

# Unit 4

## String Theory and Extra Dimensions

### Introduction

*Our job in physics is to see things simply, to understand a great many complicated phenomena, in terms of a few simple principles.*

– Steven Weinberg, Nobel Prize Lecture, 1979

General relativity, introduced in Unit 3, has been enormously successful at predicting and explaining how masses interact with each other through a warping of the very fabric of space and time. But when we try to use that theory to explain how two masses interact at very small distances, as in quantum mechanics, the theory breaks down, and gives nonsensical predictions. *String theory* is currently the best candidate as a theory of *quantum gravity*. This theory suggests that, as we zoom in to look at point-like particles (such as electrons), they aren't in fact sharp zero-dimensional points, but rather tiny one-dimensional loops called *strings*. However, evidence for string theory is still forthcoming, and possibly beyond our current abilities to obtain. Thus, while string theory is an attractive way to tie together currently incompatible theories, it has been criticized as consisting of mathematical tools rather than a falsifiable scientific theory.

### ***What Will Participants Learn?***

Participants will be able to:

1. Outline two incompatibilities between Einstein's concept of general relativity, which describes gravity at astrophysical scales, and quantum mechanics, which describes interactions at the atomic and subatomic scale. Explain how string theory appears to solve these problems.
2. Use the language of string theory (strings, branes, etc.) to describe how string theory relates different numbers of dimensions of space-time to our familiar 3-D world.
3. Contrast string theory with other branches and theories of physics in terms of the availability of evidence to support or refute it. What would such (lack of) observations mean for string theory?
4. Describe when we might use string theory versus classical physics or other theories. At which spatial scales is it appropriate to consider these theories? Does classical physics depend on an understanding of strings?

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

**Text:** This unit discusses string theory, currently the most promising candidate for providing a universal theory that incorporates both quantum mechanics and general relativity. It outlines theoretical problems regarding particle collisions at the smallest scale of length, called the *Planck length*, and large energy scales, called the *Planck mass*, as well as challenges in describing a quantum theory of spacetime itself. The hypothesis of string theory is that fundamental particles are not zero-dimensional points, but rather one-dimensional strings that exist within a higher dimensional

spacetime. Different limits of string theories can require additional dimensions to spacetime, up to a maximum of 10 spatial dimensions plus the dimension of time. Thus, 7 dimensions would be tiny and hidden from our view. This unit describes how string theory could solve some of the theoretical problems of quantum gravity, plus the ongoing search for evidence and testable predictions of the theory.

**Video:** This program shows us the work of two string theorists—Henry Tye of Cornell University and Juan Maldacena of the Institute for Advanced Study. Henry Tye is working to formulate the predictions of string theory as it applies to large cosmological events—in particular, how cosmic inflation could be related to the collision of two *branes* in the earliest moments of the universe. His work suggests what observations would provide evidence of *cosmic strings*. Juan Maldacena investigates string theory’s role in resolving certain theoretical paradoxes concerning black holes. General relativity predicts the existence of severely warped areas of spacetime—black holes—where not even light can escape. Quantum mechanics predicts that these black holes evaporate through *Hawking radiation*. This poses a problem, due to a paradox between the information *inside* the black hole (which is lost forever) and the decay of the black hole as observed from the *outside*. This paradox may be resolved using the *holographic principle*, which posits that information inside any region of space (subject to gravity) can be encoded on its boundary. Black holes are one specific case of the holographic principle, where it contains the maximum amount of information possible. Juan Maldacena’s work uses the holographic principle to model the surface and interior of black holes, to attempt to solve these theoretical problems.

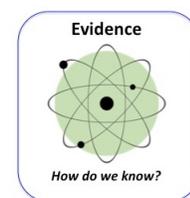
**Interactive Lab:** [\*Laser Cooling\*](#). [Learn the basics of how to manipulate atoms with light, and cool a hot atomic beam to a few millionths of a degree above absolute zero.](#)

### Activities:

- The Hook: Collapse the Dimensions (10 minutes)
- Activity 1: Tiny Things Cause Big Problems (25 minutes)
- Activity 2: What Are Strings? (30 minutes)
- Activity 3: Watch and Discuss the Video (50 minutes)
- Activity 4: Evidence and Proof (25 minutes)
- Back to the Classroom (10 minutes)

(*Note:* If you did not finish all activities in Unit 3, you may choose to finish that unit as the start of this session, as the activities in this unit are easily expanded or contracted to suit the available time.)

**Nature of Science Theme:** *Evidence*. How do we know what we know? You may wish to display the icon for *Evidence* during the session and remind participants of the main ideas of this theme. Measurement and observations are the raw materials from which we weave our stories, or explanations, about the world. Evidence consists of these data, processed through the logical framework of a model, that supports our hypotheses. Are the data consistent with the predictions of the model? If so, then the data can be used as evidence in support of the model.



# Exploring the Unit

## *The Hook: Collapse the Dimensions*

Time: 10 Minutes.

Purpose: To see a visual model of how extra dimensions could exist.

Materials:

- A long (10 meters) rope at least 5 mm thick, or garden hose, or phone cord, or a long strip of paper
- Two thumbtacks or pins with diameters smaller than the rope
- Pieces of paper for each participant
- A very small rubber band

### *To Do and To Notice*

Ask participants to look around the room and identify three-dimensional, two-dimensional, and one-dimensional objects. What's a zero-dimensional object?

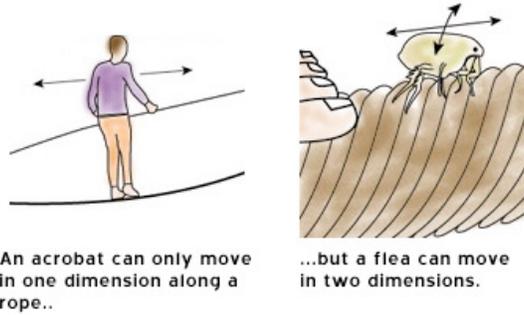
Lay the rope on the ground in a straight line. Ask a participant to walk along the rope. He/she can only move forwards and backwards. Explain that this represents a one-dimensional object, as the person can only move in one dimension—forwards and backwards. Ask another participant to stand on the opposite end of the rope, and walk towards the first one. Can they get around each other? Now, place the two thumbtacks or pins (any object with a diameter smaller than the rope) on the rope, representing ants. Can the ants get around one another if they meet on the rope?

Give each participant a piece of paper. Explain that this is a two-dimensional object, for all practical purposes, as its thickness can be treated as negligible. Challenge participants to create a one-dimensional object from this piece of paper.

Hold up the rubber band. This is one dimensional, as you could only move forward and backwards on it, or clockwise and counterclockwise. How can we make this zero-dimensional?

### *What's Going On?*

Three-dimensional objects have height, width, and length, like people. Two-dimensional objects have essentially no thickness, like paper, or the surface of the walls. One-dimensional objects have essentially no thickness or width, like the writing on the blackboard. A zero-dimensional object has no height, width, or length; it is a point.



A rope is two-dimensional when viewed at small distances<sup>1</sup>

The two people are large relative to the width of the rope, and so can only move in one dimension. Thus, the rope is one dimensional to them. The thumbtacks, or ants, are small relative to the width of the rope. They can see the width of the rope, or the second dimension of the rope. The rope is two dimensional to them. Thus, additional dimensions can be hidden from us, because they are too small to see.

A piece of paper can be rolled up and viewed from far away, appearing one-dimensional. Likewise, a rubber band can be compressed and viewed from far away, appearing zero-dimensional. Thus, if a dimension is tiny enough, it can be hidden from us.

## Activity 1: Tiny Things Cause Big Problems

Time: 25 Minutes.

Purpose: To explore the limits of general relativity in describing the action of gravity at atomic and subatomic distances.

Materials:

- Spandex model from Unit 3

### 1. The Pixels of Spacetime

#### *To Do and To Notice*

Return to your spandex model from Unit 3. Place a mass on the sheet, so that it curves.

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

- What is the smallest unit of distance that one could imagine, using this model? That is, if we were to draw a grid on this model representing spacetime, how fine of a grid could we draw? Let's call this one pixel of spacetime.
- How can we observe things at this pixel scale? (*Hint:* Think of what you learned in Unit 1).
- What do physicists mean when they say that spacetime is "foamy" on the quantum scale?
- How does this point to a problem for a quantum theory of gravity?

<sup>1</sup> Image courtesy of The Particle Adventure (<http://particleadventure.org>) of the Lawrence Berkeley National Laboratory.

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

The smallest unit of distance on this model would be either the width of a pen used to draw a grid, or the size of the thread weaving the fabric. The width of “Nature’s pen” is the Planck length, which is the smallest unit of space, and the *Planck time*, which is the smallest unit of time. These can be thought of as pixels, or grid squares, in spacetime. It’s surprisingly easy to derive the Planck length. From dimensional analysis, it’s the only length that can be formed from the relevant fundamental constants  $c$ ,  $G$  and  $h$ , where  $c$  is the speed of light,  $G$  is the gravitational constant, and  $h$  is the Planck constant. The Planck length and Planck time are the characteristic scales at which gravity becomes strong compared to the other fundamental forces.

We think that these scales are the smallest possible because our ideas of geometry probably break down at these lengths, where quantum gravity causes geometry to fluctuate. If we look at spacetime as being made of these Planck-length pixels, however, then spacetime is not smooth—it jumps from pixel to pixel. This is what is meant by “foamy” spacetime. Strings are postulated to smooth out this foamy spacetime by spreading it out in additional dimensions.

It’s impossible to see things this small with current accelerators. To view objects that are very small (the Planck length), one needs very high-energy accelerators capable of accelerating particles up to high masses (the Planck mass). See the image at [http://www.pbs.org/wgbh/nova/teachers/activities/3012\\_elegant\\_00.html](http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_00.html) for a graphical estimation of the energy scales required.

In gravitational interactions, the shape of spacetime itself is what transmits information from one mass to the other. A *graviton*, the hypothesized force carrier of gravity, is a fluctuation in spacetime. A quantum theory of gravity, then, is a quantum theory of spacetime itself. This is fundamentally different from electricity and magnetism, which is mediated by virtual photons on a background of spacetime. This is why quantum theories of gravity are so much more theoretically challenging than quantum theories of electricity and magnetism.

## **2. Particle Interactions**

### ***To Do and To Notice***

A *worldline* is the trajectory of an object through space and time, as with the single electron moving through space and time in Unit 2. The vertical axis represents time, and the horizontal axis represents space. Ask participants to sketch the following in pairs, and then share as a group.

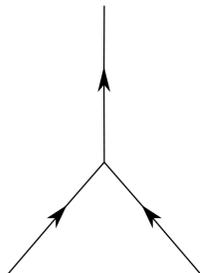
- A single moment in space and time: zero-dimensional (0-D) particle stationary in space and time
- The worldline of a 0-D particle stationary in space but moving forward in time
- The worldline of a 0-D particle moving back and forth (like a mass on a spring) in space over time
- The worldlines of two 0-D particles moving towards each other, colliding, and creating a new particle (which is stationary in space). What point on that diagram would you expect to cause difficulties in a quantum theory of spacetime?
- Now imagine that instead of being zero-dimensional, particles are made of one-dimensional loops of string (i.e., a circle). Resketch their path through spacetime. What if they were two-dimensional branes?

### What's Going On?

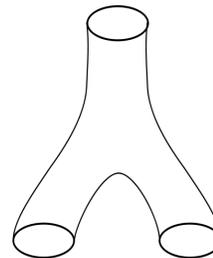
The worldline of a stationary particle, at a particular instant in time, is represented by a single point. A stationary particle that is moving through time is represented by a vertical arrow. A particle moving back and forth is a sine wave moving upwards. Two particles moving towards one another are shown below.

When we examine the point where all three lines intersect—called the vertex—there are problems because we are assuming that the particles interact at zero distance. When two such vertices get very close to one another, problems arise from infinities in the theory, for similar reasons as the discussion in *Part 1, The Pixels of Spacetime* above. For example, when two particles smash into each other, there are different possible outcomes, with different probabilities, predicted by quantum field theory as in Unit 2. This is how accelerator experimentalists predict the outcomes of their experiments. But when two vertices come incredibly close to one another, those equations are nonsense—the probabilities of all possible outcomes add up to greater than 100%. (*Note: This happens for theories other than gravity, such as electrodynamics, but in those cases the number of infinities is limited, and can be subtracted with a process called renormalization*).

String theory smears out those interactions so that they don't actually occur over zero-distance. The worldlines of particles become *worldsheets*, as below. Thus, spacetime and particle interactions become smooth instead of choppy. There are no more sharp vertices, and so vertices cannot come arbitrarily close to one another, and meaningful answers can be obtained.



Feynman Diagram: Two particles collide inelastically

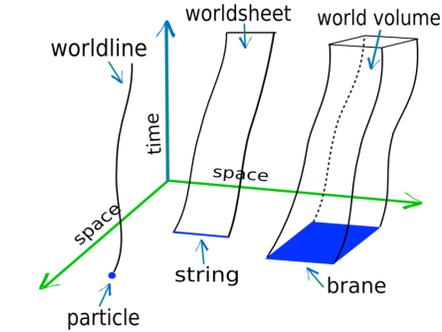


The worldsheets swept up by the intersection of two closed strings (called a “pants diagram”)<sup>2</sup>

Strings can also be open, terminating at endpoints instead of looping back on themselves. In the mid-1990s, it was discovered that open strings can only end on other kinds of objects—higher-dimensional membranes, usually called *D-branes* or just *branes*. These branes are also essential objects, so in a sense string theory should really be called “string and brane theory.” A point particle (*0-brane*) sweeps out a *worldline*, an open or closed string (*1-brane*) sweeps out a *worldsheet*, and a two-dimensional brane (*2-brane*) sweeps out a *world volume*, as below.

<sup>2</sup> Source: © Wikimedia Commons, License: None. Author: Actam, 29 June 2008.

[http://en.wikipedia.org/wiki/File:World\\_lines\\_and\\_world\\_sheet.svg](http://en.wikipedia.org/wiki/File:World_lines_and_world_sheet.svg).

Worldline, worldsheet, and world volume<sup>3</sup>

Take-home message: Whereas quantum mechanics was successfully combined with electromagnetism (in quantum electrodynamics, and then quantum chromodynamics), we don't have a verified quantum theory of gravity. The quantum theory of gravity is difficult because it amounts to a quantum theory of spacetime. When we consider particles interacting at zero distances, gravitational theory gives nonsense answers. Strings smooth out spacetime and particle interactions by spreading them over additional dimensions. String theory also posits several additional dimensions of spacetime in addition to the familiar four.

## Activity 2: What Are Strings?

Time: 30 Minutes.

Purpose: To explore the central ideas of string theory and how it describes particles.

Materials:

- One 25-foot length of rubber tubing for every two participants (you may also use a coiled phone cord, or soft and pliable rope)
- A Slinky® for every two participants
- A set of nesting Russian/Dutch dolls or nesting boxes

### 1. Vibrational Modes

#### *To Do and To Notice*

Give each pair of participants a rope. Ask them to demonstrate the fundamental, or lowest, frequency of the rope, as well as the first overtone, or next vibrational mode, by creating standing waves. They may do this by twirling the rope in a circle, or rapidly moving the rope up and down. This takes some practice, and it may be easier to achieve the first overtone by using a circular motion. Can any get to the second vibrational mode (with one node)? What do they notice as they create higher vibrational modes?<sup>4</sup>

Where did participants place strings on their concept maps from Unit 1 and Unit 2 in

<sup>3</sup> Source: © Wikimedia Commons, License: CC ShareAlike 3.0. Author: Stevertigo, 26 April 2005.

<http://en.wikipedia.org/wiki/File:Brane-wlswv.png>.

<sup>4</sup> Variations of this activity may be found at the Exploratorium at [http://www.exo.net/~pauld/summer\\_institute/summer\\_day10waves/harmonic\\_phonecord.html](http://www.exo.net/~pauld/summer_institute/summer_day10waves/harmonic_phonecord.html) and at NOVA at [http://www.pbs.org/wgbh/nova/teachers/activities/3012\\_elegant\\_03.html](http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_03.html).



their homework? How do different vibrational modes of strings relate to the mass of a particle? How do they relate to the type of particle? Are we likely to observe particles at all vibrational modes of a string?

Clicker/Discussion Questions:

1. **What are the energy scales of *ground state* vibrational modes of strings?**
  - A. About as large as the difference in atomic energy levels
  - B. An energy equivalent to the rest mass of heavy particles like the *muon*
  - C. Higher energy scales than this that are not currently observable (but will be soon)
  - D. Higher than we can conceivably measure
  - E. Something else/More than one of these
  
2. **What are the energy scales of *higher order* vibrational modes of strings?**
  - A. About as large as the difference in atomic energy levels
  - B. An energy equivalent to the rest mass of heavy particles like the muon
  - C. Higher energy scales than the above, that are not yet observable
  - D. Higher than we can conceivably measure
  - E. Something else/More than one of these



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

Strings have different vibrational modes, representing different particles. The higher vibrational modes take more energy to create. Since  $E=mc^2$ , strings in higher energy modes also represent higher mass particles.

1. (E) is the best answer. The ground state vibrational modes of strings are the fundamental particles that we have already observed – muons, neutrinos, electrons, etc. Thus, any answer (A), (B) and (C) would be admissible, and new particles could be observed at higher energy scales than we ever measure (D).
  
2. The best answer is probably (D). Higher order vibrational modes of strings are more massive than the Planck mass; thus, there's certainly no hope of seeing these with technologies that we can currently conceive, though perhaps future technologies would allow us to probe these scales.

Strings represent different fundamental particles. Strings are the new fundamental particles, in a way. If we look inside the proton, we see that it's made of quarks. If we look inside of quarks (and inside of electrons), we see that they're made of strings, as are all the fundamental *bosons*. Fundamental particles (such as those on the concept map) are all strings in their ground state, or the lowest vibrational mode. Higher vibrational modes of the strings would represent such massive particles that they would be unstable (like the *W boson* is unstable). Thus, the different particles we see in the Standard Model are not simply different vibrational modes of strings (as is commonly thought). An electron and a quark are the *same* type of string, in the ground state—their different characteristics arise from the fact that they are vibrating in some of the additional spatial dimensions, but not others.

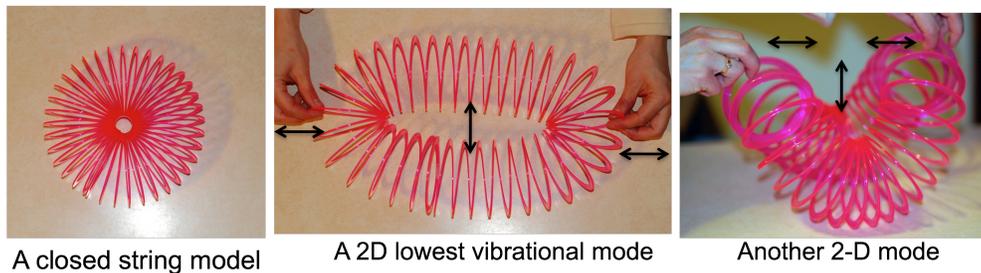
## 2. String Thing

### *To Do and To Notice*

Give each pair of participants a Slinky®. How might they use this as a model of an electron? Using what they learned in the reading, how would they represent a *graviton*? A photon? An electron? How might the graviton differ from the electron? What would a string on a *d-brane* look like?

### *What's Going On?*

A Slinky® is a good model for a string because it has vibrational energy. One might represent an electron, for example, by taping the ends of the Slinky® together into a circle, and oscillating it horizontally and lengthwise.



A *graviton* is also a closed string. This might be represented by twisting the Slinky® out of the horizontal plane—this is still a fundamental frequency, but in additional dimensions (it is oscillating in two dimensions; the electron-model was only oscillating in one dimension). There is no one right answer to this question, but this is one example. A photon is an open string, so the ends of the Slinky® would not be connected. A string on a *d-brane* has its endpoints pinned to the brane surface—thus, the Slinky® with its ends attached to a table or piece of paper would be a good model. The ends of the Slinky® can move on the *d-brane* and the *d-brane* itself may move through space. (*Note: d-branes act like particles only if they're wrapped around a more compact dimension, and they would not represent particles that we would see—they would be exotic, massive particles, due to the energy required to stretch the brane around that compact dimension*).

## 3. Looking Inside Classical Physics

### *To Do and To Notice*

Bring out the nesting dolls or nesting boxes. Take the largest one and explain that this represents classical physics. For example, that box represents what happens when you throw a baseball. In order to figure out where the ball will land, we don't need to know about most of the things we've learned about in Units 1 through 4. So, in a way, there are deeper levels of physics that we ignore when we do classical mechanics. Lay out the other boxes. What do these represent?

Optional: Where does general relativity fit in? Have participants discuss in groups of three–four and share with entire group.



### What's Going On?

There are many answers to this activity. One example is shown below:



In other words, to do classical physics, we don't need to know anything about atomic physics. To do atomic or nuclear physics, we don't need to attend to most of the details about subatomic particles. And to do particle physics, we don't need to know much about strings. The physics of these deeper levels survive as only a small set of parameters in the higher levels. One could also imagine an even larger box, called general relativity, which contains all these smaller boxes.

This is the essence of *renormalization*. In order to do particle physics, theorists artificially restricted the sizes of particles and their interactions to a limit in which their theories made sense. They kept the size of their box large enough so that the theory did not encounter the problems that arise at tiny distances, necessitating strings. In a way, then, particle physicists ignore strings the way that classical mechanics ignores atomic physics.

Take-home message: Fundamental particles are hypothesized to consist of strings vibrating in additional, tiny dimensions. Because higher vibrational modes of the hypothesized strings are equivalent to massive (and thus unstable) particles, the particles on the Standard Model are in the ground state. Classical physics, and other branches of physics, can operate without knowing the nature of strings by restricting their scale of investigation.



## **Activity 3: Watch and Discuss the Video**

Time: 50 Minutes.

### **To Do and To Notice**

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.

- 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?

In addition, assign each participant to one of three focus questions. Direct them to watch the video with this question in mind.

1. How does the nature of *Measurement & Observation* apply to string theory?
2. What is the falsifiability of string theory, or how it can be proven to be incorrect?
3. What is the nature of *Evidence* as related to string theory?

Discuss the first two guiding questions as a group, as well as any topics of the video that participants are particularly curious or confused about. Save discussion of the three focus questions for the jigsaw activity, following this activity.

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

Unlike the physicists in other videos, these physicists are theorists. We see them discussing ideas with one another and writing ideas. Their jobs are very different from the experimentalists, who work with equipment, data, and measurement. Their jobs are to come up with the theoretical predictions that would then be tested by experiment.

Participants should be able to share a variety of things that string theory has been useful for, though it hasn't yet led to testable predictions. Even if they are never verified, theories may have unexpected applications, or may lay the groundwork for insights to come along later. And even without being able to verify it yet, a theory that can reconcile quantum mechanics with gravity while extending our notions of quantum field theory and the nature of space and time, can be seen as useful in its own right, for all the future physics it has inspired and facilitated. Sometimes theoretical physics is like a vast set of tools, many of which are waiting for an application; string theory, besides providing a framework to understand how quantum gravity can be formulated, has inspired theories and models about particle physics, cosmology, heavy ion physics, and pure mathematics. It has been an extremely fertile birthing ground for new ideas. Theorists know that the ultimate job is agreement with experiment, but as far as these intermediate goals, "it's hard not to feel like string theory has already had many successes," says one theorist who contributed to the writing of this discussion.

## Activity 4: Evidence and Proof

Time: 25 Minutes.

### To Do and To Notice

Clicker/Discussion Questions:

1. Which of the following would validate string theory?
  - A. Finding extra dimensions beyond our familiar four dimensions
  - B. Evidence of *superpartners* at the Large Hadron Collider (LHC)
  - C. Certain types of tiny fluctuations in the *cosmic microwave background*
  - D. More than one of these
  - E. Something else/None of these
  
2. Which of the following would falsify or disprove string theory?
  - A. The lack of *supersymmetric* partners discovered at the Large Hadron Collider (LHC)
  - B. Finding that the  $1/r^2$  law for gravity holds for distances as small as the width of a proton
  - C. Finding that the  $1/r^2$  law for electricity and magnetism holds for distances as small as the width of a proton
  - D. Finding evidence that is incompatible with quantum mechanics
  - E. Finding evidence that is incompatible with general relativity
  - F. More than one of these
  - G. None of these



Discuss the answers to the clicker questions. Then, facilitate a Jigsaw activity. Break participants into three groups, to discuss the focus questions from the video. They may wish to consider comparing string theory to other theories discussed in the course so far.

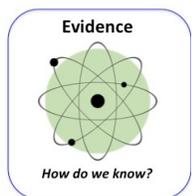
1. How does the nature of *Measurement & Observation* apply to string theory?
2. What is the falsifiability of string theory, or how it can be proven to be incorrect?
3. What is the nature of *Evidence* as related to string theory?

After the groups have discussed the questions for 5–10 minutes, create three new groups consisting of at least one member from each of the original three groups. In these new groups, participants should pool their knowledge from discussions of the first questions to answer the following question:

- Compare and contrast the evidence for string theory from that for the theories you saw in Units 1, 2, and 3. What is your opinion of string theory as a scientific enterprise?

### What's Going On?

1. Answer (C) is probably the best answer, but (A) and (B) would provide somewhat less direct circumstantial evidence. (E) is an acceptable answer. What is the difference between circumstantial evidence and inference? Is there any difference?



2. Answer (D) or (F) are acceptable. Answer (D) would definitely falsify string theory. Answer (E) is somewhat ambiguous—string theory suggests that general relativity is wrong or incomplete (in the same way that general relativity suggests that Newton’s Laws are wrong). String theory does predict that there are problems with general relativity. However, string theory is predicated upon some tenets of general relativity, and so a falsifying of general relativity more broadly would be problematic for string theory. Because falsifying string theory amounts to falsifying general relativity and quantum mechanics, its predictions are not specific enough to string theory itself. (A) and (B) only put limits on the scales at which quantum gravity operates—it operates at higher energies than the LHC and smaller scales than the width of a proton. Recall the video from Unit 3 and Eric Adelberger’s experiments on gravity at small scales. Answer (C) is compatible with string theory and thus would not falsify it.

The Jigsaw activity will generate a rich set of discussions with multiple answers. Some ideas to include are:

**Measurement & Observation:**

Direct testing is difficult, though circumstantial evidence may be available through a variety of means. One is through the *AdS/CFT correspondence* (Maldacena’s work). Another is through a variety of experiments in condensed matter theory. Superpartners are too massive to have been detected yet, though they may be detected at the LHC. The only direct evidence—detection of strings themselves—requires energies high enough to probe the Planck length, which is currently impossible. Also, theorists may not understand the theory well enough to make testable predictions.

**Evidence:**

Most evidence would be circumstantial, such as the existence of extra dimensions, the existence of superpartners, and cosmic microwave background fluctuations. Even if these data can be collected, it may have other explanations than string theory. Generally, it is harder to prove that something exists than that it does not exist (i.e., to falsify it).

**Falsifiability:**

If the LHC doesn’t discover supersymmetry, or gravity is found to hold at very small distances, or we find no evidence of extra dimensions, this doesn’t disprove string theory. It may be that quantum gravity operates at smaller scales still. Thus, these results wouldn’t falsify string theory, but only put limits on the theory. What would falsify it? Until we have predictions we can test, we won’t be able to falsify the theory.

**Comparison to Other Theories:**

Here, participants may share their opinions on string theory’s usefulness, as well as whether it qualifies as science. Be sure that they don’t dismiss string theory due to the lack of predictions—the job of theorists now is to determine what experimental results are predicted by string theory, and the video presented several promising areas of verification. In addition, string theory has had immense utility as a mathematical framework and in other areas of physics, even if it has not (yet) succeeded as a theory of quantum gravity.

The evidence for general relativity was very specific to general relativity, such as the prediction that we could see light from a sun on the other side of a star due to *gravitational lensing*. The evidence for string theory is not specific to string theory. In addition, many of the predictions of string theory are not specific to

string theory, but are more broadly applicable to other theories that it is consistent with (quantum mechanics and general relativity, in particular).

The evidence for certain fundamental particles (say, the *top quark*) is indirect but it is far beyond circumstantial. Even though scientists haven't seen the top quark as a track in a bubble chamber, the evidence is conclusive. Scientists can examine the outcome from many types of collisions at many different reactors and look for inconsistencies in the theory. This kind of precision testing is not yet available for string theory, though the AdS/CFT correspondence may eventually allow some testable predictions.

## Back to the Classroom

Time: 10 Minutes.

Following is a list of high school topics and standards that are relevant to this material. See <http://strandmaps.nsd.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.

### Topics and Standards

**Atoms and Molecules.** Atoms are made of a positive nucleus surrounded by negative electrons. Scientists continue to investigate atoms and have discovered even smaller constituents of which protons and neutrons are made. The nuclear forces that hold the protons and neutrons in the nucleus of an atom together are much stronger than the electric forces between the protons and electrons of the atom.

**Size and Scale.** Natural phenomena often involve sizes, durations, or speeds that are extremely small or extremely large. When describing and comparing very small and very large quantities, express them using powers-of-ten notation.

**The Universe.** Astronomers have observed that the whole universe is expanding. The Big Bang theory suggests that the universe began 10–20 billion years ago in a hot dense state.

**Historical Perspectives.** 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.

**Nature of Science.** 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 good arguments. 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. Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models. Although all scientific ideas are tentative and subject to change and improvement, for most major ideas in science there is much experimental and observational confirmation. 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. The usefulness of a model can be tested by comparing its predictions to actual observations in the real world. However, a close match does not necessarily mean that other models would not work equally well or better.

**Values in Science.** Curiosity motivates scientists to ask questions about the world around them and seek answers to those questions. Being open to new ideas motivates scientists to consider ideas that they had not previously considered. Skepticism motivates scientists to question and test their own ideas and those that others propose. Scientists value evidence that can be verified, hypotheses that can be tested, and theories that can be used to make predictions. To be useful, a hypothesis should suggest what evidence would support it and what evidence would refute it. A hypothesis that cannot, in principle, be put to the test of evidence may be interesting, but it may not be scientifically useful. In science, a new theory rarely gains widespread acceptance until its advocates can show that it is borne out by the evidence, is logically consistent with other principles that are not in question, explains more than its rival theories, and has the potential to lead to new knowledge. Often different explanations can be given for the same observations, and it is not always possible to tell which one is correct.

## Classroom Resources

**The Official String Theory Website.** An explanatory website tackling various aspects of string theory at basic and advanced levels. <http://superstringtheory.com/>.

**Particle Adventure.** A basic explanation of string theory aimed at high school students. [http://particleadventure.org/extra\\_dim.html](http://particleadventure.org/extra_dim.html).

**NOVA's production of the Elegant Universe** has many teaching activities and useful resources: <http://www.pbs.org/wgbh/nova/elegant/>.

- A new building block (on particles as excitation modes on a string)  
[http://www.pbs.org/wgbh/nova/teachers/activities/3012\\_elegant\\_03.html](http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_03.html).
- Deducting dimensions (on visualizing and understanding extra dimensions)  
[http://www.pbs.org/wgbh/nova/teachers/activities/3012\\_elegant\\_04.html](http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_04.html).
- And a very nice explanation of string theory  
[http://www.pbs.org/wgbh/nova/teachers/activities/3012\\_elegant\\_00.html](http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_00.html).

**String Theory: An Evaluation.** Takes a critical look at various aspects of string theory. On the website of the author, Peter Woit. <http://www.math.columbia.edu/~woit/>.

**Superstrings** site at *Imagine the Universe!* Describes the basics of string theory and how it helps describe mysteries about black holes; includes pop-up glossary. [http://imagine.gsfc.nasa.gov/docs/science/mysteries\\_l2/superstring.html](http://imagine.gsfc.nasa.gov/docs/science/mysteries_l2/superstring.html).

**Superstrings: Einstein's Dream at the New Millennium.** Offers a streaming audio lecture by Sylvester James Gates Jr., director of the Center for String and Particle Theory at the University of Maryland. The 47-minute talk includes visuals and running text. (Requires RealPlayer plug-in.) <http://www.loc.gov/locvideo/gates/intrgate.html>.

**Relativity and the Quantum.** From Einstein Online. A nice set of clear and simple articles on relativity and its lack of reconciliation with quantum mechanics. <http://www.einstein-online.info/en/spotlights/quantum/index.html>.

**Teacher Conferences Talks** from the Kavli Institute for Theoretical Physics. Online archives of talks geared towards teachers, by leading scientists and educators. Particularly relevant is *String Theory: Is it the Theory of Everything?* See also the public lectures by notable scientists on a variety of topics. <http://www.kitp.ucsb.edu/talks>.

**An interview with Sheldon Glashow** that discusses the testability and ultimate utility of String Theory. Is it useful? Is it science?  
<http://www.pbs.org/wgbh/nova/elegant/view-glashow.html>.

**Unstrung.** An excellent summary article on string theory and of the critique of its inability to offer testable predictions, from the New Yorker.  
[http://www.newyorker.com/archive/2006/10/02/061002crat\\_atlarge?currentPage=all](http://www.newyorker.com/archive/2006/10/02/061002crat_atlarge?currentPage=all).

## 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.

In the next unit, you may wish to focus on/expand either the *photoelectric effect* or the wave/particle nature of light, depending on participants' background experience and preferences. In order to assess participants' background experience, you may wish to either (a) poll participants about their familiarity and experience with the photoelectric effect or (b) request that they email the answers to the homework questions in advance so that you may assess their level of comfort. If you know in advance which activity you will be focusing on, you may wish to modify the homework below (to, for example, ask participants to learn about a topic on their own that will be covered to a lesser degree in the session).

### PARTICIPANTS

**Text:** Read Unit 5: *The Quantum World* for the next session. Write down your answer to the following question and bring it to the next session.

- From the reading, what part of quantum theory do you find most counterintuitive or hard to believe or puzzling?

**Video:** While watching the video for Unit 5, focus on the following questions:

- What's quantum about these experiments? List as many aspects of the experiments as you can.
- If the position of an electron is probabilistic, then how can atomic clocks measure time with such precision?

**Further exploration:** You will learn more about the photoelectric effect in the activity, below. We strongly recommend that you also investigate the following excellent sites to explore the complicated topics in this unit further:

1. **Physics 2000.** A great set of clear, interactive tutorials and applets on many aspects of atomic and optical physics, including two-slit interference, laser

cooling, magnetic trapping, and *Bose–Einstein condensation*. Click “what is it” to see all applets, and “table of contents” for a list of topics. <http://www.colorado.edu/physics/2000>.

2. **HyperPhysics.** If you have any outstanding questions and would like to explore them further, see the concept maps of quantum mechanics and quantum statistics for summaries of the main ideas and their interrelationships. <http://hyperphysics.phy-astr.gsu.edu>.

**Mini lesson:** See the next two pages for a guided mini-lesson on particles and waves. Use these activities to reflect on what you already know, and what you have further questions on. You may choose to do them in as much depth as you please, based on your interest and comfort level.

### Waves and Particles: Mini-lesson

#### 1. Classical Waves.

Experiments in the late 1800’s showed that if light is shone on a metal, electricity is produced (the photoelectric effect). Let’s imagine that this happens because the light “heats up” the metal, giving electrons energy so that they can jump off the metal.<sup>5</sup> How would you expect:

- (a) The frequency, or color, of the light to affect how many electrons jump off the metal?
- (b) The intensity of that light to affect how many electrons jump off the metal?

#### 2. PhET Simulation: The Photoelectric Effect

Experiment with the PhET simulation on the photoelectric effect at [http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric\\_Effect](http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect). How do the properties of the incoming photons affect the ejected electrons? How do these compare with the predictions for classical waves, above? What does this tell us about the nature of photons and atoms?

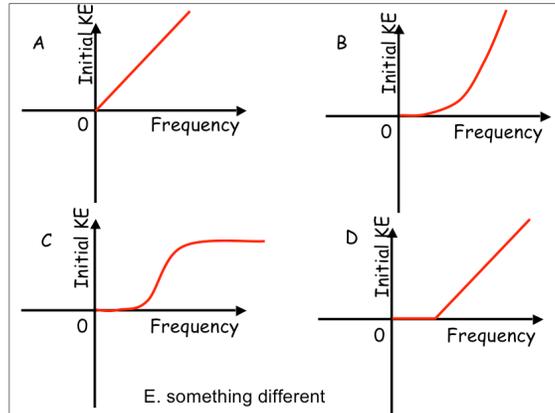
#### 3. Check your understanding.

Which of the following graphs most accurately represents your prediction for the initial kinetic energy of the electrons ejected from the metal, based on your experiments with the simulation? (*Hint:* Consider conservation of energy and the equation for the energy of a photon.) You may check your answer with the simulation.

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<sup>5</sup> You might use the following analogy: Imagine waves hitting a beach, where the shore is lined with pebbles. The pebbles are scattered by the waves as they hit the shore. How would you expect the frequency of those water waves to affect:

- (a) The number of pebbles scattered by a particular wave front?
- (b) The speed or energy that the pebbles fly away with?



Possible graphs of the kinetic energy of the ejected electron versus the frequency of the incoming photon<sup>6</sup>

For a comprehensive study on student understanding of the photoelectric effect, see [http://www.colorado.edu/physics/EducationIssues/papers/McKagan\\_et al/photoelectric.pdf](http://www.colorado.edu/physics/EducationIssues/papers/McKagan_et al/photoelectric.pdf). In particular, students at the undergraduate level often (a) believe that  $V=IR$  still applies, (b) confuse intensity and frequency of light (and thus photon energy), (c) are unable to predict an  $I-V$  graph of the experiment, and (d) cannot relate photons to the photoelectric effect.

#### 4. Light and Matter Waves

Explore the *PhET Quantum Wave Interference* simulation at [http://phet.colorado.edu/simulations/sims.php?sim=Quantum\\_Wave\\_Interference](http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference). Note the *Teacher's Guide* on the web site for the simulation and take a look at it, especially the “non-obvious controls” section. Explore the features of the first two tabs of the simulation. Make sure that you try the “double slits” feature and fire both photons and electrons from the “gun.” Write short answers to the following questions:

- What ideas might you use this simulation to demonstrate in your classroom?
- Choose the best answer for each of the following questions and defend it. Each question relates to the first tab (“High Intensity”), but you may use the second tab (“Single Particles”) in your answers.

<sup>6</sup> This question and the following questions are from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins and S. McKagan, <http://per.colorado.edu/modern>.

1. **If you shoot a photon through the two slits to hit the screen it:**
  - A. Cannot hit in the middle because the block is in the way
  - B. Hits at a random location, with an equal probability of hitting anywhere on the screen
  - C. Must hit at the maximum of the interference pattern
  - D. Has a chance of hitting anywhere on the screen, but on average a better chance at hitting where the interference pattern is brightest
  - E. Will hit anywhere that it can travel in a straight line from the gun to the screen.
  
2. Consider a photon to the left of center as in the image below. **Which slit did it go through?**

- A. Left
- B. Right
- C. Both
- D. Neither

