# Unit 3

# Gravity

## Introduction

*Gravity cannot be held responsible for people falling in love.*
– Albert Einstein

*Gravity* is the most familiar of forces, but the least understood. Scientists have not succeeded in linking it, theoretically, to the other fundamental forces and are still working on theories of gravity and experiments to better understand this unique force. Einstein recast our understanding of gravity, indicating that it is not a force in the same sense as other forces are—it represents the warping of space and time. This is the essence of Einstein's *theory of general relativity*, the elegant successor to Newton's *law of universal gravitation*. However, because gravity is such a weak force, studying these effects proves challenging, and researchers are still attempting to measure gravitational effects at minute scales, as well as to detect the tiny ripples of *spacetime* from cataclysmic astronomical events.

### *What Will Participants Learn?*

Participants will be able to:

1. Describe, compare, and contrast Newton's concept of gravity with Einstein's.
2. Describe differences and similarities between gravitational and electromagnetic forces, including theoretical descriptions and how particles interact at a distance.
3. Summarize the role of logical arguments throughout the unit, including the motivation for new theoretical descriptions of gravity and how experiment relates to those theoretical predictions.

### *What's in this Unit?*

**Text:** Unit 3: *Gravity* discusses problems with the theories of gravity, and how our understanding of it has progressed over time. Gravity is extraordinarily weak among the fundamental forces. This makes it extremely hard to measure for small objects, though its attractive nature means that it is responsible for the structure that we observe in the universe. Newton's law of universal gravitation states the result of empirical observations: The force between two masses is inversely proportional to the square of the distance between them. Newton's law of universal gravitation has been shown to be valid at a wide range of distances, but it has some problems (both theoretical and experimental). These problems were solved by Einstein and his theory of general relativity, which states that gravity is actually the curvature of spacetime. *Black holes* are extreme examples of highly curved spacetime. *Gravitational waves* are ripples in this spacetime fabric that have not yet been directly observed. A theory of how gravity operates at the smallest scales—*quantum gravity*—has yet to be completely formulated and verified. *String theory* is one such theory, which will be explored in the next unit.

**Video:** The program follows two experimentalists who are studying gravity at both the largest and the smallest scales. Eric Adelberger and the Eot-Wash Group at the University of Washington have fashioned a highly sensitive torsion pendulum to measure whether Newton's law of gravity, and its $1/r^2$ dependence, continues to hold as masses get closer and closer together. They are searching for differences in gravity between the human-sized world and that of subatomic or quantum particles. Nergis Mavalvala of the Massachusetts Institute of Technology, on the other hand, is searching for the effects of gravity on huge scales. Using the largest interferometer in the world (the Laser Interferometer Gravitational Wave Observatory, LIGO), her collaborative team is searching for the minute bending of spacetime from gravity waves—a predicted, yet so far undetected, gravitational radiation emitted when massive objects move through space.

**Video Extra:** Wolfgang Rueckner of Harvard University demonstrates a tabletop version of the Cavendish Experiment to confirm Newton's law of gravitation for small masses.

**Interactive Lab:** *Discovering Neutrino Oscillation* allows you to explore how the basic properties of neutrinos affect effect their oscillations and design an experiment to learn more about the quantum behavior of this elusive particle.

**Activities:**

- The Hook: Defying Gravity (It's not so hard!) (15 minutes)
- Activity 1: The Problem with Newton's Law (30 minutes)
- Activity 2: Fixing up Newton's Laws (20 minutes)
- Activity 3: Watch and Discuss the Video (45 minutes)
- Activity 4: Curved Spacetime (20 minutes)
- Activity 5: Fall Into a Black Hole (optional)
- Back to the Classroom (20 minutes)

(*Note*: This unit is particularly dense, with many activities. If you do not finish the activities that you wish to cover in this session, you may consider incorporating up to 30 minutes into Unit 4, which is less dense.)

**Nature of Science Theme:** *Logic & Implications*. You may wish to display the *Logic & Implications* icon during the session and remind participants of the central ideas of this theme. Science is founded on principles of logical reasoning and arguments. Can we accept the implication of a new scientific idea or model of the natural world? Sometimes the logical implications of an observation or model will cause scientists to reject previously accepted principles.

Logic & Implications
*What does it mean?*

# Exploring the Unit

<u>Before the session</u>: Write the following topics on the board, and ask participants to sign up to present one of these topics based on their research from the homework. Explain to participants that they will be presenting their research during the course of the session, usually (but not always) at the beginning of a topic. Make it clear that these presentations must be short: "I know you may have found some really exciting stuff, but please keep your presentations to 1-2 minutes."

1. Weakness of gravity/Measuring *G*
2. Special relativity/Speed of light

3. Gravitational vs. inertial mass
4. The principle of equivalence (gravity = acceleration)
5. Validation of the inverse square law
6. Gravitational waves
7. Curved spacetime/General relativity
8. Black holes
9. Quantum gravity
10. Other

## *The Hook: Defying Gravity (It's not so hard!)*

Time: 15 Minutes.

Purpose: To compare the relative strengths of forces to discover that gravity is weak, and thus understand why the universal law of gravitation was so difficult to verify.

### *To Do and To Notice*

Choose one of the following demonstrations or topics as an introductory activity or discussion. The "Flying tinsel" is one of the most dramatic, but choose one that works well given your materials and weather (electrostatics work best in dry weather).

> **Flying tinsel**[1]**.** Charge an object (like a piece of PVC pipe or a block of blue foam insulation) by rubbing it with wool. Let a piece of tinsel drop onto the charged object. It will rebound (as it acquires charge from the PVC or Styrofoam) and hover in the air.
>
> **Balloon.** Charge a balloon by rubbing it with wool and stick it to the wall.
>
> **Magnets.** Pick up a paperclip with a magnet.
>
> **Surface tension**[2]**.** Float pepper on the surface tension of water.
>
> **The gecko.** Geckos attach themselves to the wall through van der Waals forces between tiny projections on their feet (*setae)* and the molecules of the wall. It takes many millions of these setae to balance the force of gravity so the gecko stays on the wall.

Optional: Taking Einstein's introductory quote literally, calculate the attractive force of two people due to gravity. How does this compare with the gravitational force of the Earth, or an electromagnetic attraction (assuming a 1% difference in charge)?

For the demonstration that you choose, ask participants, "What are the forces at work in this situation?" Together, draw a force diagram, such as the diagram below for electrostatic levitation. In each case, there should be $F_G$ (the force due to the Earth's gravitational attraction on the object) downwards (towards Earth's center), and another force upwards, balancing it. Discuss how this is a demonstration of the weakness of

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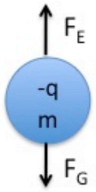
[1] See http://www.exo.net/~pauld/activities/Flying_tinsel.html and http://www.exo.net/~pauld/activities/flyingtinselpieplate.htm and http://www.exo.net/~pauld/activities/flying_hydra.html for excellent examples of electrostatic levitation demonstrations.

[2] See http://www.exo.net/~jillj/ for a useful set of surface tension activities (see "Floating paperclip").

gravity. In each case, the small magnetic or electric force can overcome the gravitational pull of the entire Earth. In the surface tension activity, the electrostatic attraction between water molecules, generating surface tension, is stronger than the gravitational attraction between the Earth and the pepper.



**Force diagram for electrostatic levitation**

Now that the group is on the same page, open the floor to the participants. If any participants researched the weakness of gravity or measuring *G,* ask them to share their presentation now. Do participants have other teaching activities to share on the weakness of gravity? Discuss. You may wish to share some of the other teaching ideas, above.

Newton showed that the orbits of the planets could be explained if the force of gravity between them was equal to a constant times $1/r^2$, where $r$ was the distance between them. He realized that he could describe the motion of a smaller object (say, an apple) with the same $1/r^2$ law. If the attraction between the Sun and the Earth was described by the same law as the attraction between the Earth and an apple, then the same thing should be true of two apples. This theory was so elegant that it was widely accepted even before experimental evidence was available. Gravity is so weak that it was very difficult to experimentally verify the law of gravitation for two small masses; Newton described his theory in the late 17th century, whereas Cavendish created the torsion pendulum in 1800. You may wish to show participants the video extra for this unit: *The Cavendish Experiment.*

Take-home message: Gravity is a very weak force. Refer to the table created in Unit 2 for a mathematical description of just how weak it is compared to the other forces.

## *Activity 1: The Problem with Newton's Law*

Time: 30 Minutes.

Purpose: To explore the theoretical puzzles regarding Newton's law, which motivated general relativity.

Materials:

- Butcher paper (or other large sketch paper)
- PhET Simulation "Radio Waves & Electromagnetic Fields" http://phet.colorado.edu/simulations/sims.php?sim=Radio_Waves_and_Electromagnetic_Fields (*Note:* You do not need to be connected to the internet to run the simulation. You may click "download" to download and run the simulation locally on your machine.)

## 1. Faster than light?

### *To Do and To Notice*

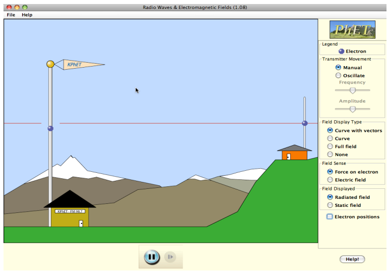
If any participants researched special relativity (specifically, the speed of light) ask them to share their presentation now.

Display the PhET Simulation “Radio Waves & Electromagnetic Fields.” Demonstrate that when you wiggle the electron at KPhET, an electromagnetic pulse is transmitted to the receiver.

Clicker/Discussion Question:

1. **When the electron is wiggled at KPhET, how quickly is the signal received by the antenna at the house?**

   A. Always at the speed of light in a vacuum (c)
   B. At the speed of light, which depends on the medium that it’s traveling through
   C. Anything up to the speed of light in that medium, but maybe slower
   D. Depends on how fast you wiggle the electron
   E. Instantly



Transmitter Movement: ● Manual ○ Oscillate
Field Display Type: ● Curve with vectors ○ Curve ○ Full field ○ None
Field Sense: ● Force on electron ○ Electric field
Field Displayed: ● Radiated field ○ Static field
☐ Electron positions

If they aren’t sure, ask how information about the location of the electron at KPhET is carried to the antenna. Now choose “oscillate” and show the radio wave traveling from the radio tower to the antenna. This radio wave is one form of electromagnetic wave. How fast does it travel? What equation(s) describe these phenomena?

Write the law of universal gravitation on the board: $F_G = \frac{GMm}{r^2}$.

Clicker/Discussion Question:

2. If the Sun disappeared, the Earth would fly out of its orbit. **How quickly would the gravitational repercussions of the Sun’s disappearance travel to Earth?**

   A. Always at the speed of light in a vacuum (c)
   B. At the speed of light, which depends on the medium that it’s traveling through
   C. Anything up to the speed of light in a vacuum, but maybe slower
   D. Instantly

***What's Going On?***

1. Best answer is (B): Electromagnetic waves travel at the speed of light in that medium.[3] This information is *not* contained in Coulomb's law: $F_E = \frac{kQq}{r^2}$. Coulomb's law is inaccurate for moving charges, but Maxwell's equations (describing the wave nature of electricity and magnetism) are always right!
2. Best answer would be (D) instantly, when using Newton's law of universal gravitation, which suggests that if *M* moves, then *m* will instantly react. But according to special relativity, nothing can travel faster than light. Thus, the answer by special relativity is (C). It should take 8 minutes for information to travel from the Sun to the Earth. The incompatibilities between Newton's law and special relativity is a clue that something is wrong with the theories of gravity. (*Looking ahead:* Just like Coulomb's law is incorrect for moving charges, Newton's law is incorrect for moving masses. Maxwell's equations and general relativity are the more general, correct formulas.)

– Puzzle #1: Gravity shouldn't travel faster than the speed of light –

## 2. Two masses fall at the same rate

***To Do and To Notice***

If any participants researched gravitational and inertial mass, ask them to share their presentation now.

Discuss the universality of free fall as a group, briefly. The Earth knows how to pull an elephant and a kitten towards itself with the same acceleration, *g*. Could you move two different objects in precisely the same way? What would you have to do in order to push an elephant and a kitten across ice with the same acceleration? How does the Earth do that?

***What's Going On?***

Gravity is unlike different forces in that the amount of "push" depends on the mass of the object. Another way of putting this is that *gravitational mass* is the same as *inertial mass.*

– Puzzle #2: Two objects with different masses fall at the same rate –
("universality of free fall")

## 3. Acceleration is like gravity

***To Do and To Notice***

If any participants researched the principle of equivalence, ask them to share their presentation now.

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[3] Note – the speed of light is dramatically reduced in this simulation!

Draw the following two pictures on the board. The image on the left represents an elevator being accelerated upwards with an acceleration *g*, and the image on the right represents that same elevator stationary on the Earth's surface.

**A person in a room in a rocket accelerating at *g* feels the same as if he were standing on Earth**[4]

Clicker/Discussion Question:

**Which of the following are NOT the same for the person in the rocket ship as the person standing on Earth?**

A. Their feeling or perception
B. The reading on a scale that they stand on
C. What they see out the window
D. How light will behave (bending toward the floor)
E. Something else/More than one

CLICKER/DISCUSSION QUESTION

Discuss as a group.

Facilitate a Think-Pair-Share discussion on the following questions. Encourage participants to sketch as part of their discussions. You may wish to provide butcher paper so sketches can be easily shared in the large group.[5]

1. What holds the person to the floor of the elevator in each situation?
2. In which reference frame is the person moving? In which reference frame is the person stationary? What is moving in the case where the person is stationary? (*Hint:* Consider how the person on Earth appears to a falling raindrop. Does the raindrop feel like it has weight?)
3. Use the equivalence principle to explain why two masses of different weight fall at the same acceleration.
4. Use the equivalence principle to construct an argument that gravity bends light. (*Hint:* Consider what would happen to a flashlight beam shining horizontally in the window of the room in each of the above cases.)

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[4] Images copyright Albert Einstein Institute/Markus Pössel via *Einstein Online.*

[5] We strongly recommend the two texts referenced in the *Classroom Resources* section for further research – *Exploring Black Holes* (Taylor and Wheeler) and *Your Cosmic Context* (Duncan and Tyler).

### *What’s Going On?*

The answer to the clicker question is (C). The only way for that person to figure out which situation they’re in is to look out the window—the two reference frames behave in just the same way![6]

1. The floor “pushes up” on the person (who would otherwise remain stationary). The floor “gets in the way” of the person (who would otherwise fall towards Earth).

2. In the rocket, the person is in motion through stationary space. On the Earth (the inertial reference frame), the person is stationary—so space must be accelerating downwards. If this is confusing to participants, think about motion in a car. The occupants of the car see themselves as stationary, and the world is moving backwards. A raindrop sees the person on Earth moving upwards—the raindrop is in the inertial frame.

3. The floor comes up to meet both masses at the same rate in the elevator; no longer a puzzle!

4. As the elevator moves, the light beam would appear to curve (just as a ball thrown horizontally would curve towards the floor). This suggests that light should also curve towards the Earth, ever so slightly, in the inertial frame, by the equivalence principle. And indeed, it does.

– Puzzle #3: Acceleration feels like gravity – (“equivalence principle”) –

Take-home message: Gravity is unlike other forces in some puzzling ways. We will see how Newton’s laws need to be changed in order to address some of these puzzles.

# *Activity 2: Fixing up Newton’s Laws*

Time: 20 Minutes.

Purpose: To discuss what these puzzles implied, and how viewing gravity as the warping of space and time helped fix up these problems.

## 1. Logic and implications

### *To Do and To Notice*

Discuss these puzzles in light of the nature of science theme *Logic & Implications*. Why did Einstein spend time working on gravity when Newton’s law had been measured and verified many times? Why didn’t Einstein reject his original idea that nothing can travel faster than light? Many of Einstein’s theories were developed through use of “thought experiments”—how might this relate to the importance of logical arguments in his theories?

**Logic & Implications**

*What does it mean?*

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[6] Actually, there *is* a way you can figure out which situation you’re in, but only if the room is large enough. Two dropped balls go towards the center of the Earth, and so are not exactly parallel. But in a small enough region, the equivalence principle holds.

***What's Going On?***

Einstein's theories relied heavily on taking ideas to their logical conclusions through thought experiments regarding things that could not yet be experimentally verified. He recognized that the implications of Newton's laws were incompatible with relativity, the principles of which were central to physical theory.

## 2. Gravity must be related to space and time

***To Do and To Notice***

Explain: No other force acts like gravity. These three puzzles suggest that gravity isn't a force in the same way that electricity and magnetism are. Einstein realized that gravity must be related somehow to space. Discuss one or both of the logical arguments, below, as a group.

A. Hand-waving explanation.
Gravity appears to be related to motion of objects through space (by the equivalence principle). So, gravity must somehow be messing with space and time.

B. Apparent forces explanation.
Consider the centrifugal force that seems to throw you off a merry-go-round. This is an apparent (or "fictitious") force that only exists because we're in a rotating reference frame. When you solve the formula, $F_C = ma = \frac{mv^2}{r}$, for acceleration, $a_c = \frac{v^2}{r}$, notice that the acceleration is the same for all objects. This is because centrifugal acceleration has nothing to do with the object itself, but is a property instead of the rotating reference frame. Similarly, gravity, $F = ma = mg$ can be solved to show that $a=g$ for all objects. So, perhaps gravity is not a property of objects themselves, but is in some way a result of the fact that, on the Earth, we're in a non-inertial reference frame. That explains why we can choose a coordinate system (the rocketship) where gravity disappears.

***What's Going On?***

Gravity is not like other forces, it's a property of the space that objects move through. Discuss, "How might the theory that 'gravity warps space and time' solve some of the puzzles about gravity?"

Take-home message: Gravity seems to be related in some way to a warping of space and time.

# *Activity 3: Watch and Discuss the Video*

Time: 45 Minutes.

If any participants researched the validation of the inverse square law or gravitational waves, ask them to share their presentation now.

If participants are watching the video in class, have them view it now. Remind them of the guiding questions listed in *Between Sessions* from the previous unit.

- What results would lead to a *Eureka!* moment in either of these experiments?
- What are the implications of negative or *null* results in each of these experiments?
- What would be the implications of positive results in each of these experiments?

Have participants share their answers with their neighbor, then share as a large group with explicit focus on the theme of *Logic & Implications*.

Logic & Implications
What does it mean?

Additional discussion questions:

- How many "If…then" statements can you make about the experiments presented in the video?
- Why would Eric Adelberger's team find it useful and interesting to measure gravity, and the $1/r^2$ law, down to such small distances?
- Do we have to throw out Newton's law because of general relativity?

The distance scales at which gravity obeys the $1/r^2$ law puts an upper bound on the size of smaller dimensions, like the measurements at the *Large Hadron Collider (LHC)* put a lower bound on the mass of the *Higgs boson*. Newton's law is still empirically correct for low values of mass and velocity.

## Activity 4: Curved Spacetime

HANDS-ON ACTIVITY

Time: 20 Minutes.

Purpose: To explore the meaning and implications of curved spacetime.
*Note:* This model will be used again in Units 4 and 10.

Materials:

- 5x5 foot spandex sheet, marked with a grid
- dowels
- marbles
- safety pins
- masses on hooks
- beach ball marked with a grid

Before the session: Prepare the models. Spandex is available from fabric supply and craft stores. It's best to sew "sleeves" into the edges of the spandex sheet, and slip the dowel into the sleeves. Secure the dowels in a board, as described online at this site[7] so the spandex is stretched taut, but not overly tight, on a square frame. You may make a smaller version of the demo using an embroidery hoop. Use permanent marker, pen, or chalk and a ruler to mark the spandex with a grid about 2 inches on a side. Alternatively, you may choose to use a bedsheet with gridlines marked on it, though the bedsheet model is less satisfying, pedagogically. Experiment with your model and the activities below before the class session. Similarly, mark the beach ball with a curved grid (i.e., longitude and latitude lines).

If any participants researched curved spacetime and general relativity, ask them to share their presentation now.

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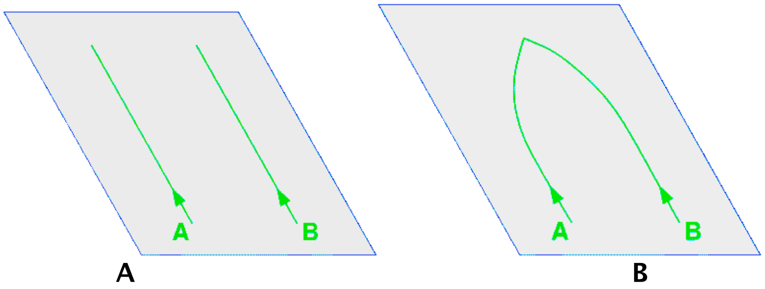
[7] http://www.pbs.org/deepspace/classroom/activity5.html.

## 1. Flat space and parallel lines

- Lay the spandex sheet flat on the floor. Explain that this represents spacetime. Give several participants marbles.
- What do the marbles represent? What happens when the marbles move across the sheet? Discuss what this analogy represents in the natural world.
- Have participants roll two marbles along two parallel grid lines. Should they ever meet? Draw diagram A, below, to represent this situation.
- What if they do curve towards each other and meet, as in Diagram B? What would participants conclude?



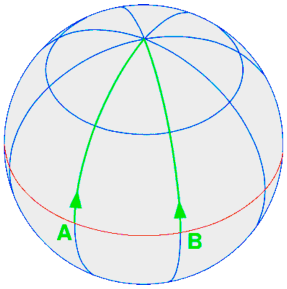
**A** **B**

**Two particles move on straight lines (A) or curve towards each other (B)**[8]

Write the following quote from John Wheeler on the board: "Matter tells space how to curve, and space tells matter how to move." Ask participants, "What does this mean?"

### *What's Going On?*

The marbles can either represent mass or light. They move in the straightest line possible, which on a flat sheet, is straight. On the flat sheet, two marbles rolled in parallel lines should never meet. If they curve towards one another, we would assume that there is a force between them, drawing them to one another. But another interpretation is that they are just moving in the straightest line possible on a curved geometry—such as a geodesic on a sphere.



**Two parallel lines on a sphere**

This is what we mean by "spacetime is curved." Gravity doesn't deflect mass or light from a straight line; it redefines what it means to move in the straightest possible way. This is a challenging concept—allow participants plenty of time to discuss these ideas, perhaps breaking into small groups.

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[8] The three images in this section are courtesy of Einstein Online http://www.einstein-online.info/en/elementary/generalRT/GeomGravity/index.html.

## 2. Masses curve spacetime

### *To Do and To Notice*

- Place a large mass in the middle of the sheet. (You may pin it to the bottom of the sheet if you have masses with hooks). Examine the gridlines. What are the geodesics of this new curved spacetime?
- If the large mass is the Earth, experiment with rolling a marble representing the moon. Let a marble accelerate towards the Earth from rest. How can we understand free fall in this model?
- If the large mass is the Sun, now what happens if the Sun disappears? Try it—remove the Sun rapidly. What happens?
- So, now how long does it take for the Earth to know if the Sun disappears?
- What are the problems with this visual model? Discuss.

### *What's Going On?*

In a curved spacetime, the geodesics are curved lines. An object in freefall is simply following one of these lines. If the Sun disappears, you should see ripples in the spandex. These are the gravity waves predicted[9]. So, space and time itself are "waving" in a gravity wave. These gravity waves take time to travel, and so if the Sun disappears, we would know about it when the gravity waves reached us. However, this model isn't perfect. Spacetime isn't curved into some other dimension as represented in this model, where the sheet is curved from being two dimensions into three. It's just curved. Plus, general relativity is a complicated set of mathematical equations connecting the three dimensions of space and time. The curvature of time is important in understanding why objects accelerate towards other masses. This spandex model is only a visual heuristic for this complicated mathematics.

Take-home message: Mass curves space and time; matter and light follow the straightest possible path, but this path is now curved.

# *Activity 5: Fall into a Black Hole (optional)*

Purpose: To connect an understanding of the equivalence between gravity and acceleration to explore black holes.

Materials:
- "Journey into a Schwarzschild Black Hole" simulation http://jila.colorado.edu/~ajsh/insidebh/schw.html

If any participants researched black holes, ask them to share their presentation now.

### *To Do and To Notice*

Show the first or second simulation, "Journey into a Schwarzschild Black Hole" at http://jila.colorado.edu/~ajsh/insidebh/schw.html. What do participants see? What are the rings around the black hole? What does the edge between black and light represent? Discuss.

COMPUTER SIMULATION

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[9] As discussed in the video, gravity waves are really weak. A collision of two black holes would change the height of the Empire State Building by less than 1/1000th the width of a proton.

Facilitate a Think-Pair-Share on the following questions:

1. How would the rocket from Activity 1 have to move in order to replicate the gravity on Jupiter?
2. How would the rocket from Activity 1 have to move in order to replicate the gravity on a black hole?

3. What does spacetime look like in the inertial frame (the person at rest) in these cases?
4. So, how does spacetime move around a black hole?
5. Why can't light escape from a black hole?

***What's Going On?***

1. It would have to have a larger acceleration upwards.

2. It would have to have a HUGE acceleration upwards.

3. Spacetime is accelerating downwards at a huge rate in the inertial frame.[10]

4. Spacetime is falling into a black hole in the inertial frame. (It also falls into smaller masses, like the Sun, but with a smaller acceleration).

5. Spacetime is falling at a velocity greater than the speed of light inside the event horizon. Light can't "swim upstream" as quickly as the "stream" of spacetime is falling past it.

Now, participants might have a better understanding of why the spandex model is only a visual representation, and doesn't fully represent how spacetime curves around massive objects.

Take-home message: Huge masses warp space and time so strongly that the equivalent non-inertial reference frame (the "rocket") is moving faster than the speed of light. Thus, light cannot escape a black hole.

# Back to the Classroom

Time: 20 Minutes.

Following is a list of high school topics and standards that are relevant to this material. See http://strandmaps.nsdl.org/ for a visual representation of science standards and benchmarks.

- **Where might this unit fit into your curriculum?** Brainstorm a list of topics with participants. You may share additional items from the list below, as you see fit.
- **What do your students know about this topic?** Brainstorm with participants.
- Optionally, you may ask participants to **find one or more of the relevant topics on the Science Literacy Maps**, and explore related ideas and misconceptions.
- Discuss *Classroom Resources*. If you have asked participants to explore the

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[10] It's tricky to think about spacetime as moving. Participants may prefer to think about this in terms of the "straightest possible lines" (the geodesics). Inside the event horizon, the geodesics do not leave the black hole – this is what is seen in the simulation as you pass the event horizon.

*Classroom Resources* for homework, have them report their findings at this time.

## Topics and Standards

**Forces and Motion.** If a force acts towards a single center, the object's path may curve into an orbit around the center (centripetal motion). The change in motion of an object is proportional to the applied force and inversely proportional to the mass ($F=ma$). All motion is relative to whatever frame of reference is chosen. Because every object is moving relative to some other object, no object has a unique claim to be at rest; therefore, the idea of absolute motion or rest is misleading. Any object maintains a constant speed and direction unless an unbalanced force acts on it.

**Gravity.** Gravitational force is an attraction between two masses; its strength is proportional to the masses and weakens rapidly with distance. Gravity is the force that keeps planets in orbit around the Sun. Everything on or anywhere near the Earth is pulled towards the Earth's center by gravitational force. Electric forces acting within and between atoms are vastly stronger than the gravitational forces acting between atoms. At larger scales, gravitational forces accumulate to produce a large and noticeable effect, whereas electric forces tend to cancel.

**Electricity and Magnetism.** Electric forces acting within and between atoms are vastly stronger than the gravitational forces acting between atoms. At larger scales, gravitational forces accumulate to produce a large and noticeable effect, whereas electric forces tend to cancel.

**Nature of Science.** Observation, evidence, and logic are important in the interpretation of experimental results. A scientific model is judged, in part, by its power to predict the outcome of experiment. Theories shift as new observations show inconsistencies or flaws in the previous model. Insist that the key assumptions and reasoning in any argument—whether one's own or that of others—be made explicit. There are different traditions in science about what is investigated and how, but they all have in common certain basic views about the value of evidence, logic, and sound arguments. Scientific investigations usually involve the collection of relevant data, the use of logical reasoning, and the application of imagination in devising hypotheses and explanations to make sense of the collected data. From time to time, major shifts occur in the scientific view of how the world works. More often, however, the changes that take place in the body of scientific knowledge are small modifications of prior knowledge.

**Historical Perspectives.** Isaac Newton, building on earlier descriptions of motion by Galileo, Kepler, and others, created a unified view of force and motion in which motion everywhere in the universe can be explained by the same few rules. For several centuries, Newton's science was accepted without major changes because it explained so many different phenomena, and could be used to predict many physical events. Among the counterintuitive ideas of special relativity is that the speed of light is the same for all observers no matter how they or the light source happen to be moving. In addition, nothing can travel faster than the speed of light. In empty space, all electromagnetic waves move at the same speed—the speed of light. A decade after Einstein developed the special theory of relativity, he proposed the general theory of relativity, which pictures Newton's gravitational force as a distortion of space and time. Einstein's development of the theories of special and general relativity ranks as one of the greatest human accomplishments in all of history. Many predictions from the theories have been confirmed on both atomic and astronomical scales. Still, the search continues for an even more powerful theory of the architecture of the universe.

## Classroom Resources

**Laser Interferometer Gravitational-Wave Observatory (LIGO) resources:**

- Overview: http://www.ligo-la.caltech.edu/LLO/overviewsci.htm
- LIGO Hanford Observatory's Teacher resources and activities http://www.ligo-wa.caltech.edu/teachers.html and http://www.ligo-wa.caltech.edu/activities.html
- LIGO Science Education Center
- http://www.ligo-la.caltech.edu/SEC/sechome.html

**Einstein Online—Elementary Einstein.** A fantastic set of online articles on relativity, black holes, and quantum gravity by the Max Planck Society: http://www.einstein-online.info/en/elementary/index.html and http://www.einstein-online.info/en/spotlights/index.html.

**Gravity: Making Waves**, a nice explanatory page from the American Museum of Natural History. http://www.amnh.org/sciencebulletins/index.php?sid=a.f.gravity.20041101.

**Tutorials on black holes and gravitational waves** from the Cardiff University School of physics and astronomy http://www.astro.cardiff.ac.uk/research/gravity/tutorial/. See also *Black Hole Hunter*, a game where the goal is to distinguish a small signal from background noise. http://www.blackholehunter.org/.

**Einstein@Home.** Participants process gravitational wave data on their home computers. http://einsteinathome.org/index.html. Includes background explanation of gravitational waves: http://einsteinathome.org/gwaves/predict/index.html.

**Einstein's Messengers—Classroom activities.** Three activities: Create a model Michelson interferometer, searching for gravitational waves in noisy data, and extracting astrophysical information from simulated gravitational-wave signals. http://www.einsteinsmessengers.org/activities.htm. See also the documentary about LIGO (20 minutes; http://www.einsteinsmessengers.org).

**Alice and Bob in Wonderland.** A charming set of 1-minute animated shorts, suitable for classroom viewing, on some of the mysteries of nature. From the Perimeter Institute of Theoretical Physics. Relevant videos include "*Why doesn't the moon fall down?*" and *"Can we travel through time?"* and "*What keeps us stuck to the earth?"* http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.

**Gravitational Waves** from *Imagine the Universe* from NASA Goddard. http://imagine.gsfc.nasa.gov/docs/features/topics/gwaves/gwaves.html.

**Free black hole posters, information, and activity booklets** at NASA's *Imagine the Universe.* http://imagine.gsfc.nasa.gov/docs/teachers/blackholes/blackholes.html (see especially "the anatomy of black holes" link with several student activities).

**Spacetime Wrinkles.** A set of articles on general relativity at a high school level. http://archive.ncsa.illinois.edu/Cyberia/NumRel/NumRelHome.html.

**Relativity materials** at The Physics Front. A wide variety of high school level materials. http://www.compadre.org/precollege.

**Teachers' Domain** videos on special relativity and reference frames. http://www.teachersdomain.org/collection/k12/sci.phys.fund.special/ and gravity http://www.teachersdomain.org/collection/k12/sci.phys.maf.gravity/.

**Cosmic Times.** A collection of curriculum materials for grades 7-12 that traces the history of our understanding of the universe from general relativity to the discovery of dark energy in newspaper-style posters including inquiry lessons. http://cosmictimes.gsfc.nasa.gov/.

**NASA's Spaceplace—Classroom activities.** Various classroom activities, some of which are appropriate for high school level, including a few on gravity waves ("Listening for Rings from Space," and "Catch a Gravitational Wave, Dude.") http://spaceplace.nasa.gov/en/educators/teachers_page2.shtml.

**A Classical and Relativistic Trip to a Black Hole.** From PBS's *Mysteries of Deep Space* series, this classroom activity works through an imaginary trip into a black hole. http://www.pbs.org/deepspace/classroom/activity4.html.

**Warped Space-Time Model.** From PBS's *Mysteries of Deep Space series,* this classroom activity creates a model of spacetime from spandex and embroidery hoops. http://www.pbs.org/deepspace/classroom/activity5.html.

**Public lectures** from the Kavli Institute for Theoretical Physics. A variety of public lectures by notable scientists on relevant topics, including *The Future of Gravity*. http://www.kitp.ucsb.edu/talks.

**Your Cosmic Context: An Introduction to Modern Cosmology**. Todd Duncan and Craig Tyler, Pearson: Addison-Wesley, 2009. A very readable and lively text including many topics found in this course, such as general relativity, the expansion of the universe, redshift, the cosmic microwave background, dark matter, and dark energy. Highly recommended.

**Exploring Black Holes: Introduction to General Relativity.** Edwin Taylor and John Wheeler, Addison Wesley Longman, 2000. A very insightful text with helpful exercises at an introductory undergraduate level. Covers special and general relativity at a conceptual level. Highly recommended.

# Between Sessions

## FACILITATOR

You may wish to share the *Classroom Resources* section of the next unit with participants for their homework.

You may wish to share the learning goals of the next unit from *What Will Participants Learn?* with participants in preparation for the next session.

Describe the homework, below.

## PARTICIPANTS

**Text:** Read the text for Unit 4: *String Theory and Extra Dimensions*.

Also recommended are the pages at NOVA's *Elegant Universe* site at http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_00.html (for descriptions of the theory) and the article Unstrung from the *New Yorker* at http://www.newyorker.com/archive/2006/10/02/061002crat_atlarge? (for discussions of the critiques of string theory).

**Preparatory assignment:** Write a paragraph or two on the following questions for the next session:

- Where would strings fit in your concept map from Units 1 and 2?
- How are these physicists' jobs different from the jobs of physicists you've seen in other videos? What are they doing?
- How is string theory useful? What is your opinion of string theory as a valid scientific enterprise?
- Optional: Compare and contrast the evidence for string theory to the evidence for the theories you saw in Units 1, 2, and 3.

**Video:** Watch the video for Unit 4.

- How are these physicists' jobs different from the jobs of physicists you've seen in other videos? What are they doing?
- How is string theory useful?