former velocity of 16-17 miles per second and flew off in a straight line.

Here on Earth, everything that moves is slowed down by *friction*. Friction is a contact force between two objects. When a ball is rolling on the ground, the frictional force of the ground causes the ball to slow down and eventually stop. If there were no friction or any other external force, then the ball would keep moving forever at a constant velocity, like Oumuamua.

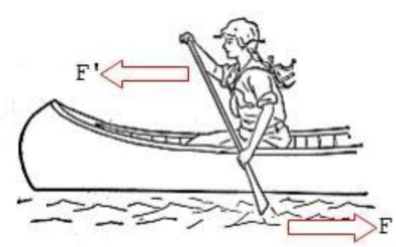
4. Explain the motion of Oumuamua using Newton's first law.

5. Using Newton's first law, explain to a child why they should wear a seatbelt.

Newton's second law of motion states that an object acted upon by a constant force will accelerate at a rate proportional to the force. We represent force with a capital **F**.

6. Imagine two situations, one in which you are pushing a car and the other in which you are pushing a bike. Imagine you push the bike and the car with the same amount of force. Which will accelerate faster, the car or the bike? Explain using Newton's second law.

Newton's third law of motion states: "*When two objects interact, the force of interaction between the two objects is equal in magnitude and opposite in direction*." That is, for every action, there is an equal and opposite reaction. One of the classic examples can be observed when paddling a canoe. See the figure to the right.[1]



7. When you push backward with the paddle, what happens to the canoe? Explain using Newton's third law.

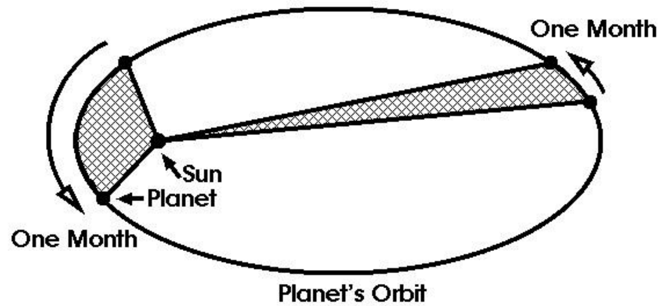
Note that classical mechanics uses some everyday words in very specific ways. This is typical of physics and the other sciences. For instance, velocity is the speed of an object in a specific direction. Mathematically, velocity is the change in position of an object over time. Acceleration is the change in velocity over time.

Classical mechanics forms the basis for what we usually think of when we think of physics. It explains all sorts of things about *mechanisms* we use every day: how a spring recoils, how pulleys work, how things move on smooth or rough surfaces, how balls roll and wheels spin, what happens to objects thrown into the air, how gears work, the behavior of pendulums, and so on.

Newton's Theory of Gravity

The asteroid Oumuamua was a visitor from outside our solar system. It does not orbit the sun and moves too fast to be pulled into the sun. It is not coming back!

All objects within our solar system have orbits. Moons orbit planets and planets orbit the sun. As we learned in unit 1, Johannes Kepler discovered that planets have elliptical orbits around the sun. Kepler's second law states that a line connecting a planet and the sun sweeps out an equal amount of space in an equal amount of time, as shown in the figure to the right.[2]



Kepler's Second Law

Today we recognize the tendency of the planet to move in this elliptical orbit as the *conservation of angular momentum*: the closer to the sun the planet gets, the faster it moves. This is the same property that makes a spinning figure skater spin more quickly when they pull their limbs in closer.

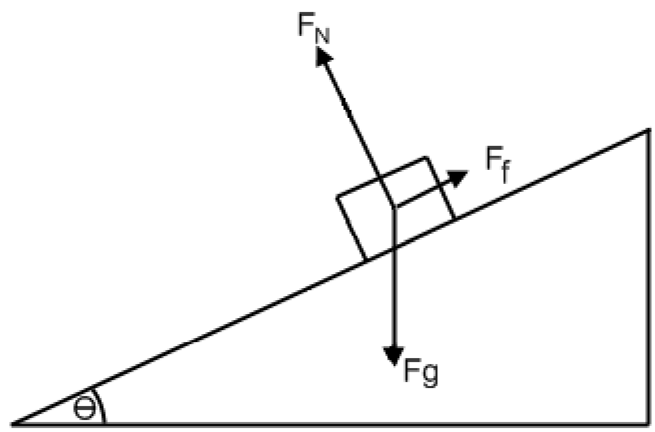
Newton's theory of gravity provided the reason the planet is pulled constantly toward the sun: *gravity*. Without gravity, the planet would immediately fly off in a straight line.

8. Suppose the force of gravity here on Earth could suddenly be switched off. What would happen to a person standing on the surface?[3]

Newton's theory of gravity explains the constant pull we feel toward the center of the Earth. A falling object falls with a constant acceleration, called **g**, meaning the object speeds up as it falls. Earth's constant of acceleration, **g**, equals 9.8 meters per second per second.

9. In reality, an object falling to Earth accelerates toward Earth but eventually reaches a terminal velocity — a maximum speed. What do you think stops the mass from continuing to accelerate?

If an object is not accelerating, the forces acting on it must be equal. When you stand on the ground, the ground resists your weight with the same force as the Earth's gravity. A box on a ramp is held in place by a combination of the ramp's resistance plus its frictional force. See the figure to the right. Gravitational force, $\mathbf{F_g}$, is balanced by the ramp's resistance — the normal force, $\mathbf{F_N}$ — and the force of friction, $\mathbf{F_f}$.



mass balanced on a ramp

10. If the force of friction is not enough to keep the box in place, what happens to the box?

11. Suppose the ramp has no friction (like a sheet of ice). Describe how the box will slide down the ramp. Will it slide with the same acceleration as if it had fallen from the air?

Part 3: Optics

As we learned in unit 1, Isaac Newton also studied the properties of light, a field called *optics*. The ancient Greeks thought that human vision worked through rays coming out of human eyes. By the tenth century (about a thousand years ago), the Arab polymath Alhazen understood that vision happens when light *reflects* off an object and is redirected toward the eye. Alhazen is called the "father of modern optics."

Alhazen studied optical *refraction*. See the image to the right.[4] When you look through a pair of reading glasses or at something underwater, you are looking at refracted light. As the light bounces off the object on the way to your eye, the light is bent. Newton's prism experiments also demonstrate refraction.

Refraction in action

12. Chances are when you look *directly* at an object (not reflected by a mirror) and it appears distorted, light from that object is refracted on its way to your eyes. What examples of refraction can you give from everyday life other than a straw in a glass of water? (hint: reread the paragraph above)

Like classical mechanics, optics has a wide range of practical uses. Lenses have been used to aid vision since ancient times, but it took the study of optics to enable high-quality lenses to be developed for vision, microscopy, and use in telescopes. Today, we rely on optics technologies such as lasers for computer storage and printers, fiber optics (which allow us to communicate overseas), and laser surgery.

Part 4: Electromagnetism

There are *magnets* and there are *magnetic materials*: different but related things. We don't know when people first discovered that naturally occurring magnets attract magnetic materials such as iron. But most ancient cultures knew about magnets and recognized that they have a "north" and a "south" *pole*. By the 12th century (roughly 900 years ago), the Chinese were using magnets as compasses for navigation.

In 1600, the English scientist William Gilbert published the first scientific investigation of magnets, *On the Magnet and Magnetic Bodies*. Gilbert's work is important because it did not rely on old ideas about magnets. Prior to Gilbert, people thought that a giant island magnet at the North Pole was the reason compasses pointed north. Gilbert recognized that such ideas were fanciful. He built a miniature model Earth and claimed, correctly, that compasses work because the Earth itself acts like a giant magnet.

13. A compass needle points north but also points slightly downward (toward the ground). Why?

Like magnetism, *electricity* had been known to people since before recorded history. You could get a shock from an electric eel or by rubbing silk on glass. In his work on magnetism, Gilbert also discussed electricity. In 1752, Benjamin Franklin attached a metal key to a kite string and flew the kite in a stormy sky. Sparks like the shocks of an eel jumped from the key to the back of his hand, showing that lightning was electrical in nature.

While preparing for an evening lecture in 1820, Danish scientist Hans Christian Ørsted noticed that a compass needle was pulled away from magnetic north when an electric current was nearby. This convinced him that a *magnetic field* radiates from all sides of a wire carrying an electric current, just as light and heat do, and that electricity and magnetism are related.

Today, we refer to *electromagnetism* to describe the related phenomena of electricity and magnetism. Some aspects of optics are also part of the study of electromagnetism, since light, too, is affected by an electromagnetic field.

Part 5: Fields

We have been discussing magnetic fields and electromagnetic fields. But what exactly is a *field*? Let's look at two examples.

Gravitational Field

Newton's law of gravity states that every mass in the universe attracts every other mass. Every mass has a pulling influence around itself, extending in all directions. We call this influence the *gravitational field* of the mass, and it follows two simple rules.

1. The gravitational field of a mass is *proportional* to the mass. If the mass doubles, its gravitational pull at a fixed point some distance away from the mass will also double. If the mass is increased by ten times (10x), its gravitational pull at a fixed point away from the mass will increase by 10x.
2. The gravitational field is also proportional to the *square of the distance* away from it. If we move away from a mass so that we are twice as far from it as before, the gravitational field of the mass will be one quarter what it was before. If we move 10x farther away from a mass, the gravitational field of the mass will be one hundredth what it was before.

14. Do planets more massive than Earth have gravitational fields that are stronger, weaker, or about the same as Earth's? Explain.

15. Say you are in a spaceship some distance from the sun. If you move farther away from the sun, would you feel a stronger gravitational pull from the sun, a weaker pull, or a pull of about the same strength as before? Explain.

Electric Field

An *electric field* is similar to a gravitational field, except that it applies to electric *charges* instead of masses. An electric charge is either positive or negative (like the + and - ends of a battery). Opposite charges attract each other; "like" charges (charges that are the same) repel each other. A negative electric charge is caused by an excess of *electrons* (a type of subatomic particle that will be discussed in unit 3) in a substance. Each electron has a negative charge and repels all other electrons. A positive electric charge just means there are not enough electrons in a substance, like "holes" where electrons would normally be. These holes repel each other, too. But holes and electrons attract each other.

16. A Van de Graaff generator builds up charge on its surface. When you touch it, the charge spreads out over the surface of your body. See the image to the right.[5] Why does it make this person's hair stick out straight? (hint: reread the paragraph above)


Van de Graaff Generator

The rules of an electric field are remarkably similar to those of a gravitational field. An electric field is proportional to the charge and inversely proportional to the square of the distance away from the charge.

The main difference is that whereas gravity is always a pulling force, an electrical field can pull or push (attract or repel) depending on whether charges are opposite or the same.

Part 6: Energy

Energy is another concept that has a specific meaning in physics. In many physics textbooks, energy is defined as "the ability to do work." Energy is something that must be applied to an object in order to move it or heat it.

Our sun is the source of energy delivered to Earth. Earth does have a hot interior, but most of that heat is trapped. The sun delivers its energy in the form of electromagnetic radiation. We feel this as heat, but in truth the sun is not delivering heat directly; rather, our bodies and everything else on Earth converts the sun's radiation into heat. The warm Earth allows life to thrive and all activity to occur. In order to deliver its energy, the sun transforms matter in its core, freeing the energy contained in the matter.

If this sounds like one form of energy — matter, radiation, heat, motion — is getting converted to another, you are correct! Energy is what is called a *conserved* property. This means, in all the universe, *energy cannot be created or destroyed*. It can only be converted from one form to another.

There are many forms of energy. The most straightforward are energies associated with motion, called *kinetic* and *potential*:

- **Kinetic energy** is related to motion. It is what you would need to make an object move through space. It depends on the mass of a body and its velocity.
- **Potential energy** is related to an object's position relative to something else. There are many types of potential energy, such as gravitational potential energy, electrical potential energy, and elastic potential energy, among others. It is often useful to think of potential energy as energy that could become kinetic, like a child at the top of a slide, or a drawn bow (see image below).[6]

For example, hold a pen, pencil, or book up in the air. Relative to the earth (the floor), that object has a gravitational potential energy, which depends on the height of your hand above the floor and the object's mass.


Potential Energy

17. If you drop the object, its height decreases as it falls; therefore, its gravitational potential energy also decreases. What type of energy does this potential energy get changed into?

An electric motor (for example, an electric fan), converts electrical energy into kinetic energy — in this case, the motion of the fan blades.

Other forms of energy include heat and nuclear, magnetic, elastic, mechanical, and chemical energy.

18. Electric motors never convert 100% of available electrical energy into kinetic energy. Let's say an electrical motor converts 90% of available electrical energy into kinetic energy. What kind of energy do you think the remaining 10% is converted into? (hint: place your hand on an active motor case)

19. Since energy cannot be created, where did electrical energy come from in the first place? Name one or more sources of electrical energy (the electricity available from a wall outlet).

20a. What kind of energy is stored in a car battery?

20b. If you put hot coffee in an insulated container, what kind of energy are you trying to store?

Part 7: Einstein

Sound, such as the crack of thunder, travels at about 1,125 feet per second. If it takes 5 seconds to hear thunder after seeing a flash of lightning, it means the lightning struck 1,125 x 5 = 5,625 feet away (a little more than a mile). Let's say you are in a car travelling at 100 feet per second (about 68 miles per hour) and you see a lightning strike straight ahead. From your perspective (measured from inside the car) the sound of the thunder is moving at 1,125 + 100 = 1,225 feet per second. The sound of the thunder is moving toward you, and you are moving toward the sound. So, you add the speed of the car to the speed of the thunder.

One of the most important discoveries of the late 19th century is that light doesn't work this way. All light — from low-energy radio waves to high-energy X-rays — travels at exactly the same speed. We call this speed **c** — the speed of light in a vacuum. **c** is approximately equal to 186,000 miles per second (nearly a million times faster than sound), and it doesn't seem to get faster or slower to an observer moving toward or away from it. *The speed of light is the same for all observers.*

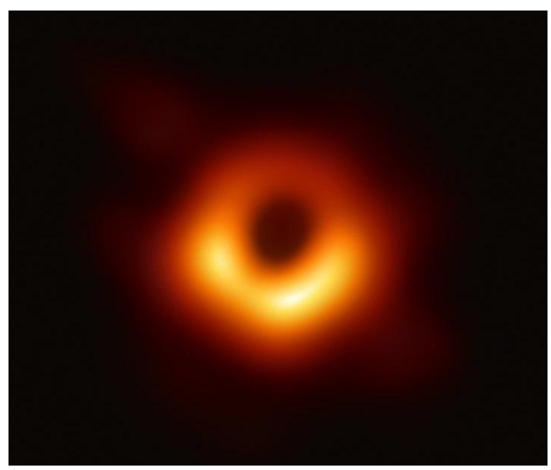
In the early 20th century, the German-born physicist Albert Einstein developed a theory called *special relativity* to explain the very strange consequences of light's constant speed. Special relativity states that nothing can exceed the speed of light. If you were to accelerate an object — say, a spacecraft — very close to the speed of light, its mass would increase toward infinity! If you took a spacecraft flying at a significant fraction of the speed of light away from Earth, and then returned after a year, you would notice your friends had all grown old whereas you had aged just a year. According to your onboard spacecraft clock, you had been gone a year, but according to the clocks back on Earth you were gone 50 years!

21. Do you think it would be possible to launch a manned spaceship at close to the speed of light? What about an unmanned spaceship? Explain your answer.

Perhaps the most famous result of special relativity is the equivalence of energy and mass, which Einstein formulated as $\mathbf{E = mc^2}$. This formula states that every mass has an *inherent* (built-in) energy equal to the mass times the speed of light squared. Even modest-sized objects therefore contain enormous amounts of energy. Nuclear energy, including nuclear bombs, are examples of how much energy may be released when a small amount of mass is converted to energy.

Einstein's *general relativity* theory, published in 1915, extends special relativity. General relativity gives us the concept of *space-time*, which states that our universe can be viewed as having three spatial dimensions, plus one time dimension. The gravity of objects with large masses like planets, stars, and galaxies distorts space-time similarly to the way a bowling ball would distort a bed mattress if placed on it.

General relativity predicts that supermassive objects called *black holes* may be formed as the remnants of dead stars or in the centers of galaxies. Black holes are so massive and so dense that even light cannot escape them. The figure to the right shows the first-ever image of a black hole, assembled by computer scientist Katie Bouman from data collected by radio telescopes all over the world and released on April 10, 2019.[7]



First ever image of a black hole

22. Scientists continue to test Einstein's theories more than 100 years after he published them. Why do you think it is important a theory be tested repeatedly?

Part 8: Quantum Theory

Our final topic in physics is *quantum theory*, which states that many physical properties — distance, mass, light — have a smallest amount: an amount that cannot be divided into smaller and smaller amounts.

Many things in everyday life are like this. They are *countable*. A coin has two sides, not 2½. There are 52 cards in a deck, not 51.998. A house has eight windows, not 8.625, and so on. But in nature, we think of most quantities as *continuous*. We think of distance, time, temperature, etc. as being measurable to whatever precision we need. If we need a more precise measurement, we just need a better ruler (or clock, or thermometer).

Quantum theory, sparked by the work of physicist Max Planck in 1900, states that lots of things are in fact *quantized*, meaning there is a smallest possible amount. The smallest possible amount of light is called a *photon*. Light is both a wave and a particle! Energy is also quantized. So is matter. All matter consists of atoms, which in turn consist of more fundamental particles — protons, neutrons, electrons. Perhaps there is a smallest amount of gravity and a smallest period of time. Scientists don't know.

By the middle of the 20th century, scientists were able to identify four *fundamental forces* of nature, two they were already familiar with — gravity and electromagnetism — and two new ones given by quantum theory. Note, "fundamental" means that all other forces we experience are the result of one or more of these forces. The four fundamental forces of nature are:

1. *Gravitational force*, responsible for sea tides, motion of the planets, and keeping us on Earth's surface
2. *Electromagnetic force*, which occurs between electrically charged objects or particles, such as protons and electrons
3. *Strong force*, which holds protons and neutrons together in an atom's nucleus
4. *Weak force*, responsible for radioactive decay within atoms

23. When a car is in collision, the bent metal and broken glass are largely the result of just one of the four fundamental forces. Which one do you think it is? Explain.

Much work is going on presently to try to bring together these four fundamental forces with a single unified theory. You may have heard of *string theory*, which is one of these unified theories. Most of these theories are not yet testable.

24. Why do you think it is important a theory be testable?

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are; if it doesn't agree with experiment, it's wrong."
—American physicist Richard Feynman (1918–1988)

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Remember: First names only & please let us know if your address changes

Citations

1. Canoe image: Herong's Notes on Physics
2. Kepler's second law image: One-Minute Astronomer
3. Question 8: Physics Part 1, R. Weidner, Allyn and Bacon, Inc.
4. Refraction image: Molecular Expressions, Optical Microscopy Primer, fsu.edu
5. Van de Graaff generator image: Department of Physics, the Leys School
6. Potential energy (Katniss) image: highpoint.edu/physics
7. Black hole image: Event Horizon Telescope Collaboration

Answers and hints to selected questions

5. Hint: is the external force of a seatbelt more or less damaging than the external force of a windshield?
6. With a constant force, F, when the mass, m, is large, the acceleration, a, is small; conversely, when m is small, a is large.
8. Hint: use Newton's first law of motion. Before gravity was switched off, was the person on the surface in motion?
9. Air
10. It will slide down.
11. It will slide down, but more slowly than if it had been dropped.
17. Kinetic energy

20a, 20b: Chemical, heat/thermal

23. Electromagnetic (is this surprising?)