Annenberg Media
Facilitator's Guide

Physics for the 21st Century

An 11-part multi-media course in modern physics

Produced by the Harvard-Smithsonian Center for Astrophysics

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is produced by the Harvard-Smithsonian Center for Astrophysics

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Table of Contents

Course Overview

New tools and techniques have allowed physicists to probe the extent of the physical universe—from particles smaller than we can imagine to the outer reaches of the universe. Powerful, precision instruments—such as the most powerful particle accelerators ever created, finely-tuned atomic freezers, or galactic surveys providing terabytes of data about the universe—have opened the landscape of physics, allowing us to answer age-old questions about what makes up the universe, and how it works. As many questions as we have answered in recent decades, however, ever more crop up to be explored.

This course begins with an exploration of what is currently known at the very smallest realm—the fundamental particles, and the forces that they create and with which they interact (Units 1 and 2). Open questions regarding the nature of the most familiar force—gravity—and the potential of string theory to resolve these questions will be detailed in Units 3 and 4. The following three units (Units 5, 6, and 7) will cover quantum mechanics, and the surprising behaviors physicists have revealed through the manipulation of atoms and light. Looking at larger scales, Units 8 and 9 examine the collective behavior of individual pieces which give rise to new material properties and open up the frontiers of biophysics. With Units 10 and 11, the course concludes with an examination of the physics of the cosmos—the mysterious substance that created the structure in the universe, and the energy that is pushing it apart.

We intend this *Facilitator's Guide* to be used by a facilitator running an on-site professional development course for high school physics teachers. Thus, these materials are designed to be used by a facilitator in shaping such a course, rather than used directly by practicing teachers, although many of the activities are quite suitable for use in a high school classroom setting. Further, although designed for use in a professional development course, independent learners may also find the *Facilitator's Guide* valuable.

Each unit consists of:

- An online text written by an expert in the field;
- Video case studies describing two current research programs in that topical area;
- An interactive lab; and
- The written activities in the *Facilitator's Guide*.
  (*Note*: Some units also include an extra video segment.)

For more information about receiving graduate credit for participating in this course, either in on-site synchronous sessions or as an independent learner, please visit http://www.learner.org/workshops/graduate_credit.html.

Course Components

Online Text, Video, Interactive Labs

Introduction to the Online Text by Christopher Stubbs

For centuries, physicists have been trying to figure out the world around them. The accumulated work of these physicists is traditionally passed on to new students in a roughly historical sequence. It takes most people years to make the progression from mechanics to electromagnetism to quantum mechanics, and many leave their physics studies before even learning about the current research frontier of physics. The approach in *Physics for the 21st Century* is different. We jump directly to "the new stuff" by highlighting some of the fascinating topics currently studied by the physics community. The choice of topics in this course is representative, and is meant to convey the excitement, the mystery, and human aspects of modern physics.

Unit 1. The Basic Building Blocks of Matter by Natalie Roe

In this unit, we explore particle physics, the study of the fundamental constituents of matter. These basic building blocks lay the foundation for all of the ambitious projects detailed throughout this course. Dramatic discoveries over the last century have completely changed our view of the structure of matter.

Video: Matter's basic building blocks have been linked together into a theoretical framework—the Standard Model—that has been very successful in making predictions that were later confirmed by experiment. Even so, there are hints that the Standard Model is incomplete, and that a deeper theory lies behind it, waiting to be teased into the open. Learn how the Standard Model was developed and what it explains—and where it falls short—tantalizing 21st century physicists.

Featured Scientists: Bonnie Fleming (Yale University)
Mark Kruse (Duke University)

Interactive Lab: *Discovering Neutrino Oscillations.* Explore how the basic properties of neutrinos affect their oscillations, and design an experiment to learn more about the quantum behavior of this elusive particle.

Unit 2. The Fundamental Interactions by David Kaplan

This unit takes the story of the basic constituents of matter beyond the fundamental particles that we encounter in Unit 1. It focuses on the interactions that hold those particles together or tear them asunder. Today we recognize four fundamental forces: gravity, electromagnetism, and the strong and weak nuclear forces. Detailed studies of those forces suggest that the last three—and possibly all four—were themselves identical when the universe was young, but have since gone their own way. But while physicists target a grand unification theory that combines all four forces, they also seek evidence of the existence of new forces of nature.

Video: Key to physicists' search for a new underlying theory of the physical world is a better understanding of the fundamental interactions. One starting point is to investigate the microscopic description of forces: electromagnetism, gravity, the strong nuclear force, and the weak force. Such microscopic theories also explain other diverse phenomena, from the existence of solid materials, to all of chemistry, to the shining of stars and radioactivity. Discover how clues from echoes of the Big Bang and today's particle accelerators are driving the search for the unification of the fundamental interactions in a new theory of supersymmetry.

Featured scientists: Ayanna Arce (Lawrence Berkeley National Laboratory)
Srini Rajagopalan (Brookhaven National Laboratory)

Interactive Lab: *Discovering Neutrino Oscillations.* Explore how the basic properties of neutrinos affect their oscillations, and design an experiment to learn more about the quantum behavior of this elusive particle.

Unit 3. Gravity by Blayne Heckel

Although it is by far the weakest of the known forces in nature, gravity pervades the universe and has played an essential role in the evolution of the universe to its current state. Newton's law of universal gravitation and its elegant successor, Einstein's theory of general relativity, represent milestones in the history of science and provide the best descriptions we have of gravity. Current research is attempting to improve the precision to which the laws of gravity have been tested and to expand the realm over which tests of gravity have been made. Gravitational waves, predicted by general relativity, are expected to be observed in the near future. The unit reviews what we know about gravity and describes many of the directions that research in gravitation is following.

Video: How can gravity, which in many ways is the dominant force in the universe, be at the same time by far the weakest of the four known forces in nature? See how physicists are approaching this question through topics of intense research in gravitational physics today: short scale measurements of gravity, the study of black holes, the search for gravitational waves, and the search for clues to the composition and evolution of the universe.

Featured Scientists: Eric Adelberger (University of Washington)
Nergis Mavalvala (Massachusetts Institute of Technology)

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 Oscillations.* Explore how the basic properties of neutrinos affect their oscillations, and design an experiment to learn more about the quantum behavior of this elusive particle.

Unit 4. String Theory and Extra Dimensions by Shamit Kachru

One area of active work in physics is the effort to develop a “theory of everything” that brings all four forces of nature under the same conceptual umbrella. The most prominent aspect of that effort is the family of string theories that envision the basic units of matter as minuscule stretches of threadlike strings rather than point particles. The unit introduces string theory in the context of quantum gravity and explores the relationship of string theory to particle physics. The unit also details links between string theory and cosmic inflation, and, finally, summarizes the understanding that string theory brings to our fundamental understanding of gravity.

Video: In the 20th century, twin breakthroughs, quantum mechanics and general relativity, provided fresh insight into phenomena at the sub-atomic and cosmological scales, respectively. Yet physicists are still struggling to develop a consistent theory that bridges quantum mechanics and gravity. One approach to "quantum gravity" is string theory, a mathematical description of particles and forces at scales 10^{31} times smaller than a proton. So far, however, observational evidence for string theory has been elusive. Find out how string theory extends the Standard Model and where physicists are looking for the hard evidence needed to support it: from microscopic hidden dimensions to large-scale cosmological structures

Featured Scientists: Juan Maldacena (Institute for Advanced Study)
Henry Tye (Cornell University)

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.

Unit 5. The Quantum World by Dan Kleppner

This unit covers a field of physics that is simultaneously one of the most powerful, transformational, and precise tools for exploring nature and yet, for non-physicists, one of the most mysterious and misunderstood aspects of all science. Developed early in the 20th century to solve a crisis in understanding the nature of the atom, quantum mechanics has laid the foundation for theoretical and practical advances in 21st century physics. The unit details the reasoning that led to ever-deeper awareness of the nature of particles, waves, and their interrelationships; provides a primer on present-day understanding of the field; and outlines ways in which that understanding has led to significant applications today.

Video: We are in a new quantum age in which the abstract concepts of the quantum revolution have become concrete due to rapid advances in controlling and manipulating atoms, molecules, and light. Practical applications, from lasers and atomic clocks to telecommunications and mp3 players, are only part of the story. Find out how laser cooling and trapping prompted the discovery of a new form of matter, the Bose-Einstein condensate, and how recent experiments are extending the frontiers of our understanding of how matter behaves.

Featured Scientists: David J. Wineland (National Institute for Standards and Technology)
Martin Zwierlein (Massachusetts Institute of Technology)

Video Extra. John Lowe of the National Institute for Standards and Technology (NIST) discusses atomic clocks.

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.

Unit 6. Macroscopic Quantum Mechanics by William P. Reinhardt

The fundamentals of quantum mechanics that we met in Unit 5 characteristically appear on microscopic scales. Macroscopic quantum systems in which liquids, or electric currents, flow without friction or resistance have been known since the early part of the 20th century: These are the superfluids and superconductors of traditional condensed matter physics that are discussed in Unit 8. In this unit we focus on an entirely new state of matter only recently created in the laboratory—the gaseous macroscopic quantum mechanical system known as a Bose-Einstein condensate, or BEC.

Video: Quantum mechanics manifests itself in phenomena at macroscopic scales, including lasers, clouds of ultra-cold atoms, superfluids, and superconductivity. Of these phenomena, the recent discovery of new kinds of high-temperature superconducting materials is a particularly intriguing problem because there is still no widely accepted theory about how they work. Delve deeper into quantum mechanics using the example of how researchers are approaching this problem from two different directions: A "top-down" approach closely examining the materials themselves, and a "bottom-up" approach looking at model systems that mimic the quantum interactions of the superconducting electrons inside the materials

Featured Scientists: Jenny Hoffman (Harvard University)
Deborah S. Jin (NIST/University of Colorado)

Video Extra: Wolfgang Rueckner of Harvard University demonstrates the Meissner effect, where a magnet will levitate above a superconductor as the superconductor expels all magnetic field lines.

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.

Unit 7. Manipulating Light by Lene Hau

This unit focuses on experimental achievements in reducing the speed of light by factors of tens of millions and delves into the implications of that research. First we look at the critical importance that the speed of light in a vacuum plays in our understanding of our universe. The unit then details the type of experimental setup used to slow down light in the laboratory and analyzes the fundamental quantum processes that permit physicists to reduce light's speed dramatically—and even to stop light altogether and hold it in storage. Next, the unit covers methods of converting light into matter and back again. And finally, it looks at some of the potential real-world applications that these incredible experimental achievements might open up in the future—such as quantum processing.

Video: Tools of the new quantum age are opening new possibilities for controlling and manipulating light. In 2001, Lena Vestergaard Hau stopped a pulse of light in a cloud of atoms and then released it, along with the information it contained. Explore not only how light interacts with matter at the quantum level, but also the concepts of entanglement and action at a distance, and see how experiments with storing information in matter might lead eventually to an entirely new technology: quantum computing and secure encryption.

Featured scientists: Lene Hau (Harvard University)
Paul Kwiat (University of Illinois at Urbana-Champaign)

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.

Unit 8. Emergent Behavior in Quantum Matter by David Pines

This unit takes an approach to physics that differs markedly from much of what we have encountered in previous units. Rather than studying phenomena that occur at the microscopic level and involve the elementary components of matter, we look at what happens at the macroscopic scale when complex interactions among those components lead to entirely new—emergent—behavior. After introducing the concept of emergence, this unit examines emergent behavior in solids, the liquid forms of two very different isotopes of helium, conventional superconductivity, and superfluidity in stars.

Video: Reductionism—breaking things into their component parts to study how they work—is an effective tool in physics. But when the computational requirements are too massive or the theories that govern the component parts are inadequate, many complex systems have yielded to the physics of emergence, which seeks organizing principles at the system level. Find out how superconductors, hydrodynamics, and even the formation of structure in the universe, are all fruitful areas where the physics of emergence are leading to new understanding.

Featured scientists: Paul Chaikin (New York University)
Piers Coleman (Rutgers University)

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.

Unit 9. Biophysics by Robert Austin

In many ways, biologists work in a very different realm than physicists, studying diverse and incredibly complex phenomena involving living systems. Even so, ideas and approaches from physics have provided key insights into the world of biology, helping advance the frontiers of both research and medicine. This unit explores some of the ways that physics has informed understanding in biology, especially the forces involved in DNA and protein folding, principles that describe organisms' fitness levels, and the emergent phenomenon of mind and consciousness.

Video: The broad, rapidly developing field of biophysics brings many disciplines under its umbrella. The physics of biological systems provides new insights into how flowers explode into bloom and how bacteria travel. Computational biophysics works to develop designer drugs and a new understanding of neural networks in the brain. Molecular biophysics opens the possibility of manipulating DNA and proteins, perhaps leading in the future to nanofabrication of biologically active molecules. And medical physics is already providing novel ways of imaging living tissues, as well as curing disease through new uses for old accelerators with radiation therapy.

Featured scientists: Harald Paganetti (Massachusetts General Hospital/Harvard Medical School)
Vinothan Manoharan (Harvard University)

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.

Unit 10. Dark Matter by Peter Fisher

Most of the mass in galaxies like our own Milky Way does not reside in the stars and gas that can be directly observed with telescopes. Rather, around 90 percent of the mass in a typical galaxy is "dark matter," a substance that has so far evaded direct detection. Scientists can make this astonishing claim because we can infer dark matter's existence from the gravitational pull it exerts on the luminous material we *can* see. Additional evidence supports this claim as well. However, the nature of what dark matter is has yet to be understood. In this unit, we review the observational and theoretical evidence for dark matter, and describe the attempts that are under way to find it.

Video: Since Swiss astrophysicist Fritz Zwicky first inferred its existence in 1933, dark matter has remained one of the greatest unsolved mysteries in cosmology. Astronomical measurements have shown dark matter to be about 3/4ths of all matter, but at present it cannot be accommodated in the Standard Model of particle physics. See how both astrophysicists and particle physicists are developing more accurate methods of measuring the effects of dark matter and learn about their attempts to identify the particles or other phenomena responsible for it.

Featured scientists: Doug Finkbeiner (Harvard University)
Rick Gaitskell (Brown University)

Interactive Lab: *Evolution of Large Scale Structure in the Universe.* Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.

Unit 11. Dark Energy by Robert P. Kirshner

This unit focuses on one of the biggest questions in 21st century physics: what is the fate of the universe? In recent years, astronomers have been surprised to discover that the expansion of the universe is speeding up. We attribute this to the influence of a "dark energy" that may have its origin in the microscopic properties of space itself. Even very simple questions about dark energy, like "has there always been the same amount?" are very difficult to answer. Astronomers can observe the past but can only predict the future: If dark energy takes the simplest form we can think of, the universe will expand faster and faster, leaving our galaxy in a dark, cold, lonely place.

Video: Today's astronomical measurements show that dark energy makes up about 70% of the mass-energy in the universe. This deep mystery lies right at the heart of understanding gravity. See how observations that measure the history of cosmic expansion more precisely and the growth of lumpy structures in the universe are helping to pin down the nature of dark energy.

Featured scientists: Robert P. Kirshner (Harvard University)
David Spergel (Princeton University)

Interactive Lab: *Evolution of Large Scale Structure in the Universe*. Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.

Course Components

Facilitator-Led Components: On-Site Sessions

The *Physics for the 21st Century Facilitator's Guide* is intended to provide structure, resources, discussion questions, and activities for use in teacher professional development. These materials are designed to support a facilitator in creating an effective course for participants (practicing and/or future teachers). We recognize that these units will be (and are designed to be) tailored to local conditions. These materials may also be used as a self-study guide. These materials are based on research on student learning, best-practices in teacher education and professional development, and significant prior work in these content areas of modern physics.

The course consists of thirteen two-and-a-half hour sessions: an introductory unit, eleven content-focused units, and a review session. Each session has a consistent structure including pre-session assignments, descriptions of the unit, learning goals for participants, activities and discussions related to the content of the online text and videos, discussion of how to use these activities and topics in a high school classroom, connection to national standards and benchmarks, and online resources for further exploration. Each unit is developed based on principles of education research, and reviewed by experts in relevant fields. Below are the different components of each unit.

Introduction
Each unit includes a pertinent quotation from a scientist. You may wish to display this quotation in the beginning of the session for that unit. The introductory text summarizes the content of the unit, and how it relates more broadly to our understanding of the natural world.

What Will Participants Learn?
This section provides 3-4 learning goals which are intended outcomes for participants by the end of that unit. These goals are achieved primarily through the investigation of the activities in the unit, and by participating in discussions. The learning goals are directly related to the activities in that session, but assume that participants will also have read the online text and watched the video. Activities are built into each session to promote and support this pre-session work on the part of participants. The learning goals in each unit not only address the content knowledge that participants will learn, but also how that content relates to the nature of science (or, how science is done) and to classical physics.

What's in this Unit?
This section provides an overview of:
- The online text, and the key ideas covered
- The video, and the researchers highlighted therein
- The video extra, if there is one associated with the unit
- The interactive lab associated with the unit
- Activities in the unit, as well as suggested time length for each activity
- The nature of science theme associated with the unit

Important: The suggested activity times are approximate only! As each individual group of participants will vary quite widely in their familiarity with these sophisticated topics, as well as the kinds of activities that they find most enriching, the onus will be on the facilitator to determine how much or little to focus on a particular activity. In order to provide materials for a wide range of interests and knowledge levels, we have erred on the side of being *more* inclusive rather than less. This means that in most cases, facilitators may wish to choose to reduce the amount of coverage from that described. Use caution, as some activities build on the understanding from previous activities, and some learning goals are predicated on the completion of certain activities.

In-session viewing of the video: The timing allotted to each activity, above, assumes a two-and-a-half hour session length, with the video being viewed as part of that on-site session. If you have the flexibility to do so, we suggest assigning the video viewing as an at-home activity, with discussion of the video in-session. This allows participants to view the video at their own pace, and for session time to be used to make sense of that material.

Nature of science theme: Each unit has an associated nature of science theme, such as *Measurement & Observation* or *Logic & Implications*. These themes are described in the Introductory Unit. The online resource, *Facilitator's Guide High Resolution Graphics*, includes high-quality versions of the icons that accompany each theme, for use in handouts or digital presentations.

Exploring the Unit

THE HOOK

Each unit begins with a *Hook,* designed to pique participants' interest. These are intended to be short (10-15 minutes), and typically involve a striking visual, short demonstration or hands-on activity, or compelling question.

ACTIVITIES

Each unit includes between four and seven activities designed to help participants digest the content of the online text and video, and to achieve the learning goals outlined in *What Will Participants Learn*? These activities are based on principles of interactive engagement from the educational research literature, as well as the best practices in working with adult learners, who are able to direct their own learning and inquiry.

Each activity is organized into two main parts:

- ***To Do and To Notice***. This contains instructions on what participants are meant to do, or questions for discussion.
- ***What's Going On?*** Here, both a description of the science, as well as the main points of the activity, are outlined. Answers to clicker questions, and explanations of what participants were meant to learn, are given.
  Take-home message. In most activities, especially longer ones, the main idea is encapsulated in a take-home message at the end of the *What's Going On?* portion of the activity.

This organization is intended to clearly separate the description of the activity from the discussion of the meaning of that activity. It is also intended to frame each activity as an exploration, rather than an exercise with clearly defined answers. This activity framing is borrowed from the Exploratorium's style at http://exploratorium.edu/snacks.

Some longer activities are divided into several numbered sub-sections, each with their own heading and *To Do and To Notice* and *What's Going On?* portions.

TYPES OF ACTIVITIES

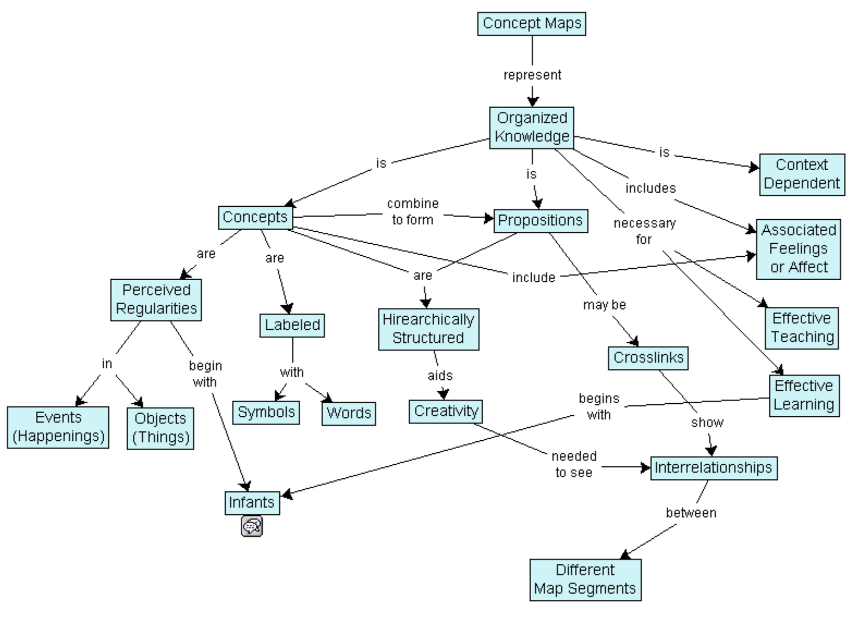
Activities take one of five main forms, as described below. All activities—except for discussion activities—are signaled in the text with an icon, so that facilitators are aware that additional equipment is needed at those times. Tips for facilitating the different types of activities are included in *HInts for Facilitators and Independent Learners*.

1. **Large or Small Group Discussion.** Participants are often asked to discuss concepts and problems in pairs, groups, or as a whole class. These discussions may take a more structured form, as described in the three formats below.

   Think-Pair-Share. In a Think-Pair-Share, participants are asked to *Think* about a question or questions on their own, *Pair* up to discuss it with a neighbor, and then *Share* the results of their discussion with the group as a whole.

   Jigsaw. In a jigsaw, individuals become experts on a particular topic or subtopic through reading or discussion in a group. Different groups are assigned different topics, so that different participants are experts on different topics. In this guide, we use a modified Jigsaw, where all smaller groups share their results with the larger group (rather than first rearranging into new small groups to share their expertise). This sharing of the individual pieces to develop a larger understanding on the part of the whole group is the essence of the jigsaw.

   Concept Mapping. A concept map is a diagram showing the relationship between a set of ideas, phrases, or concepts. The concepts are generally shown as circles or boxes, and connected with arrows or lines that are labeled to denote the relationship (such as “is a” or “results in” or “is an example of”). An example concept map is shown below.



Example Concept Map[1]

[1] Source: (c) Wikimedia Commons, License: Gnu Free Documentation. Author: Vicwood40. http://commons.wikimedia.org/wiki/File:Conceptmap.gif

2. **Clicker/Discussion Questions.** These are another type of discussion strategy, but focused on a question. *Clicker* is another term for *classroom response system.* This is a technology-enabled means of asking a question to the class, allowing them to answer anonymously by pushing a button on an individualized remote, providing instantaneous feedback to the instructor and the participant, as well as a focal point for discussion. If clickers are not available, colored cards may be substituted. We promote the use of clickers in conjunction with *peer discussion*, rather than as a silent quiz-taking tool. As not every facilitator will have access to clicker hardware, we term these "clicker/discussion questions." All clicker questions are included in a form suitable for presentation software in the online resources.

3. **Computer Simulations.** To assist learners with forming visual and conceptual models of the ideas in the units, we often include particularly illustrative or interactive computer simulations, many from the PhET project at http://phet.colorado.edu.

4. **Hands-On Activities.** Several activities using physical manipulatives are included in this guide. These are called hands-on activities.

5. **Watch and Discuss the Video.** The video is included in each unit, along with discussion questions. If you have the flexibility to do so, we suggest assigning participants to watch the video on their own, and reserving session time for discussion of the video. The location of *Watch and Discuss the Video* varies (i.e., it may be towards the beginning or towards the end of the session), depending on whether the activities are intended to help participants digest the content of the video, or to further explore the ideas described therein.

Back to the Classroom

Each unit contains the same questions for participants to consider:

- Where might this unit fit into your curriculum?
- What might your students know about this topic?
- Explore these topics on the Science Literacy Maps (see *Connection to National Standards,* below).

While the intent is that participants will brainstorm throughout the session how to bring these activities and topics into their classroom, this section provides a focused time to consider these important questions. It also provides a venue for participants to consider what common ideas their students might have about these topics, some of which may be complementary to instruction and some which may be contradictory.

This section also provides two valuable sub-sections: **Topics and Standards**, which lists the relevant concepts from the Science Literacy Maps (see *Connection to National Standards,* below), and **Classroom Resources**, which provides a list of exemplary online resources suitable for further exploration and/or classroom use.

Both of these sub-sections may be used as a jumping-off point for participant discussion. Participants may explore the Science Literacy Maps, and discover connections to other topics that they currently teach. You may wish to have participants look through several of the suggested *Classroom Resource* links, and report out to the group on the ones that they think would be most valuable.

Between Sessions

In preparation for the next session, participants are asked to both read the online text and to watch the video associated with the next unit. (Of course, if you plan to watch the video in class, then viewing of the video on their own is optional). It is suggested that the facilitator share the information from *What Will Participants Learn?* and the *Classroom Resources* sub-section of *Back to the Classroom* to guide participants' reading and exploration between sessions. You may also choose to have participants look through several of the suggested *Classroom Resource* links, and report to the group on the ones that they think would be most valuable at the beginning of the next session. This could be done as individuals or in teams, and can be a useful strategy to encourage participation and reading on the part of participants. It is particularly important that participants feel that the homework assignments are valuable, and will be used in the next session. See *Hints for Facilitators and Independent Learners,* below.

Hints for Facilitators and Independent Learners

General Hints

Creating a supportive learning environment. Be sure to give participants a chance to test their ideas about concepts in a non-threatening way. The material and concepts in this course are challenging. Solicit participant responses for questions, and hear from multiple people before explaining what answer you favor and why. Approach questions with a spirit of group curiosity, and seek to find the positive aspects of participants' answers as well as to correct misunderstandings of the material. Sometimes questions will arise that you, as the facilitator, do not know the answer to. This is a great opportunity to model how to deal with sophisticated and challenging questions for which you don't have the answer. "I don't know, but I know how to find out," is a great strategy for dealing with these types of questions. Another effective strategy to get at participant ideas is to ask, "What might your students say/think?" In addition, prompt participants to think about how these ideas and materials might be used in their classrooms.

Keep an eye on the clock. As described in *Course Components*, above, we have erred on the side of inclusivity in these materials. It's easy to lose track of the time and then run out of time before getting to key activities. Keep discussions focused. On the other hand, you don't want to cut valuable discussions short. Do your best to maintain a flexible balance between coverage of important concepts and allowing discussions to take their course.

Hints on Specific Course Elements

Hands-On Activities. Have enough materials for groups of 3-4 participants. If you have a document camera, you may use this to demonstrate material set-up in larger groups.

Videos. Be sure to check all videos and simulations on your computer before class on the computer that you will be using to project.

Simulations. Simulations can be valuable tools for visualization and exploration of ideas. However, if used as a demonstration, participants often do not come away with the most important ideas. Use simulations interactively, asking participants for suggestions on what to do with the simulation, questions they would like to answer with the simulation, and/or predictions ("what if" questions) of what will happen when you change a particular parameter in the simulation.

Clicker/Discussion Questions. Research on teaching and learning has shown that peer instruction (when two peers discuss a topic in order to better understand it) is a valuable method for facilitating learning. Thus, we recommend the use of clicker/discussion questions as a tool to facilitate peer instruction, rather than as a silent voting tool, especially if the concept is a difficult one. If the question is a review question, you may sometimes choose to have participants vote on their own. Some tips for successful use of clicker/discussion questions in the classroom:

1. Use them regularly. If participants are familiar with the process, they will feel more comfortable with peer discussion and voting.

2. Have participants discuss the questions with one another before they vote (peer instruction).
3. Allow 2-5 minutes per clicker question.
4. Facilitate a whole class discussion at the end of the question, and ensure that all participants know the correct answer at the end of that discussion. It is important to know not just why the right answer is right, but why the wrong answers are wrong.
5. Show the histogram of participant responses *after* the whole class discussion of the answer, unless the vote is clearly split across categories. This allows you to discuss all answer choices, before participants know how their peers voted. Remember, giving the answer shuts down participant thinking!

You can find many detailed resources on the use of clicker/discussion questions, including research on their use, clicker question banks, and short videos on best practices in the use of clickers, at http://STEMclickers.colorado.edu.

Think-Pair-Share, Clicker/Discussion Questions, Jigsaw—Facilitating Small-Group Discussion. Sometimes participants may be reluctant to talk to one another. Make it clear from the beginning that this is what we do in this course—discuss and debate ideas. This class is about reasoning and sense-making more than getting the answer. It's helpful to circulate around the room during a discussion to listen in, and to suggest additional questions for consideration. Be sure to allow adequate time for discussion, but pay attention to when discussion starts to turn to other things. Generally 2-4 minutes is adequate time for most discussions.

Think-Pair-Share, Clicker/Discussion Questions, Jigsaw— Facilitating Whole-Class Discussion. Oftentimes, participants are asked to discuss a question in small groups and then share out. This works well in smaller courses (under 10 participants), and allows the participants to take the role of teacher or facilitator for part of the course. However, with more than 10 participants in the course often a few people will tend to dominate. As a facilitator, you will need to be prepared to keep these participants in check, to keep the discussion within time limits, and allow all to participate. The use of clicker questions (see below) is intended to create an open environment where all feel comfortable discussing their ideas. Other techniques that you can use are requiring share-out from individual groups after participants discuss in pairs, or asking for an answer "from this side of the room." Whatever techniques you choose to use, set a clear example on the level of participation expected from all participants early in the course, and find techniques for allowing the more talkative participants to share their ideas without dominating conversation.

Between Sessions Assignments. It's important to provide participants incentive to complete the *Between Session* work before the next session. If session activities hinge on participants' completion of these assignments, then those who have not completed them will be motivated to do so the next time, and those who have completed it will be encouraged to continue. By the mid-point of a workshop series, this will allow engaging interactions between groups of participants who are, on the whole, dedicated to doing the work required to process the content of the course.

Notes for Individual Learners

If you are using this course as an individual learner for class credit, rather than enrolling in a synchronous course, you will need to translate the directions to facilitators in this guide in order to direct your own learning.

The separation of activities into *To Do and To Notice* and *What's Going On?* is designed to enable you to engage in the activities before seeking insight into the essential concepts and ideas in the activity—i.e., to not give the answer away. Thus, do the activities in *To Do and To Notice* before reading the discussions in *What's Going On?*

You can be creative in how you adapt these activities to your learning. You may wish to use the *Clicker/Discussion Questions* as guiding questions to answer through your reading and further exploration. You can do a jigsaw by choosing two topics and teaching them to a colleague at your school. You can create your own discussions by writing a short paragraph about your thinking on the topic. You may even choose to post this short paragraph on one of the many online discussion boards devoted to science topics, thus discussing with other individuals and broadening your understanding.

Note: You should still plan on a two-and-a-half hour long session devoted to each unit. This will include your viewing of the video associated with each unit as well as going through the unit's accompanying *Facilitator's Guide* activities. However, you should not include reading the online text or the other parts of the *Facilitator's Guide's Between Sessions* assignments in this two-and-a-half hour session.

For more information about obtaining graduate credit for independent study of the materials in this guide, see http://www.learner.org/workshops/graduate_credit.html.

Materials

For each session:

- Digital projector
- Classroom response (“clicker”) system (if you have one)
- High-quality graphics and Clicker/Discussion Questions from the online resource *Facilitator’s Guide High Resolution Graphics* (suitable for projection)

(*Note:* You do not need to be connected to the internet to run the PhET simulations described below. You may click “download” to download and run the simulations locally on your machine.)

Introductory Unit

The Hook: What We See Isn’t What We Get

- Three copies of a full-page face from a magazine cover or a digital image

Activity 1: Why Teach Physics?

- Nature of Science themes handout from the *Facilitator’s Guide High Resolution Graphics*
- Optional: Icons of Nature of Science themes from the *Facilitator’s Guide High Resolution Graphics*

Activity 2: The Shape of Things—Measurement & Observation

- Pie plate
- Wooden “mystery shapes” to hide under pie plate
- Marble(s)
- Ramp (such as a plastic ruler with a groove)
- Pen or marker
- Containment fence (e.g., a hula hoop)

Activity 3: How Do We Know? Evidence

- “What Can We Learn from a Tooth?” http://www.exploratorium.edu/webcasts/explotv_player.php?id=00001107&type=flv
- Optional: “Why did the Neanderthals Disappear?” http://www.exploratorium.edu/webcasts/explotv_player.php?id=00001084&type=flv

Activity 5: Turning Gears—Logic & Implications

- Optional: Mirage toy (e.g., http://www.arborsci.com/prod-Mirage-210.aspx)

Activity 6: Rules of the Game—Coherence & Consistency

- Image of puzzle and solution from the *Facilitator’s Guide High Resolution Graphics*

Back to the Classroom

- A computer with Internet access for each group of two to three participants

Unit 1: The Basic Building Blocks of Matter

The Hook: Our World as an Atom

- Tennis ball
- Computer with internet access

Activity 1: Revisiting *"The Shape of Things"* – Particle Accelerators

- *The Shape of Things* apparatus from the Introductory Unit

Activity 2: The Particle Zoo

- Optional: Handout of example concept map from online resources
- Optional: Physical cutouts of words for concept map

Activity 3: Quark Math

- Quark cards (3 copies for each group 3-4) from *Facilitator's Guide High Resolution Graphics*

Between Sessions

- Optional: Handout for table of the fundamental forces

Unit 2: The Fundamental Interactions

Activity 1: What is a Field? What is a Force?

- "Electric Field Hockey" PhET simulation http://phet.colorado.edu/simulations/sims.php?sim=Electric_Field_Hockey
- Optional: "Charges and Fields" PhET simulation http://phet.colorado.edu/simulations/sims.php?sim=Charges_and_Fields
- Optional: Van de Graaff generator
- Optional: Mylar balloon
- Optional: String

Activity 2: Feynman Theater

- 1-2 tennis balls
- Optional: skateboards

Unit 3: Gravity

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

- *Note:* you may choose the demonstration based on the materials available
- "Flying tinsel": an object like a piece of PVC or block of blue foam insulation; wool; tinsel
- "Balloon": balloon; wool
- "Magnets": paperclip; magnet
- "Surface Tension": pepper

Activity 1: The Problem with Newton's Law

- Butcher paper (or other large sketch paper)
- "Radio Waves and Electromagnetic Fields" PhET simulation http://phet.colorado.edu/simulations/sims.php?sim=Radio_Waves_and_Electromagnetic_Fields

Activity 4: Curved Spacetime

- *Note:* the model from this activity will be re-used in Units 4 and 10
- 5x5 foot spandex sheet, marked with a grid
- Dowels
- Marbles
- Safety pins
- Masses on hooks
- Beach ball marked with a grid

Activity 5: Fall into a Black Hole (optional)
- "Journey into a Schwarzschild Black Hole" simulation
  http://jila.colorado.edu/~ajsh/insidebh/schw.html

Unit 4: String Theory and Extra Dimensions

The Hook: Collapse the Dimensions
- A long (10 meters) rope at least 5mm 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

Activity 1: Tiny Things Cause Big Problems
- Spandex model from Unit 3

Activity 2: What are Strings?
- One 25-foot length of rubber tubing for every two participants (or 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

Between Sessions: Mini Lesson
- "The Photoelectric Effect" PhET Simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect
- "Quantum Wave Interference" PhET Simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference

Unit 5: The Quantum World

The Hook: How To Make Something Really Cold
- Ping-pong balls (about 15)
- 5 marbles
- An enclosure, such as a hula hoop
  Note: you may use different types of balls depending on your available materials

Activity 2: Photoelectric Effect (Optional)
- Digital projector
- "Photoelectric Effect" PhET simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect

Activity 3: The Wave/Particle Nature of Light
- Digital Projector
- "Quantum Wave Interference" PhET simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference

Activity 4: Matter is a Wave (But What's Waving?)
- "Quantum Wave Interference" PhET simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference

Unit 6: Macroscopic Quantum Mechanics

The Hook: Superfluid Coffee

- Mug of coffee or other liquid
- Video of superfluid helium (e.g. http://www.youtube.com/watch?v=2Z6UJbwxBZI)

Activity 1: Models of the Atom

- Optional: "How can atoms exist?" video from Alice and Bob's Adventures in Wonderland http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/
- Optional: Handout of different models of the atom from online resources

Activity 2: Periodic Chessboard

- Butcher paper
- Colored markers
- 30 small paper or plastic cups
- Copy of the periodic table
- Tape
- Copy of atomic orbital simulation http://www.falstad.com/qmatom/

Activity 4: Bose-Einstein Condensates

- Marbles and an enclosure (from Unit 5)
- Animation of the Bose-Einstein condensation at http://www.colorado.edu/physics/2000/bec/images/evap2.gif
- Optional: Video "Bose-Einstein Condensate" from BBC with Dan Kleppner http://www.youtube.com/watch?v=bdzHnApHM9A&feature=related
- Optional: "Quantum Bound States" PhET simulation http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Bound_States

Unit 7: Manipulating Light

Activity 1: Slowing Light

- Internet access or downloaded simulation from http://webphysics.davidson.edu/applets/Superposition/GroupVelocity.html or http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/sines/GroupVelocity.html)

Activity 3: Entangled Socks

- Two identical boxes (any size)
- Two different colored socks (such as pink and blue)

Unit 8: Emergent Behavior in Quantum Matter

The Hook: Who's the Leader?

- Images and video of flocking birds or schools of fish

Activity 3: To See the World in a Grain of Sand

- Circular fruit-flavored cereal (such as Froot Loops®)
- Rice
- Sugar
- Variety of funnels (1/4" opening works well)

- Cups
- Shallow containers
  Note: You will use the cereal again in Unit 9, so get plenty

Activity 4: Hard Condensed Matter
- Pitcher of water
- Circular fruit-flavored cereal (such as Froot Loops®)
- Bowls

Unit 9: Biophysics

The Hook: Big Forces at Small Distances
- A heavy ball (e.g. steel ball)
- A light ball (e. g. ping-pong ball)
- Digital projector
- "Gas Properties" PhET simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Gas_Properties

Activity 1: Life and the Second Law
- Latex gloves (enough for every one or two participants)
- Digital projector
- "Stretching DNA" PhET simulation
  http://phet.colorado.edu/simulations/sims.php?sim=Stretching_DNA

Activity 2: Breakfast Proteins
- Fruit-flavored donut-shaped cereal (such as Froot Loops®)
- Chenille stems
- String
- Scissors
- Pencil
- Paper

Activity 5: Pulling it Together
- "Find the Highest Note" http://www.exploratorium.edu/exhibits/highest_note/
- Optional: related files at http://asa.aip.org/demo27.html
- Optional: Traveling salesman route through Germany from *Facilitator's Guide High Resolution Graphics*

Unit 10: Dark Matter

The Hook: More Than We Can See
- Visualization of the Sloan Digital Sky survey
- Optional: example concept map from *Facilitator's Guide High Resolution Graphics*

Activity 1: PhET My Solar System" PhET Simulation
- Tennis ball on string
- "My Solar System" PhET simulation
  http://phet.colorado.edu/simulations/sims.php?sim=My_Solar_System

Activity 2: Gravitational Lensing
- One or several wine glasses with a curved bottom
- Spandex model from Unit 3

- Heavy object (e.g. a stapler)
- Tennis ball
- Graph paper
- Optional: Images of light bending by a lens and light bending by gravity from *Facilitator's Guide High Resolution Graphics*

Unit 11: Dark Energy

The Hook: The Night Sky is Dark

- Optional: "Why is it dark at night?" video http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/

Activity 2: How Far Away Is It?

- Optional: Light meter

Activity 3: How Fast Is It Moving?

- Football or other ball with embedded buzzer (or a buzzer on a string)
- "Wave Interference" PhET simulation http://phet.colorado.edu/simulations/sims.php?sim=Wave_Interference
- Optional: "Sound" PhET simulation
- http://phet.colorado.edu/simulations/sims.php?sim=Sound
- Optional: "Doppler Shift" simulation http://scatter.colorado.edu/STEM-TPSoft/

Activity 4: The Universe is Expanding

- Balloons
- Paper
- Tape
- Hubble Plot and Closed/Open Universe plot (from the text)
- Optional: Transparencies and overhead projector, and image from http://www.exo.net/~pauld/activities/astronomy/ExpandingUniverse.html
- Optional: Digital image of expanding dots from *Facilitator's Guide High Resolution Graphics*

Activity 5: Looking Back in Time (Optional)

- Drawing paper
- Optional: "Is that star really there?" from Alice and Bob's Adventures in Wonderland http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/

Review Unit

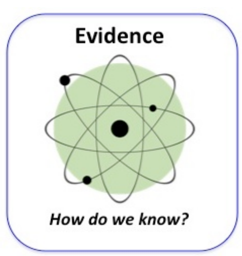
Activity 1: How Does It Hook Together?

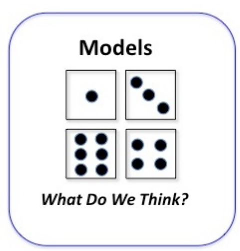
- Butcher paper
- Index cards
- Markers
- Digital camera
- Optional: Handout of recommended concept-mapping terms from *Facilitator's Guide High Resolution Graphics*

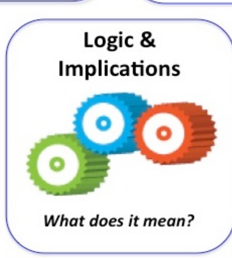
Connection to National Standards
and Nature of Science Themes

Each unit has an associated theme related to the Nature of Science—or, the views that the scientific community has about the natural world and how we can study it. The frontiers of research provide a natural platform for discussing the nature of the scientific enterprise and investigation. These themes also help support the science standards regarding the nature of science. See the Introductory Unit for more information on these themes, and how they relate to the content of this course. High quality versions of the icons for these themes are available in the online resource: *Facilitator's Guide High Resolution Graphics*.

NATURE OF SCIENCE THEME →	Measurement & Observation	Evidence	Models	Logic & Implications	Coherence & Consistency
Unit 1: The Basic Building Blocks of Matter	✓				
Unit 2: The Fundamental Interactions			✓		
Unit 3: Gravity				✓	
Unit 4: String Theory and Extra Dimensions		✓			
Unit 5: The Quantum World	✓				
Unit 6: Macroscopic Quantum Mechanics			✓		
Unit 7: Manipulating Light					✓
Unit 8: Emergent Behavior in Quantum Matter			✓		
Unit 9: Biophysics					✓
Unit 10: Dark Matter		✓			
Unit 11: Dark Energy				✓	
Review Unit					✓







In order to provide alignment with the National Science Education Standards (NSES), and the American Association for the Advancement of Science (AAAS) Project 2061 Benchmarks, we have provided linkages of the topics in each unit to the AAAS Atlas of Science Literacy. These Science Literacy Maps form a tool for teachers to find how topics relate to specific science and math topics, and how concepts build upon one another across grade levels. The online versions of these Science Literacy Maps are found at http://strandmaps.nsdl.org. Each unit ends with recommendations that participants explore the online Science Literacy Maps, and gives a list of relevant concepts from those maps. *Note:* The text in the Science Literacy Maps is primarily derived from the Project 2061 Benchmarks, in conjunction with the NSES.

	Unit										
	1	2	3	4	5	6	7	8	9	10	11
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).			✓							✓	
Gravitational force is an attraction between two masses; its strength is proportional to the masses and weakens rapidly with distance.										✓	✓
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.			✓								✓
An unbalanced force acting on an object changes its speed, or direction of motion, or both.	✓	✓							✓		
Any object maintains a constant speed and direction unless an unbalanced force acts on it.		✓	✓						✓		
The idea of absolute motion or rest is misleading.			✓								
Energy											
The total amount of energy in a system remains constant if no energy is transferred in or out.	✓				✓	✓				✓	
Energy appears in many forms (such as kinetic and potential).					✓	✓			✓	✓	
Thermal energy in a system is associated with the disordered motions of its atoms or molecules.					✓	✓			✓		
Chemical energy is associated with the configuration of atoms in molecules that make up a substance.								✓	✓		
The total amount of order in the universe always tends to decrease.									✓		
Electricity and Magnetism											
Moving electrically charged objects produce magnetic forces.	✓										
The nuclear forces that hold the protons and neutrons in the nucleus of an atom are much stronger than the electric forces between the protons and electrons of the atom.		✓		✓							

	1	2	3	4	5	6	7	8	9	10	11
Electric forces hold solid and liquid materials together and act between objects when they are in contact—as in sticking or sliding friction.		✓									
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.		✓	✓								
In many conducting materials, such as metals, some of the electrons are not firmly held by the nuclei of the atoms that make up the material.						✓					
At very low temperatures, some materials become superconductors and offer no resistance to the flow of electrons.						✓		✓			
Atoms and Molecules											
Atoms are made of protons, neutrons and electrons.	✓			✓		✓					
Scientists continue to investigate atoms and have discovered even smaller constituents of which neutrons and protons are made.	✓	✓		✓							
The nuclear forces that hold the protons and neutrons in the nucleus of an atom are much stronger than the electric forces between the protons and electrons of the atom.		✓		✓							
Atoms are made of a positively charged nucleus surrounded by negatively charged electrons.					✓	✓					
An atom's electron configuration, particularity the outermost electrons, determines how the atom can interact with other atoms.						✓					
When elements are listed in order by the masses of their atoms, the same sequence of properties appears over and over again in the list.						✓					
Size and Scale											
When describing and comparing very small and very large quantities, express them using powers-of-ten notation.	✓	✓		✓						✓	✓
Natural phenomena often involve sizes, durations, or speeds that are extremely small or extremely large.	✓	✓		✓	✓				✓	✓	✓
Gravity											
Gravitational force is an attraction between two masses; the strength of the force is proportional to the masses and weakens rapidly with distance between them.		✓	✓								
Gravity is the force that keeps planets in orbit around the sun.		✓	✓								

	1	2	3	4	5	6	7	8	9	10	11
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.			✓								
Waves and Light											
For an object to be seen, light must be emitted by or scattered from it.										✓	
Visible light is a small band in the electromagnetic spectrum.							✓			✓	✓
The observed wavelength of a wave depends on the relative motion of the source and the observer.											✓
Wave behavior can be described in terms of how fast the disturbance spreads, and in terms of the wavelength.					✓	✓					
The wavelength of light varies from radio waves, the longest, to gamma rays, the shortest.					✓						
Light acts like a wave in many ways.					✓	✓	✓				
Waves can superpose on one another, bend around corners, reflect off surfaces, be absorbed by materials they enter, and change direction when entering a new material.							✓				
The energy of waves (like any form of energy) can be changed into other forms of energy.							✓				
The Universe											
Galaxies are made of billions of stars and are most of visible mass of universe.											
The Big Bang theory suggests that the universe began 10-20 billion years ago in a hot dense state.				✓						✓	✓
Some distant galaxies are so far away that their light takes several billion years to reach the Earth										✓	
Astronomers believe the whole universe is expanding				✓							✓
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.			✓								
Among the counterintuitive ideas of special relativity is that the speed of light is the same for all observers. In addition, nothing can travel faster than the speed of light.			✓				✓				

	1	2	3	4	5	6	7	8	9	10	11
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.			✓								
A decade after Einstein developed the special theory of relativity, he proposed the general theory of relativity, in which the gravitational force is a distortion of space and time.			✓	✓							
The Mathematical World											
How probability is estimated depends on what is known about the situation.					✓	✓					
States of Matter											
A system usually has some properties that are different from those of its parts, but appear because of the interaction of those parts.								✓			
Different arrangements of atoms into groups compose all substances and determine the characteristic properties of substances.						✓	✓	✓			
Atoms may link together in well-defined molecules, or may be packed together in crystal patterns.								✓			
An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.						✓	✓	✓			
Systems											
Most systems above the molecular level involve so many parts that it is not practical to determine the existing conditions, and thus the precise behavior of every part of the system cannot be predicted. Even in some very simple systems, it may not always be possible to predict accurately the result of changing some part or connection.								✓			
As the number of parts in a system grows in size, the number of possible internal interactions increases much more rapidly, roughly with the square of the number of parts.								✓			
Nature of Science											
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.			✓	✓		✓					

	1	2	3	4	5	6	7	8	9	10	11
Observation, evidence, and logic are important in the interpretation of experimental results.	✓		✓	✓						✓	✓
New technologies make it possible for scientists to extend their research in new ways or to undertake entirely new lines of research; technology often sparks scientific advances.							✓				
Investigations are conducted for different reasons, including to explore new phenomena.							✓				
The selection of appropriate measurement and observation tools is important in answering a particular experimental question.										✓	
Increasingly sophisticated technology is used to learn about the universe.										✓	
Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models.		✓		✓		✓		✓		✓	✓
A mathematical model uses rules and relationships to describe and predict objects and events in the real world.		✓						✓			
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.	✓		✓	✓	✓	✓		✓			
Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations.					✓	✓		✓		✓	✓
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.			✓					✓			
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.				✓							

About the Contributors

Note: More detailed information about all the contributors may be found in the *Physics for the 21st Century* course materials on-line at www.learner.org.

Course Developer

Christopher Stubbs: Harvard University
Christopher Stubbs is an experimental physicist working at the interface between particle physics, cosmology, and gravitation. His interests include experimental tests of the foundations of gravitational physics, searches for dark matter, and observational cosmology.

Course Liaison

Claire Cramer: National Institute of Standards and Technology
Claire Cramer is a physicist at the National Institute of Standards and Technology. Her work centers around developing novel techniques for using lasers to improve the precision of astronomical measurements, with applications to dark energy surveys, finding and characterizing extrasolar planets, and mapping dark matter within our galaxy.

Content Developers

UNIT 1
Natalie Roe: Lawrence Berkeley National Laboratory
Natalie Roe is a senior scientist in the physics division at the Lawrence Berkeley National Laboratory, a fellow of the American Physical Society, and former Chair of the APS Division of Particles and Fields. Roe has worked on a variety of particle physics experiments at CERN, Fermilab, and SLAC.

UNIT 2
David Kaplan: Johns Hopkins University
David E. Kaplan is a professor in the Department of Physics and Astronomy of Johns Hopkins University. His primary research interests are in theoretical particle physics with particular focus on electroweak superconductivity and potentially related physics such as supersymmetry, new fundamental forces, extra dimensions, and dark matter.

UNIT 3
Blayne Heckel: University of Washington
Blayne Heckel is professor of physics and chair of the Department of Physics at the University of Washington. His research interests focus on tests of fundamental symmetries: torsion balance tests of spatial isotropy, the equivalence principle, and the gravitational inverse square law, and searching for time reversal symmetry violation in the electric dipole moments of atoms.

UNIT 4
Shamit Kachru: Stanford University
Shamit Kachru is a professor of physics at Stanford University. His research interests include string theory and quantum field theory, and their applications in cosmology, condensed matter physics, and elementary particle theory.

UNIT 5

Daniel Kleppner: Massachusetts Institute of Technology

Daniel Kleppner is the Lester Wolfe Professor of Physics, Emeritus at MIT. He is the founding Director of the MIT-Harvard Center for Ultracold Atoms, funded by the National Science Foundation. He is the coauthor of two textbooks and the recipient of the Oersted Medal of the National Association of Physics Teachers and of the National Medal of Science.

UNIT 6

William P. Reinhardt: University of Washington

William P. Reinhardt is a professor of chemistry and adjunct professor of physics at the University of Washington. His research is in two main areas: (1) modeling the structure and dynamics of the newest state of matter, the gaseous Bose-Einstein condensate (BEC); and (2) development of novel techniques for determination of the entropies and free energies of complex molecular systems, including clusters and polymers.

UNIT 7

Lene Hau: Harvard University

Lene Vestergaard Hau is the Mallinckrodt Professor of Physics and of Applied Physics at Harvard University. Prior to joining the Harvard faculty in 1999, she was a member of the scientific staff at the Rowland Institute for Science at Harvard in Cambridge, Massachusetts. She earned a Ph.D. in physics from the University of Aarhus, Denmark.

UNIT 8

David Pines: UC Davis and University of Illinois at Urbana-Champaign

David Pines is the founder and co-director of the Institute for Complex Adaptive Matter (http://icam-i2cam.org), a global institute with over 60 branches worldwide, dedicated to promoting research and education in emergent behavior in matter and society. He is also a Distinguished Professor of Physics at UC Davis, where he teaches one quarter every year, and Research Professor of Physics and Professor Emeritus of Physics and Electrical and Computer Engineering in the Center for Advanced Study, University of Illinois at Urbana-Champaign, where he was a faculty member from 1959-1999.

UNIT 9

Robert H. Austin: Princeton University

Robert H. Austin is a researcher in the Department of Physics of Princeton University, who probes the biological limits of evolving organisms under stress. His research focuses primarily on the use of microarrays and nanotechnology to further our physical understanding of biological processes, such as the dynamics of cells when subjected to stress. He ultimately wants to understand, and possibly guide, the evolution of microrganisms by culturing them inside custom-made microenvironments.

UNIT 10

Peter Fisher: Massachusetts Institute of Technology

Peter Fisher is a professor of physics and division head of Particle and Nuclear Experimental Physics at MIT. His main activities are the experimental detection of dark matter using a new kind of detector with directional sensitivity.

UNIT 11

Robert P. Kirshner: Harvard University

Robert P. Kirshner is Clowes Professor of Science at Harvard University. Professor Kirshner is an author of over 250 research papers dealing with supernovae and observational cosmology. His work with the "High-Z Supernova Team" on the acceleration of the universe was dubbed the "Science Breakthrough of the Year for 1998" by *Science Magazine*.

Facilitator's Guide Developers

Stephanie Chasteen: University of Colorado at Boulder and sciencegeekgirl enterprises
Stephanie Chasteen is a science teaching fellow at the University of Colorado at Boulder, funded through the Science Education Initiative, and owns and operates an independent science education consulting business. Her primary interests are in creating effective teacher professional development programs and in engaging the public in scientific inquiry. She earned her PhD in condensed matter physics from the University of California at Santa Cruz. Her interest in communicating science to the public led her to an AAAS Mass Media Fellowship at National Public Radio's science desk in Washington, D.C. She was a postdoctoral fellow in the Teacher Institute at the Exploratorium Museum of Science, Art, and Human Perception in San Francisco where she produced teacher workshops and several audio podcast series, one of which won Best Professional Development Podcast from *The Teacher's Podcast*. She has created over 50 feature articles, academic publications, and videos, and over 60 audio podcasts, primarily aimed at K-14 teachers or the general public. Her research on student learning and educational reform has been published in key journals in the field. She maintains a popular blog on science education at http://sciencegeekgirl.com.

Noah Finkelstein: University of Colorado at Boulder
Noah Finkelstein is currently an associate professor of Physics at the University of Colorado at Boulder and conducts research in physics education. He received a Bachelor's degree in mathematics from Yale University and his PhD. for work in applied physics from Princeton University. He serves as a director of the Physics Education Research (PER) group at Colorado, one of the world's largest research groups in physics education. Finkelstein is PI or Co-PI for many nationally funded research grants to create and study conditions that support students' interest and ability in physics. These research projects range from the specifics of student learning to the departmental and institutional scales, and have resulted in over 70 publications. Finkelstein is also a co-PI and a Director of the Integrating STEM Education initiative (iSTEM), an NSF-i3 funded program to establish a Center for STEM education. Finkelstein serves on five national boards in physics education, including: the Physics Education Research Leadership Organizing Council, and the Committee on Education of the American Physical Society. In 2007 he won the campus-wide teaching award and in 2009 he won the campus Diversity and Excellence award. More on Noah can be found at http://spot.colorado.edu/~finkelsn.

Introductory Unit

"Nothing shocks me. I'm a scientist."
– Harrison Ford (as Indiana Jones)

This unit of the *Facilitator's Guide* introduces the *Physics for the 21st Century* course and key themes related to how science is practiced, or the nature of science. In this unit, participants will explore a variety of activities related to the following nature of science themes: *Measurement & Observation*; *Evidence*; *Models*; *Logic & Implications*; and *Coherence & Consistency*. We also examine broader questions, such as: Why study physics? Why study current topics in physics research? Why are these topics useful for teachers and their students?

What Will Participants Learn?

Participants will be able to:

1. Describe two major nature of science themes that will be present in this course and argue why they are important.
2. Discuss the relationship of the nature of science to a few topics in this unit.
3. Argue why modern physics topics are useful in the high school science classroom.

What's in the Introductory Unit?

Text: The *Introduction to the Online Text* provides an overview of the rationale behind a course on modern physics, the content in each chapter, and how the content relates to common themes throughout this course. The text begins with several examples of reductionism—breaking down complex systems into simpler units (Chapters 1-3) through identification of subatomic particles and their interactions. Physicists also use experimentation and observation to determine how phenomena can be explained through general principles (Chapters 4-7), with sometimes surprising applications. We may gain insight into complex systems, with many interacting parts, by looking at the interactions of many pieces to see the creation of a more complex whole (Chapters 8-9). The theme of *Evidence*, or how we know what we know, helps to pinpoint our interpretation of experimentation (Chapters 10-11).

Video: There is no video accompanying the *Introduction to the Online Text*.

Interactive Lab: There is no interactive lab accompanying the *Introduction to the Online Text*.

Activities:

- The Hook: What We See Isn't What We Get (10 minutes)
- Activity 1: Why Teach Physics? (20 minutes)
- Activity 2: The Shape of Things—*Measurement & Observation* (20 minutes)
- Activity 3: How Do We Know? *Evidence* (20 minutes)
- Activity 4: The Farmer and the Seeds—*Models* (30 minutes)
- Activity 5: Turning Gears—*Logic & Implications* (10 minutes)
- Activity 6: Rules of the Game—*Coherence & Consistency* (10 minutes)
- Back to the Classroom (30 minutes)

All other units in this course focus on one aspect of the nature of science in the discussion of a particular physics topic. This introductory unit introduces participants to all nature of science themes in the course, but does not have a particular theme itself.

Exploring the Unit

The Hook: What We See Isn't What We Get

Time: 10 Minutes.

Purpose: To introduce the role that perception plays in understanding the natural world—and why our observations should always be carefully examined.[1]

Materials:

- Three copies of a full-page human face from a magazine cover or a digital image.

Before the Session: Create two versions of a face using the "Vanna" activity at http://www.exploratorium.edu/snacks/vanna/index.html. You may scan this image and use it with a digital projector, or use the cropping tool in digital image editing software.

To Do and To Notice

Display the image that has its eyes and mouth reversed, but upside-down. Tell participants that in this course, we'll be exploring some unfamiliar things. Casually ask them, "What do you notice?" (*Hint:* Don't display the image for more than 10 seconds.) Display the same image right side up. Now what do they see? Participants will usually want you to switch between the two images a few times.

Ask participants for suggested reasons why they may not have noticed something strange about the upside-down face; whereas when it was turned right side up, it looked grotesque.

What's Going On?

We are used to seeing faces in a particular way. Our brains don't process the pieces of a face as individual parts, but rather see the face as a whole. Thus, when the face is upside-down, the gestalt processing of the entire face is disrupted. We don't notice that there is something strange—or if we do, it doesn't look as strange as it does right side up.

[1] Inspired by the Exploratorium's Snack, "Vanna," at http://www.exploratorium.edu/snacks/vanna/.

Observation is an important part of the scientific process. Yet our perception has inherent flaws, which can lead us to make errors in what we report. Our eyes are not cameras. In this course, we will explore some of the curious things about nature that scientists have discovered by measuring things that are out of the realm of our ability to perceive.

Going Further

You may also wish to use the auditory illusion "Find the Highest Note" at http://www.exploratorium.edu/exhibits/highest_note/ex.about.fr.html. (Scroll over the key to play the sound. This can be slow to load—be patient or use the noninteractive version at http://asa.aip.org/demo27.html). Be sure to play the continuous version at http://asa.aip.org/demo27.html as well—it's striking. Ask participants, "What do you notice? What's going on?" Each key is actually a collective of notes spaced by an octave. The volume of the different notes in the chords changes as you go around the keyboard, creating the illusion of a never-ending staircase of sound.[2]

Activity 1: Why Teach Physics?

Time: 20 Minutes.

Purpose: To share past experiences and discuss how participants approach the nature of science in the classroom.

Materials:

- *Nature of Science Themes* handout from the online resource: *Facilitator's Guide High Resolution Graphics*
- Icons of nature of science themes from the online resource: *Facilitator's Guide High Resolution Graphics* (optional)

To Do and To Notice

Ask participants to take a few minutes to write down their answers to the question, "Why teach physics?"[3] What do they want to help their students learn? Then, ask participants to discuss the issue in groups of three to four. Write their responses on the board and look for ways to organize the different reasons that are presented.

Then, facilitate a Think-Pair-Share on the following questions. (*See: Hints for Facilitators and Independent Learners* for a description of Think-Pair-Share activities.)

1. What do your students think science is?
2. What do you think science is?
3. What activities in your classroom demonstrate what science is, or the nature of science?

[2] More on this activity here: http://www.exo.net/~pauld/summer_institute/summer_day1perception/find_the_highest_note.html.

[3] "Why Teach Physics?" and the accompanying discussion are provided by Dewey Dykstra, *Piaget Beyond "Piaget" Workshop*, Boise, ID (2009).

List the nature of science themes from this unit on the board. (*See: What's Going On?* below.) A handout-ready copy is available in the online resource: *Facilitator's Guide High Resolution Graphics.*

Ask participants to list the content areas of this course on the board: *The Basic Building Blocks of Matter*; *The Fundamental Interactions*; *Gravity*; *String Theory and Extra Dimensions*; *The Quantum World*; *Macroscopic Quantum Mechanics*; *Manipulating Light*; *Emergent Behavior in Quantum Matter*; *Biophysics*; *Dark Matter*; and *Dark Energy*. Why teach these topics in the classroom?

What's Going On?

We have many valid reasons for teaching physics. Highlight participant responses that are related to the process of doing science, or scientific inquiry, such as the scientific method, the process of discovery, or the role of logic. Explain that we often struggle to help students see science as a dynamic process for exploring, understanding, and modeling the natural world, rather than a collection of facts.

The research and ideas that make up this course represent areas of physics that are still under active exploration. They demonstrate how science is a process of exploring the natural world through observation and model building, and then more observation to confirm, reject, or modify those models. These themes help support the science standards on the nature of science—the scientific community's views about the natural world and how we can study it.

Teaching 21st century physics in the high school classroom can have many advantages. It can spark student interest and motivation, and can help the teacher and students learn about the frontiers of physics. Showing that physics is an ever-changing field of unanswered questions serves to present physics as an exciting career choice. Students may not recognize that the fundamental ideas in physics (such as conservation of energy) are tools used in the frontiers of research to answer fundamental questions about the universe. Each unit in this course contains a list of connections to the science standards and benchmarks. In addition, the frontiers of research provide a platform for discussing the nature of the scientific enterprise and investigation.

List the following themes on the board, and indicate that these will be explored in today's session.[4] (These themes are also available in the online resource: *Facilitator's Guide High Resolution Graphics*.) The table below shows how each theme is distributed throughout the units.

[4] These themes are borrowed heavily from E.F. Redish and D. Hammer, *Am. J. Phys.*, 77, 629-642 (2009), and are supplemented by F.J. Rutherford and A. Ahlgren, *Science for All Americans,* Oxford University Press (1991).

Nature of Science Themes

	Measurement & Observation	**Evidence**	**Models**	**Logic & Implications**	**Coherence & Consistency**
Unit 1: The Basic Building Blocks of Matter	✓				
Unit 2: The Fundamental Interactions			✓		
Unit 3: Gravity				✓	
Unit 4: String Theory and Extra Dimensions		✓			
Unit 5: The Quantum World	✓				
Unit 6: Macroscopic Quantum Mechanics			✓		
Unit 7: Manipulating Light					✓
Unit 8: Emergent Behavior in Quantum Matter			✓		
Unit 9: Biophysics					✓
Unit 10: Dark Matter		✓			
Unit 11: Dark Energy				✓	
Review					✓

1. ***Measurement & Observation*: What Do We See?** Because we cannot always trust our direct perception, we must confirm our observations via measurement. Thus, much, if not all, scientific evidence relies on indirect measurement. A variety of tools allow scientists to probe aspects of the natural world that are beyond our human capacity to perceive.

2. ***Models*: What Do We Think?** Scientists create models, or hypotheses and theories, to make sense of their observations. Hence, a model is a scientific account of nature. A good model is testable and suggests evidence that would support or refute it. When experimental observations do not match the existing model, scientists may change their ideas about nature.

3. ***Evidence*: How Do We Know?** How do we know what we know? The data collected through measurement and observation 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 support 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.

4. ***Logic & Implications*: What Does It Mean?** Science is founded on the 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.

5. ***Coherence & Consistency*: How Does It Hook Together?** Science is not a set of independent facts and formulas, as often viewed by students. Rather, scientific findings are accepted as true because they hold together with other ideas and findings. Conflicts between results or between experiment and theory reduce scientists' confidence in either the experiment or the theory.

Activity 2: The Shape of Things— Measurement & Observation

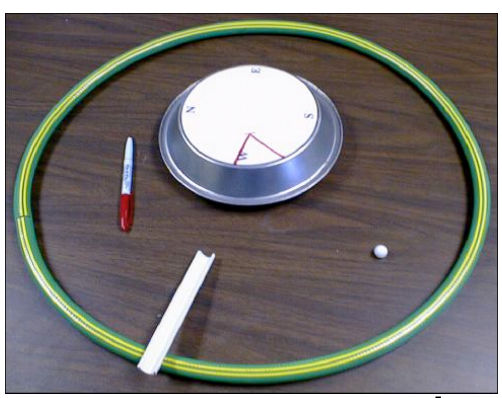
HANDS-ON ACTIVITY

<u>Time</u>: 20 Minutes.

<u>Purpose</u>: To highlight the role of indirect measurement in science.

<u>Materials</u>:
- Pie plate
- Wooden "mystery shapes" to hide under pie plate
- Marble(s)
- Ramp (such as a plastic ruler with a groove)
- Pen or marker
- Containment fence (e.g., a hula-hoop)

<u>Before the Session</u>: Attach the wooden mystery shape to the inside of the pie plate so that it's hidden from view when the pie plate is turned over, and there is space for the marble to roll under the lip of the pie plate. Make a ramp out of a piece of PVC pipe or other object, such as a plastic ruler with a groove in it. Place a containment fence, such as a hula-hoop or a section of garden hose, around the apparatus. For a large class, you may want to build multiple setups with similar or different unknown mystery shapes, depending on how much structure you need to provide.



Materials for *The Shape of Things*[5]

[5] Image and activity used with permission from Thomas Jefferson National Accelerator Facility Office of Education. http://education.jlab.org/beamsactivity/6thgrade/shapeofthings/overview.html.

To Do and To Notice

Bring the class close to the setup or use a document camera to demonstrate the design. Participants may not look under the pie plate, and may only roll marbles under it to figure out what's there.

1. What is the shape of the object?
2. Where is the object located?

Facilitate discussion during the activity about how to determine the answer to these questions. When participants make a statement (e.g., "It must be toward the center"), ask them, "How do you know that?" Help them to make their reasoning explicit (e.g., that the angle of incidence of the marble is equal to the angle at which it hits the object). (*Hint:* One method of data collection is to place a piece of paper on top of the pie plate so that participants may draw lines showing where the marble entered and exited from the pie plate. These lines represent inferred paths of travel, as we cannot directly observe the marble's trajectory.)

Once participants have fully explored the activity, facilitate a class discussion using the ideas provided below:

1. How did you determine the shape and location of the object?
2. If you only shoot marbles from one side of the pie plate, which mystery objects would look the same?
3. How is this similar to Rutherford's gold foil experiment?
4. What other kinds of phenomena are not directly observable and thus need special equipment to measure?
5. How do you imagine that *Measurement & Observation* relates to other topics covered in *Physics for the 21st Century,* or to other topics you've taught?

Facilitate a Think-Pair-Share. How can you use this in your classroom?

What's Going On?

Once participants have fully explored the activity, facilitate a class discussion using the ideas provided below. If possible, do so while standing beside one example, or use a document camera so students can see a visual reference during the discussion.

1. **How did you determine the shape and location of the object?** We inferred it indirectly by observing the resultant motion of the marbles. Discuss the assumptions that go into this result (e.g., the marble that exits is the same marble that entered; marbles bounce off solid objects; the angle of reflection equals the angle of incidence).

2. **If I'm only shooting marbles from one side of the pie plate, which mystery objects would look the same?** Discuss that some solutions are not unique—it's difficult and sometimes impossible to discern a triangle from a circle if you're just probing it from one direction. Experiments have limitations in what we can deduce from them.

3. **How is this similar to Rutherford's gold foil experiment?** The marbles are analogous to alpha particles; the unseen space under the pie plate is analogous to the gold foil (or a cross-section of it); and the mystery object is the nucleus.

The fact that the alpha particles ricocheted off something indicated that there was something large and dense in the atom (i.e., the nucleus).

4. **What other kinds of phenomena are not directly observable and thus need special equipment to measure?** Some examples include electric and magnetic fields, changes over time, and many astronomical observations.

5. **How do you imagine that *Measurement & Observation* relates to other topics covered in *Physics for the 21st Century,* or to other topics you've taught?** For example, particle physics (the subject of Unit 1), astronomy (the subject of Units 10 and 11), or other areas where the type of knowledge in a field is strongly related to the measurement techniques available.

6. **How can you use this activity in your classroom?** For example, students may not use the term "infer." This would be a good activity to help them expand their science vocabulary. Inform participants that lab sheets and related activities can be downloaded from the activity website, at http://education.jlab.org/beamsactivity/6thgrade/shapeofthings/index.html.

Take-home message: We cannot always trust our direct perception and must confirm our observations via measurement. In addition, we cannot directly perceive many of the phenomena studied in physics. Therefore, much, if not all, scientific evidence relies on indirect measurement with sophisticated tools. A variety of tools allow scientists to probe aspects of the natural world that are beyond our human capacity to perceive. We will use the following icon to signal when *Measurement & Observation* is a key theme of a particular unit in this course.

Activity 3: How Do We Know? Evidence

Time: 20 Minutes.

Purpose: To explore the idea of evidence, or "How do we know what we know?" through a series of clicker questions. Since this is the first clicker question of the course, explain to participants the concept of peer discussion, as described in *Hints for Facilitators and Independent Learners (page 13).*

Materials:

- "What Can We Learn from a Tooth?" http://www.exploratorium.edu/webcasts/explotv_player.php?id=00001107&type=flv

- Optional: "Why Did the Neanderthals Disappear?" http://www.exploratorium.edu/webcasts/explotv_player.php?id=00001084&type=flv

To Do and To Notice

Clicker/Discussion Questions: How do we know that something exists? [6]

1. **Do you think we can be reasonably certain of the existence of something we can't see? Is that scientific?**

   A. Yes, we can have evidence even if we can't see it.
   B. If we never see it, we can't be sure.

2. **Have you ever seen an atom?**

   A. Yes
   B. No

3. **How sure are you that atoms exist?**

   A. Not very sure
   B. Somewhat sure
   C. Very sure
   D. Certain

Watch the video on "What Can We Learn from a Tooth?" from the Exploratorium's Evidence project[7] (2 minutes). What types of claims could be supported by evidence from teeth? You may also wish to show "Why Did the Neanderthals Disappear?" (2 minutes) to demonstrate the types of theories generated by anthropologists.

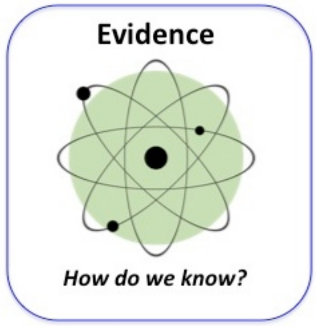
Discuss the answers to the clicker questions and reactions to the video as a group, focusing on *Evidence.* How do you imagine that *Evidence* relates to other topics covered in *Physics for the 21st Century,* or to other topics you've taught?

What's Going On?

In order to assess any scientific claim, it's important to ask, "How do you know?" Much evidence comes from observation and measurement, and takes the form of numbers. How these numbers were collected (e.g., the number of measurements and the experimental conditions) is an important part of evaluating evidence. Many claims rely on rather meager evidence, such as certain theories about the nature of early species that rely on a single fossil. Others, such as the existence of the atom, rely on multiple lines of evidence and many different kinds of measurements. In this course, for example, multiple lines of evidence point toward the existence of atoms and quarks (Unit 1), the quantum nature of matter and light (Unit 5), or dark matter and energy (Units 10 and 11).

[6] Questions developed by Dr. Douglas Duncan at the University of Colorado at Boulder.
[7] See all videos from the Exploratorium's website Evidence here: http://tinyurl.com/yze6plx and the full Evidence site at http://www.exploratorium.edu/evidence/.

Take-home message: Evidence consists of data and its interpretation. More compelling evidence rests on well-founded assumptions, accurate data, and good sampling techniques. A good skeptic should be in the habit of asking, "How do we know?" We will use the following icon to signal when *Evidence* is a key theme of a particular unit in this course.



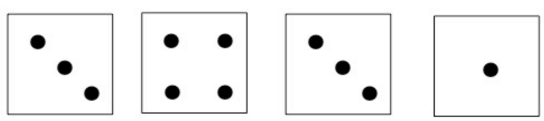
Activity 4: The Farmer and the Seeds—Models

Time: 30 Minutes.

Purpose[8]: To create models of how different types of seeds sprout in order to recognize that models are based on observations, new observations can throw doubt on existing models, and one can never have final proof that a model is correct.

To Do and To Notice

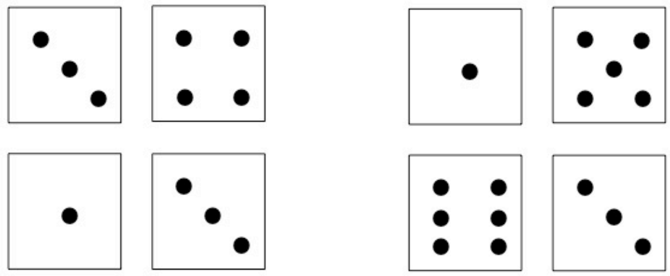
A farmer has some strange seeds. Each seed is a square with dots on it, as shown below (images available in the online resource: *Facilitator's Guide High Resolution Graphics*).



Four different kinds of seeds

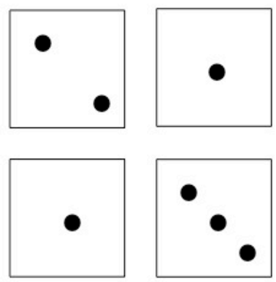
He wants to know how many sprouts he will get, depending on what seeds he sows. On two of his plots, he sows the seeds as shown below, getting four and six sprouts in each, respectively. Tell participants, "On your own, come up with a scheme that would predict how many sprouts are generated depending on the dot patterns showing on the seeds." After they have generated their own ideas, ask them to share their scheme with one or two people sitting near them. They don't have to reach consensus.

[8] Credit: D. Dykstra, *Piaget Beyond "Piaget" Workshop*, Dewey Dykstra, Boise, ID (2009). See that text for an alternative example exploring an anthropologist's examination of markings made by an ancient culture (attributed to Andy Johnson).



Group 1: 4 sprouts **Group 2:** 6 sprouts

Now, the farmer plants another plot of seeds and gets the following result:



Group 3: ______

Ask participants, "What prediction does your scheme give for this seed grouping?" Once they've made their predictions, tell them that it yields seven sprouts**.** Does this change their model?

Facilitate a discussion.

1. Where did each of our schemes come from?
2. How should we use the results of the comparison between predictions and the results from the third seed planting?
3. If we have found a scheme that has worked for several different seed plots so far, how do we know that it will work on the next one?
4. How do we know if we have figured out all the possible schemes? How do we know that our scheme is really the answer?
5. Why does this activity matter?
6. How do you imagine that *Models* relates to other topics covered in *Physics for the 21st Century,* or to other topics you've taught?
7. How do we teach that scientific models are not reflections of reality, yet give students the sense that science is trustworthy since it's very predictive?

What's Going On?

Scientists make up theories to explain the data that they see. As learners, we also construct our own understanding. We can't always look inside a seed (or atom) to see how it works, so we use observations (both direct and indirect) as evidence for our models, theories, and hypotheses. In this way, scientific models are human constructions used to form an account of nature based on the result of evidence and observations. Models are judged, in part, by their power to predict the outcome of experimentation. Even though we can't know the absolute "truth," we can create models that have fantastic powers to explain and predict.

1. **Where did each of our schemes come from?** We made decisions about what elements of observations to use and how to use them. They came from us—they were not “out there” waiting to be discovered (as many students think about scientific “facts”).

2. **How should we use the results** of the comparison between predictions and the results from the third seed planting? We should modify our model.

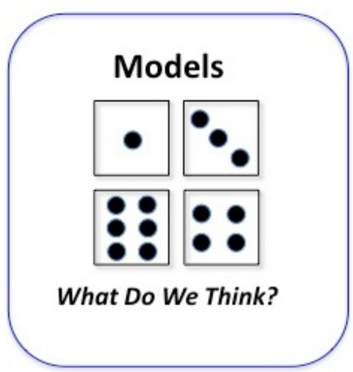
3. **If we have found a scheme that has worked** for several different seed plots so far, how do we know that it will work on the next one? Answer: We don’t!

4. **How do we know if we have figured out all the possible schemes?** How do we know that our scheme is really the answer? Answer: We don’t!

5. **Why does this activity matter?** It can be a useful way for students to understand the nature of scientific models and questions. Note the similarity between this and the previous clicker questions on the atom. The existence of the atom, and its structure, is a model, but one which has good evidence. This also has deep implications for how our students learn, and how we will learn in this course—we cannot teach a set of facts, but we can help students make sense of ideas by constructing their own mental models and explanations.

6. **How do you imagine that *Models* relates to other topics covered in this course, *Physics for the 21st Century,* or to other topics you’ve taught?** Most of our ideas in physics are models, even if we don’t realize it, such as the model of the atom (which has changed over the centuries). Particle physics (Unit 1) and quantum theory (Unit 5) shed light on our model of the atom, while gravity (Unit 3) and string theory (Unit 4) discuss our models of spacetime itself.

<u>Take-home message</u>: Models are human constructions, rather than an accurate picture of nature. Because models can have predictive power, they are useful in creating explanations of the natural world. We will use the following icon to signal when *Models* are a key theme of a particular unit in this course.



Activity 5: Turning Gears—Logic & Implications

Time: 10 Minutes.

Purpose: To examine a chain of gears in order to talk about the analogy that one idea leads to implications in a logical chain. These ideas can then be extended to talk about scientific models using a parabolic reflector.

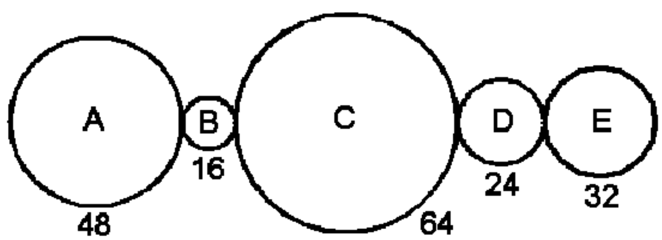
Materials:
- Mirage toy[9] (optional)

To Do and To Notice

Clicker/Discussion Question: Turning of Gears.[10]

Given five gears, each with a different number of teeth, as shown below: **If Gear A is turned 10 times clockwise, how many times does Gear E turn, and in what direction?**

A. 15 turns counterclockwise
B. 10 turns counterclockwise
C. 15 turns clockwise
D. 10 turns clockwise
E. Something else



Discuss the question as a class. How does this relate to science in general, and to topics and ideas in physics and this course in particular?

Sometimes, new theories lead to predictions that, though surprising, are true. Can you think of some? New theories sometimes lead to predictions that cause scientists to throw out the theories. Can you think of any theories like these?

What's Going On?

The best answer is (C). Ten clockwise turns of Gear A causes every subsequent gear to ratchet through 480 teeth; 480 divided by 32 is 15. Odd gears turn clockwise, and even gears turn counter-clockwise; so Gear E turns clockwise.

When the gears turn, we assume that the gears follow certain simple rules, like the teeth don't slip, and it rotates through all teeth in a full turn. These assumptions, and logical arguments, can tell us how Gear E behaves in response. This is an analogy for the roles

[9] For example, http://www.arborsci.com/detail.aspx?ID=210.
[10] Question and image courtesy of E.F. Redish and D. Hammer, *Am. J. Phys.*, 77, 629-642 (2009).

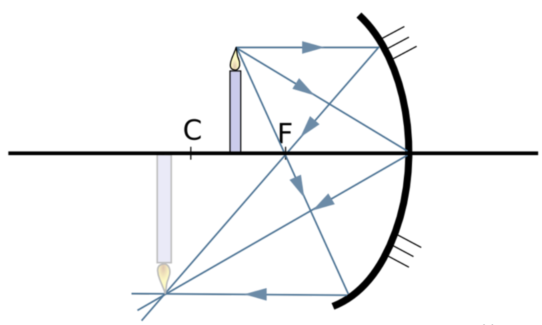
that logic and implications play in the scientific enterprise. Given certain ideas (such as, the world is made of atoms), what are its implications? Can we accept those implications? Einstein's theory of relativity, for example (Unit 3*),* led to the prediction that light would bend around an object—a surprising prediction, which turned out to be true. Quantum theory (Unit 5) predicted that matter acts like waves, creating interference patterns, which also turned out to be true.

Going Further

Ask participants to help you create a list of the principles of light that relate to how we see an object, such as "some objects give off light" or "light scatters in all directions when it hits an object." Below is an example of such a list:

- Light travels in straight lines through empty space.
- Light bounces off smooth surfaces at an angle of reflection equal to an angle of incidence.
- We only see something when light coming directly from it enters our eyes.
- Our eyes identify a point as being on an object when rays traced back converge at that point.

Use these principles to come up with a prediction of what will happen when an object is placed near a spherical mirror. Below is a ray diagram that participants may draw.



An image formed by a spherical mirror[11]
(Available in the online resource: *Facilitator's Guide High Resolution Graphics)*

Using the Mirage toy, demonstrate that this indeed is what happens. We see a surprising result—an image that appears to float in midair. The implications of our assumptions and our model lead to predictions, which can be verified experimentally. Discuss in terms of the ideas of logic and implications.

<u>Take-home message</u>: Following the implications of our ideas and assumptions is an important part of science. When scientists have a new idea or theory, they look to see what its implications are. Sometimes, these implications cause them to reject the theory, or sometimes they predict new phenomena. We will use the following icon to signal when *Logic & Implications* is a key theme of a particular unit in this course.

[11] Concave mirror producing image when the object is between the curvature's center and the focus. Source © Wikimedia Commons, License: CC ShareAlike 3.0. Author: Marcelo Reis, 27 November 2004. http://commons.wikimedia.org/wiki/File:Concavo_3.png.

Activity 6: Rules of the Game— Coherence & Consistency

Time: 10 Minutes.

Purpose: To discuss and explore how physical theories must be consistent across the discipline as a whole.

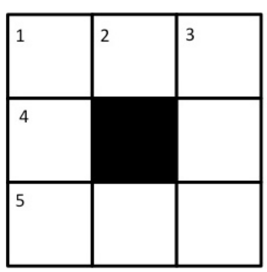
Materials:

- Image of puzzle and solution from online resource: *Facilitator's Guide High Resolution Graphics*

To Do and To Notice

Ask participants to complete the following crossword puzzle in pairs. Ask them to consider these questions:

1. Are you sure of your answers? Are there any answers you're unsure of? Why?
2. Can anyone find a second solution to the puzzle?
3. What if the clue for 3-Down was "Tit for ___"?
4. How does this relate to physics topics you've taught?

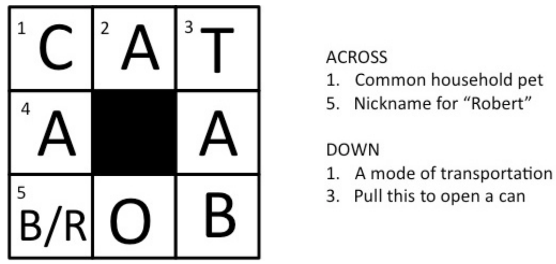


ACROSS
1. Common household pet
5. Nickname for "Robert"

DOWN
1. A mode of transportation
3. Pull this to open a can

What's Going On?

Here is the completed puzzle:



There are some ambiguities in the puzzle, which may or may not be resolved by consistency with the rest of the puzzle:

- **1-Across** could be CAT or DOG. Consistency with 1-Down and 3-Down requires that it be CAT.
- **5-Across** could be BOB or ROB. Either answer is consistent with 1-Across.
- **1-Down** could be CAB or CAR. Because 5-Across could begin with "R" or "B," the data ends up being insufficient to distinguish between these two possibilities.
- **3-Down** should be TAB from the clue. What if the clue were "Tit for ___"? This would be incompatible with the evidence from other clues, suggesting that one of the clues is wrong, analogous to incorrect measurements in science.

As in all games, this crossword puzzle has a set of rules. The clues are used to solve the puzzle, but some of the clues lead to ambiguous answers. Those ambiguities are resolved by requiring the letters of one word to be consistent with the overlapping letters from other words. When the letters of one word aren't consistent with the rest of the puzzle, this leads to frustration. Similarly, in science there may be multiple theories that are consistent with the data, leading scientists to seek more clues. Because physics is a well-established science, it has a high degree of consistency. Students, however, often see physics as a set of independent facts and formulas—or disconnected words that are not part of a larger puzzle. Many students will make ad-hoc guesses as explanations for new phenomena, rather than using larger principles and ideas that are accepted by the physics community to make meaning of the new observation.

<u>Take-home message</u>: Science seeks consistency in its theories, in order for the principles to be as broad as possible. Physicists come to accept ideas and findings as true because they hold together with other ideas and findings as a coherent framework. We will use the following icon to signal when *Coherence & Consistency* is a key theme of a particular unit in this course.

Back to the Classroom

Time: 30 Minutes.

Purpose: To explore the *National Science Digital Library Science Literacy Maps* as a tool for investigating science standards and benchmarks, and discover how participants might use them in their own teaching.

Materials:

- A computer with Internet access for each group of two to three participants

To Do and To Notice

Ask participants to navigate to http://strandmaps.nsdl.org. Give them the following tasks in small groups, and then facilitate a large group discussion about what they find.

1. Explore the Science Literacy Map to find the concept related to the basic structure of the atom.
2. What concepts are connected to this topic? What do students need to know to understand this concept, and what does knowledge of this topic allow them to understand?
3. What else can you find out from the Science Literacy Map?
4. How might you use this information to help teach the nature of the atom, in conjunction with the *Shape of Things* activity? (*Note:* Make sure that participants discuss how to use students' prior knowledge about the topic in teaching that topic.)
5. Explore the Science Literacy Map to find the nature of science concept that discusses how predictions are compared to observations to test a scientific model. What other topics are connected to this concept?
6. How would you use this information to help teach the nature of science, in conjunction with the *Shape of Things* or *The Farmer and the Seeds* activities?

What's Going On?

The Science Literacy Maps are a rich area for exploration of scientific concepts and how they relate to one another, and to find classroom resources for addressing these topics.

To find the science content on the basic structure of the atom, they must navigate to "The Physical Setting" > "Atoms and Molecules" and locate the concept "Atoms are made of a positive nucleus surrounded by negative electrons." Participants should notice the arrows leading toward and from that concept, and that vertical height is related to higher-level concepts. Clicking on the concept will bring up related benchmarks, standards, and resources. Clicking on "Show Student Misconceptions" will show a related list of misconceptions.

Classroom Resources

"The Shape of Things" classroom activity from the Thomas Jefferson National Accelerator Facility Office of Science Education.
http://education.jlab.org/beamsactivity/6thgrade/shapeofthings/overview.html.

"The Rutherford roller" classroom activity from the Exploratorium's Eric Muller. A variation on "The Shape of Things." http://www.exo.net/~emuller/activities/index.html.

"The ghost particle" classroom activity from PBS's *The Elegant Universe* allows students to make inferences about an object they can't see. http://www.pbs.org/wgbh/nova/teachers/activities/3306_neutrino.html.

Educational activities on perception at the Exploratorium's fabulous Snack Page http://www.exploratorium.edu/snacks/iconperception.html and a day's worth of activities on perception as it relates to the question of "What is Science?" at http://www.exo.net/~pauld/summer_institute/summer_day1perception/day1_perception.html.

Evidence: How Do We Know What We Know? An interactive and thought-provoking website on evidence and the nature of science from the Exploratorium, including a case study in human origins, a visual diagram of the scientific process, and the ability to map your own beliefs.
http://www.exploratorium.edu/evidence/.

Black Box Activity. An excellent alternative to the *Farmer and the Seeds* activity that demonstrates the nature of models and their explanatory power. Contained in a teacher's guide from the Perimeter Institute.
http://www.perimeterinstitute.ca/Perimeter_Explorations/Quantum_Reality/The_Challenge_of_Quantum_Reality/.

Science for All Americans by the AAAS Project 2061. Readable and lucid recommendations on what constitutes scientific literacy, including the nature of science themes. Online at http://www.project2061.org/publications/sfaa/online/sfaatoc.htm.

The Science Media Group Digital Library has videos on a variety of topics, including the scientific method and nature of science. This video library may be searched by Strand Map, Benchmarks, and other criteria. http://www.hsdvl.org/. See for example:

- A Private Universe (20 minutes) http://www.learner.org/resources/series28.html
- A Private Universe Project in Science, Program 3: Physics: Hands-On/Minds-On Learning (90 minutes) http://www.learner.org/resources/series29.html
- Minds of Our Own, Program 1: Can We Believe Our Eyes? (60 minutes) http://www.learner.org/resources/series26.html
- The Science of Teaching Science, Program 2: Eliciting Students' Prior Knowledge (90 minutes) http://www.learner.org/resources/series90.html

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.

Divide participants into four groups for a jigsaw activity during the next session. The participants in each group have the responsibility of becoming "experts" on one of the fundamental forces—gravity, electricity and magnetism, the weak force, or the strong force. They will work together as a group to determine the fundamental aspects of their force, and teach the class about that force.

PARTICIPANTS

Text: If you haven't already done so, read the *Introduction to the Online Text*. Also read Unit 1: *The Basic Building Blocks of Matter*.

While reading Unit 1, you may choose to organize your reading by using the following table and bring it in to class, prepared to discuss. You will not necessarily have entries for all cells of the table—simply use this as a tool to organize your understanding of the topics presented in the chapter. In the next session, you will use this table to help create a concept map of the relationships between the different ideas in the chapter. *(Optional:* You may create a concept map as you read the chapter, instead of using the table.)

Particle family	**What does the name mean?**	**What particles are included in this family?**	**What are these particles made of (or are they irreducible)?**	**Other notes**
Leptons				
Mesons				
Baryons				
Quarks				

Be sure that you include the following particles somewhere on your table: proton, neutron, electron, and neutrino. Does the Higgs boson belong on this table? Why or why not?

Consider the following questions:

1. Where could antimatter belong on your table?
2. Some of these particles were difficult to observe. Describe what you understand the difficulties were.
3. Some particles were impossible to observe. What evidence appears to support their existence?

Video: Watch the video for Unit 1: *The Basic Building Blocks of Matter.* While you watch, consider the following focus questions. You may wish to make some notes to bring to the class discussion.

1. *Why do we care?* What would discovery of each of the particles discussed in the video (the Higgs boson and the neutrino) tell us about the universe? Why are they important?
2. *What is our approach?* Why is it difficult to detect the Higgs boson? The neutrino?
3. *How do we know?* What evidence would let researchers know if they have produced the Higgs boson? The neutrino?

Interactive Lab: You may wish to explore the interactive lab associated with this unit: *Discovering Neutrino Oscillation.* Explore how the basic properties of neutrinos affect their oscillations, and design an experiment to learn more about the quantum behavior of this elusive particle.

Unit 1

The Basic Building Blocks of Matter

Introduction

Just because things get a little dingy at the subatomic level
doesn't mean all bets are off.
– Murray Gell-Mann, Physicist. Received the Nobel Prize in
Physics, 1969, for work on the theory of elementary particles.

The first unit of *Physics for the 21st Century* explores the most basic constituents of the material universe. Over the last century our understanding of the fundamental building blocks of the universe has become more complete. Atoms, already unimaginably small, are built of even more minute particles—electrons, neutrons, and protons. Neutrons and protons are comprised of *quarks*. *Neutrinos* move like ghosts, passing through the material substance of the world. The construction of new, ever-larger particle accelerators has allowed us to probe the structure of matter and the universe, providing evidence for a dizzying "particle zoo" that had been previously invisible to us. A relatively new theoretical framework—the *Standard Model*—has been successful in making predictions that were later confirmed by experiment. Yet these experiments have raised additional questions about the building blocks of matter, which researchers are trying to answer.

What Will Participants Learn?

Participants will be able to:

1. State the fundamental building blocks of matter (i.e., quarks and *leptons*) and contrast them with the particles that were historically considered fundamental, and are the focus of science standards and benchmarks (i.e., electrons, neutrons, and protons).
2. Organize these particles by their basic properties and recognize the organizational framework inherent in the Standard Model.
3. Explain how conservation laws (particularly energy and charge) relate to the mass/energy of particles generated from particle collisions and the reason that more energetic accelerators are needed to produce more massive particles.
4. Describe how indirect measurement can provide evidence for the existence of subatomic particles, such as the *Higgs boson* or neutrinos.

What's in this Unit?

Text: Unit 1: *The Basic Building Blocks of Matter* provides a historical overview of particle physics, from the discovery of electrons and the nucleus, to the use of particle accelerators to uncover more subatomic particles. The kinetic energy from the remarkably high-speed collisions in particle accelerators produces new matter, consistent with energy-mass equivalence and the conservation of energy and momentum. Thus, more energetic particle accelerators have allowed scientists to investigate a wider variety of particles and anti-particles. Quarks were theoretically predicted and indirectly detected, both from scattering experiments and the decay products of signature particles. The organization of these particles into the Standard Model provided some structure to the particle zoo. At the same time, this research has suggested new questions in need of exploration (such as neutrino mass, *antimatter* and *CP-violation*, and mass and the Higgs boson), questions which remain to be answered.

Video: This program gives us a glimpse at two research teams' attempts to detect two different kinds of elusive subatomic particles and the evidence that would confirm their theoretical predictions. Both experiments would give physicists further insight into the building blocks of matter. First, Professor Mark Kruse of Duke University describes experiments to create and detect the Higgs boson at Fermilab. Hypothesized to be a very heavy particle, highly energetic collisions would be required to produce the Higgs. The Higgs is an important particle, because it could be the means by which matter gains mass. Since the Higgs would be very short-lived, it would not be detected directly, but rather inferred by the detection of the particles into which the Higgs would decay. Similarly, Professor Bonnie Fleming and her team at Fermilab are looking at a particle that is difficult to detect—very light particles called neutrinos. Previously assumed to be massless, new evidence suggests that neutrinos do have mass, and this team's investigations into how neutrinos change from one type to another (*neutrino oscillations*) will help determine whether they do have mass. Neutrinos are abundant, but don't interact much with the material world. Dr. Fleming creates neutrinos in particle collisions that are detected—as with the Higgs—indirectly. In the case of neutrinos, experimenters are looking for particles that have resulted from interactions of neutrinos with matter.

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

Activities:

- The Hook: Our World as an Atom (10 minutes)
- Activity 1: Revisiting "The Shape of Things" - Particle Accelerators (20 minutes)
- Activity 2: The Particle Zoo (30 minutes)
- Activity 3: Quark Math (20 minutes)
- Activity 4: Watch and Discuss the Video (50 minutes)
- Back to the Classroom (20 minutes)

Nature of Science Theme: *Measurement & Observation*. You may wish to display the *Measurement & Observation* icon during the session and remind participants of the central ideas of this theme. We cannot always trust our direct perception and must confirm our observations via measurement. Thus much, if not all, scientific evidence relies on indirect measurement. A variety of tools allow scientists to probe aspects of the natural world that are beyond our human abilities to perceive.

Exploring the Unit

The Hook: Our World as an Atom

Time: 10 minutes.

Purpose: To help participants think about the nature of matter.

Materials:
- Tennis ball
- Computer with internet access

Before the Session: Go to an online mapping service and locate your building on the map. It's best if you can put a thumbtack icon as a placeholder here prior to the session. See examples below.

To Do and To Notice

An atom is made mostly of electrons and neutrons. Ask participants:

- **Where are the electrons relative to the nucleus?**

So, the atom is made mostly of empty space. Hold up the tennis ball, representing the nucleus. Ask participants to walk to where the first electron would be. Discuss, qualitatively, that you can't walk that far away. Tell participants that you're going to explore, as a group, what this means. Consider this building. (*Note*: For best effect, consider a large building.) Ask participants:

- **If our building is 10 meters in radius, how far away is the electron?**

Zoom out on the mapping tool until your view is equivalent to this distance of the electron. (*Note:* One way to do this is to notice the scale when you are zoomed into your building—e.g., 20 meters—and zoom until the scale is four orders of magnitude larger than that—e.g., 20×10^4 meters or 200 kilometers. In the case shown below, at the University of Colorado, this takes us into the border of Utah. You may consider showing the short Eames' film, "Powers of 10."

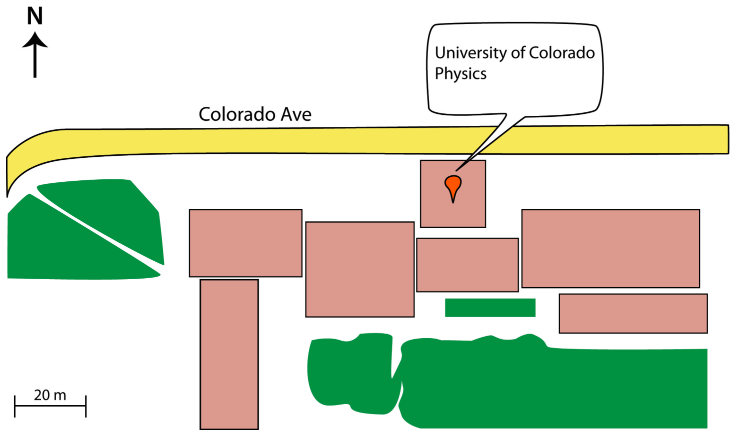
What's Going On?

The electrons in an atom are very far away from the nucleus relative to the size of the nucleus: The radius of an atom is 10,000 times the radius of its nucleus. If the tennis ball is on the order of 10^{-1} meters, then the inner electrons are on the order of 10^3 meters away. Similarly, if the building you're in is 10 meters in radius, then the electron is 10^5 meters, or 62 miles from its center.

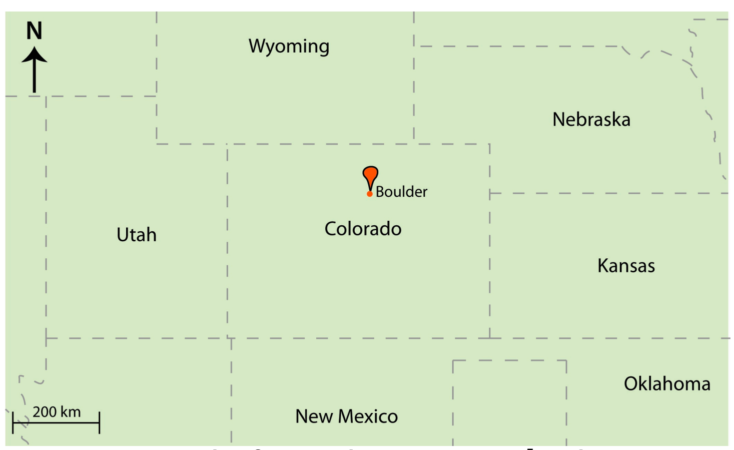
This gives a sense of just how much empty space is in the atom relative to the size of the nucleus, or the building, which is quite small. But there is a lot going on in that small space. In today's session, we'll be discussing the stuff inside the building—which isn't even part of this map at all.

Here are some relevant size and scale figures:

10^{-6} m = human hair
10^{-10} m = large atom (zoomed-out map)
10^{-15} m = proton, neutron (a room in our building)
10^{-9} m = DNA, virus
10^{-14} m = large nucleus (our building)
<< 10^{-15} m = electron, quark (points!)



Example of zoomed-in view at smallest scale
(Both images available in the online resource: *Facilitator's Guide High Resolution Graphics)*



Example of zoomed-out view at 10^5 scale

Activity 1: Revisiting "The Shape of Things" – Particle Accelerators

Time: 20 Minutes.

Purpose: To explore the nature of particle accelerators, recognizing that new particles are created (in accordance with the conservation of energy) rather than simply bouncing existing particles off one another as in the Rutherford experiments.

In the Introductory Unit, participants used an activity entitled "*The Shape of Things*," in which they inferred the shape and location of a mystery object (hidden under a pie plate) by rolling marbles under the platform and observing their resulting path. Here, the activity is revisited to provide a bridge to understanding how particle accelerators work by contrasting them with *elastic scattering* experiments, like the Rutherford experiment.

Materials:
- *The Shape of Things* apparatus from the Introductory Unit

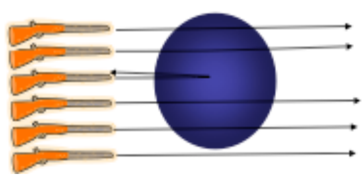
To Do and To Notice

Remind participants of *The Shape of Things* activity by demonstrating the apparatus.

Discussion/Clicker Questions:

1. Imagine that you have a blob of something that looks like grape Jell-O and a gun that shoots rubber bullets. You want to find out what the inside of the blob looks like, so you shoot several bullets into it and see something like the picture below. **What's the inside like?**

   A. Hollow
   B. Solid Jell-O
   C. Hard heavy core surrounded by Jell-O
   D. Bunch of hard objects distributed through blob



2. Elastic scattering describes this kind of process, when one object bounces off another, leaving them both unchanged. **Why can't this kind of elastic scattering be used to find most subatomic particles?**

   A. The "bullets" aren't being fired fast enough
   B. Most subatomic particles aren't there to begin with
   C. The "bullets" aren't small enough
   D. We *do* use elastic scattering to find most subatomic particles
   E. Something else/More than one

CLICKER/DISCUSSION QUESTION

Discuss these clicker questions using the points from *What's Going On?* below. Remind participants of the analogy given in the online text of a particle accelerator being akin to smashing a Swiss watch to see how it works. Ask participants where the Swiss watch analogy fails.

Measurement & Observation: What Do We See?

Group Discussion Questions:
1. How would the picture of the guns and Jell-O change if the bullets represented protons fired at nucleons in a particle accelerator?
2. How would we change *The Shape of Things* to make it a model of a particle accelerator?

3. How does this activity relate to *Measurement & Observation*? How does the idea of indirect measurement relate to activities or ideas you teach in the classroom?

What's Going On?

Answer to Discussion/Clicker Question 1: Best answer is (C). This question is simply a reminder of the Rutherford scattering experiment.

Answer to Discussion/Clicker Question 2: Best answer is (B). Elastic scattering can't be used to find most particles because most subatomic particles don't already exist inside matter (e.g., *z-boson*, *top quark*, and *mesons*); they need to be created from energetic collisions. Many particles (even fundamental particles) are not stable; they only exist under highly specialized conditions. The particles created must obey conservation of energy (including their kinetic energy and rest mass, which is related to energy by $E=mc^2$), conservation of charge (the total charge before and after the collision must be constant), and conservation of momentum.

Answers to Group Discussion Questions:

1. **How would the picture of the guns and Jell-O change if the bullets represented protons fired at nucleons in a particle accelerator?** In inelastic scattering, where new particles are created, such as when protons are fired at neutrons, a spray of new particles would come out rather than the single bullet bouncing back in the direction it came from. This is what is seen in particle accelerator experiments.

2. **How would we change *The Shape of Things* to make it a model of a particle accelerator?** *The Shape of Things* activity would change in a variety of ways if it were a model of a particle accelerator. Here are some examples:
   a. <u>The marble should be very energetic</u>. Instead of simply bouncing off a target, the particles in accelerators are intended to generate energetic collisions that destroy the original particle.
   b. <u>The mystery object (and/or the marbles) should be changed by the collision</u>. Some participants may say that the "mystery object" should be something that could break apart and release particles from inside (e.g., a glass ball that releases beads when smashed). This represents a misunderstanding of how most particle accelerators work. The kinetic energy of the collision produces new matter (rather than releasing particles that were already present inside the original).
   c. <u>The mystery object should be moving</u>. Most accelerators smash two moving particles into each other, though this is by no means universal. Some smash particles into a stationary target. This is not an important point.
   d. <u>The detectors become very complicated</u>. Instead of using our eyes to detect the direction of the marble, particle accelerators use instruments to track the momentum, energy, and trajectory of the final particles.

3. **How does this activity relate to *Measurement & Observation*?** This activity relates to *Measurement & Observation* in that the particles can't be directly detected—they're inferred through a series of indirect measurements.

Activity 2: The Particle Zoo

Time: 30 Minutes.

Purpose: To make some sense of the particles described in the text.

Materials:
- Handout of example concept map from online resource: *Facilitator's Guide High Resolution Graphics* (optional)
- Physical cutouts of words for concept map (optional)

Before the Session: You may wish to make physical cutouts of the words for the concept maps (you may use the example concept map on the next page) that participants may maneuver on the table.

To Do and To Notice

Ask participants to share their completed table, from the homework, in groups of three. Then as a group, complete the table on the blackboard. The final version could look like the table below.[1]

Next, have participants take the key words from this table, and (in groups of 2-3) make concept maps of these topics. A concept map is made of key words connected by arrows and phrases describing their relationship. You may share the example concept map (below) with participants after they have created their own. Discuss the relationships of the atomic particles (electrons, neutrons, protons) to other particles and the indivisible or fundamental nature of quarks and leptons. Participants may put a star or other symbol on the fundamental particles on the concept map.

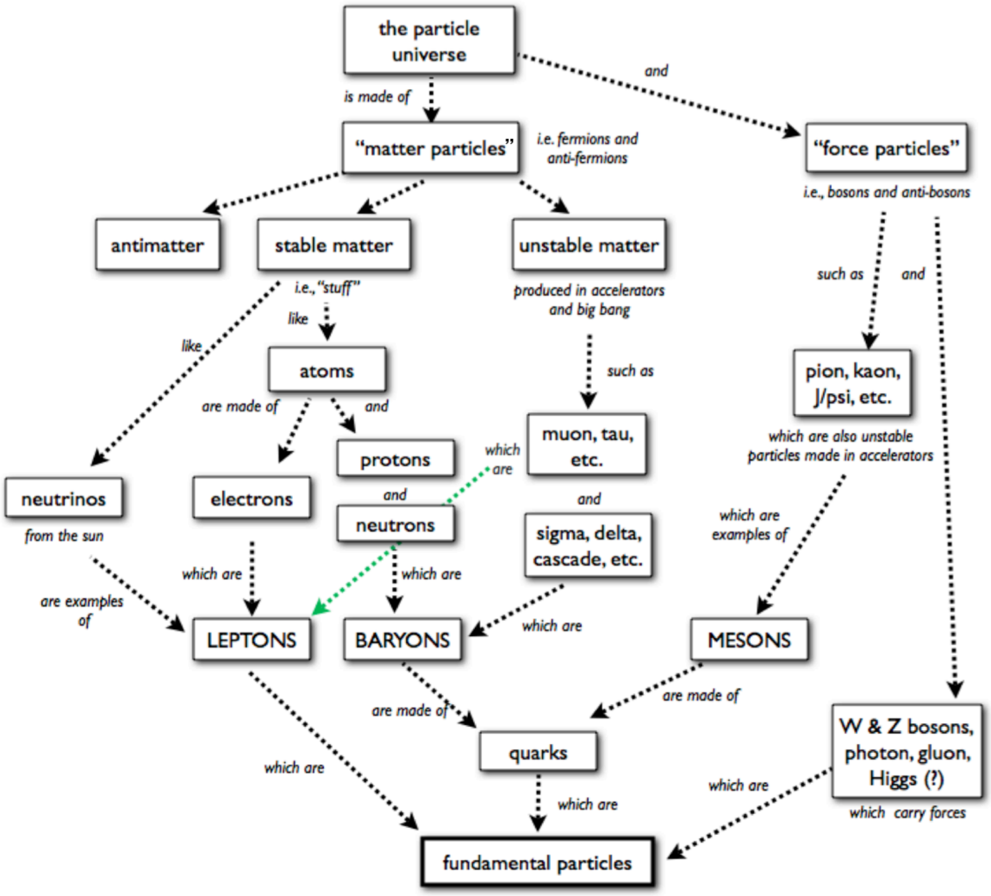
At the end of the activity, have participants make a clean copy of their group's concept map (or their own concept map, based on class discussions). This personal copy of their concept map will be used several times in later sessions.

What's Going On?

Example table:

Particle family	**What does the name mean?**	**What particles are included in this family?**	**What are these particles made of (or are they irreducible)?**	**Other notes**
Leptons	Light	Electron, muon, and tau neutrinos (3 types)	Irreducible (we think!)	Along with quarks, are fermions and fundamental building blocks of matter
Mesons	Medium	Pion, kaon, J/Psi, upsilon, etc.	Quark and anti-quark pairs	These are examples of bosons (but not fundamental particles)
Baryons	Heavy	Proton, neutron, sigma, cascade, delta, etc.	Three quarks	Along with leptons and quarks, are fermions (but not fundamental building blocks of matter
Quarks	Whimsical origins	Up, down, top, bottom, charm, and strange	Irreducible (we think!)	Along with electrons, are fermions and fundamental building blocks of matter

[1] The table does not include *fermions*, as they are not treated in the text. Leptons and *baryons* are types of fermions—particles with half-integer spin. Fermions contrast with *bosons,* which have integer spin, and thus very different properties.



Example Concept Map
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

Electrons and quarks are fundamental, irreducible particles (as far as we know), whereas in the past the electron, proton, and neutron were thought to be the fundamental particles. Fermions (leptons and quarks) are the fundamental building blocks of matter. Bosons are the force particles, but this is the topic of Unit 2: *The Fundamental Interactions.* Mesons are examples of bosons. Heavier particles are called "exotic" because they are too heavy to be stable, and are only seen in particle accelerators and other extreme conditions (like the early universe). Such exotic particles are mesons and baryons (but not all baryons are exotic; protons and neutrons are both baryons).

<u>The take-home message</u>: It's called the particle zoo for a reason—this wide array of particles can be understood by what they are made of (e.g., their fundamental constituents) or what they make (e.g., stable matter, unstable matter, or forces).

Activity 3: Quark Math

<u>Time</u>: 20 Minutes.

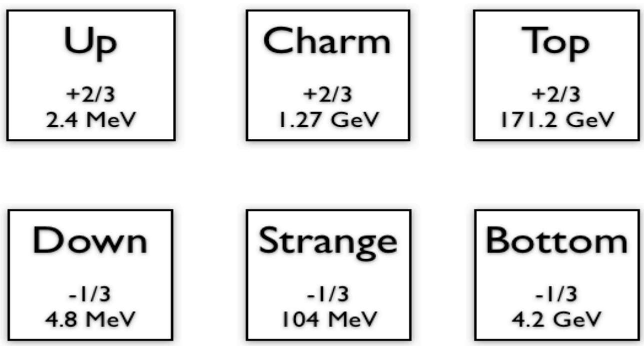
<u>Purpose</u>: To see how quarks combine to make the particles shown on the concept map, as well as how the Standard Model organizes quarks by their properties similarly to how the periodic table organizes the elements.

<u>Materials</u>:

- Quark cards (3 copies for each group of 3-4; copies available in the online resource: *Facilitator's Guide High Resolution Graphics*)

To Do and To Notice

Break participants into small groups and give each group three copies of the cards. The cards represent quarks, their charge, and their mass. Ask them to work as a group to solve problems 1-3 below and record their answers. Tell them to write some notes so they can explain their answers. Discuss as a large group once all have finished the three problems.



Tiles for *Quark Math*
(Available in the online resource: *Facilitator's Guide High Resolution Graphics)*

Problems:

1. Arrange the cards by mass and charge.
2. Find several different ways to make something with charge "+1" using exactly three quarks (which need not be different). The constituent quark masses don't add up to the proton mass—why?
3. Find several different ways to make something with charge "0" using exactly three quarks (which need not be different).

Discuss these questions with participants, as well as the following:

- Why use three quarks instead of two or four?
- How do these results relate to the search and discovery of new particles?
- What does it mean to have a mass measured in units of energy?
- What do you think happens when a proton decays? Does it emit its constituent quarks?

What's Going On?

1. When organizing quarks by mass and charge, participants should arrive at something like the arrangement above, which mirrors the Standard Model. This gives an organizational scheme for quarks as the Periodic Table did for elements.

2. One possibility is two up quarks and one down quark (the proton). The other combinations produce other (heavier) baryons. The 1/3 and 2/3 fractional charges of these particles require that they come in threes to give us particles with integer charge.

3. One possibility is one up quark and two down quarks (a neutron). The other combinations produce other (heavier) baryons.

What does this have to do with the discovery of new particles? Physicists had not seen a particle consisting of three strange quarks. This suggested the existence of a new particle, which was later found (the omega-minus baryon). Just as the existence of gaps in the periodic table had predictive power for the discovery of new elements, the gaps in the standard model had predictive power. The *third generation* of quarks—the top quark and bottom quark—were theoretically predicted due to the observation of a massive particle (the tau), which must be made of heavier constituent particles than previously observed. Thus, this model had *predictive power*.

Masses of particles are represented in units of energy—the more massive a particle, the higher its energy as given by $E=mc^2$. Thus, more massive particles take more energetic particle accelerators to create them. (*Note*: This is a theme in other units in the course.)

When a proton decays, it does not emit its constituent quarks. Quarks cannot exist alone, and the decay products of particle collisions are different from the building blocks of the original particles. However, they must obey the conservation of energy—the masses (and momentum) of the byproducts of decay must add up to the energy and momentum of the parents.

Activity 4: Watch and Discuss the Video

VIDEO

<u>Time</u>: 50 Minutes.

If participants are watching the video in session, have them view it now. Remind them of the focus questions listed in *Between Sessions* from the previous unit and use them to direct discussion:

1. *Why do we care?* What would discovery of each of the particles discussed in the video (the Higgs boson and the neutrino) tell us about the universe? Why are they important?
2. *What is our approach?* Why is it difficult to detect the Higgs? The neutrino?
3. *How do we know?* What evidence would let researchers know if they have produced the Higgs? A neutrino?

Outline the following overarching principles by the end of the discussion:

- **Conservation laws.** Higher energy accelerators are needed to produce more massive particles. The particles created by a collision must be of a lower rest mass than the energy of the collision.

- **Evidence and indirect measurement.** The Higgs is difficult to observe because it is short-lived. Experimenters detect the particles into which the Higgs decays.

- There are a variety of types of evidence that would indicate the presence of a Higgs, all of which are indirect. The neutrino is difficult to observe directly because it passes through most matter undisturbed. They create a *muon neutrino,* which decays to a *muon,* which itself is indirectly detected.

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. Facilitate a discussion with participants:

- **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

Forces and Motion. An unbalanced force acting on an object changes its speed or direction of motion or both.

Energy. The total amount of energy remains constant if no energy is transferred into or out of a system. The creation of new particles (as the aftermath of collisions) and building of particles from constituents (such as quarks) obeys conservation of energy (as well as momentum, and charge). Special relativity states that matter is a form of energy ($E=mc^2$).

Electricity and Magnetism. Moving electrically charged objects produce magnetic forces. Charged particles from accelerators are bent from a straight track by electromagnets, in an example of the *Lorentz force law.*

Atoms and Molecules. Atoms are made of protons, neutrons, and electrons. Atoms have periodic properties that are encoded by the periodic table. Scientists have discovered smaller constituents of matter comprising these atomic particles.

Size and Scale. When describing and comparing very small and very large quantities, express them using powers-of-ten notation. Natural phenomena often involve sizes, durations, and speeds that are extremely small or extremely large. These phenomena may be difficult to appreciate because they involve magnitudes far outside human experience.

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.

Classroom Resources

Fermilabyrinth. Set of games for kids related to Fermilab accelerator, several of which relate to the content in the videos. http://ed.fnal.gov/projects/labyrinth/games/.

The Particle Adventure from Lawrence Berkeley National Laboratory. Interactive website on particle physics, including wall-charts, classroom activities, and explanatory text. http://particleadventure.org/. See particularly, "What is the world made of?" http://particleadventure.org/quarks_leptons.html.

"Particle Puzzle Pieces" classroom activity from PBS's *Elegant Universe.* Students build a proton and a neutron from quarks using quark "recipe rules."
http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_01.html.

"Beyond the 1930's atom" set of classroom activities from The Wright Center for Science Education. A 52-page PDF with a set of activities, student worksheets, quizzes, and other material on the standard model and particle interactions, an activity similar to "Quark Math".
http://www.tufts.edu/as/wright_center/products/lessons/pdf/docs/activities/beyond_atom.pdf.

Inquiring Minds from Fermilab. Includes introductory material about the nature of matter, a timeline of discoveries leading to the Standard Model, and a short video. http://www.fnal.gov/pub/inquiring/matter/index.html.

LHC rap. A fun rap explaining the importance of the Large Hadron Collider. http://www.youtube.com/watch?v=j50ZssEojtM.

Printable particle chart. http://www.cpepweb.org/cpep_sm_large.html and printable nuclear wall chart http://www.lbl.gov/abc/wallchart/index.html.

Hyperphysics concept map of particle physics. http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html.

QuarkNet program (from Fermilab) providing real data for high school classes: http://quarknet.fnal.gov/, plus a list of online resources on particle physics http://quarknet.fnal.gov/biblio.shtml.

Jefferson Lab's education page, with games and activities, http://education.jlab.org/ including a cloud chamber: http://education.jlab.org/frost/cloud_chamber.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 *Particle Physics in the Age of the Large Hadron Collider*. See also the top-rated teacher presentations prepared from that conference here: http://www.kitp.ucsb.edu/news/2008-raab-contest-winners. See also the public lectures by notable scientists on a variety of topics, http://www.kitp.ucsb.edu/talks.

PhET Simulation: Models of the Hydrogen Atom. Run a scattering experiment and see how scientists predicted models of the atoms without being able to see inside. http://phet.colorado.edu/simulations/sims.php?sim=Models_of_the_Hydrogen_Atom.

Quark Cards. A more detailed and sophisticated version of the Quark Math activity. http://www.mariachi.stonybrook.edu/wiki/index.php/Quark_Cards.

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 from *What Will Participants Learn?* of the next unit with participants in preparation for the next session.

Divide participants into four groups for a jigsaw activity during the next session. We recommend using different groups than the jigsaw activity in Unit 1. The participants in each group have the responsibility for becoming experts on one of the fundamental forces—gravity, electricity and magnetism, the weak force, or the strong force. They will work together as a group to determine the fundamental aspects of their force, and teach the class about that force. The table below is available in the online resource, *Facilitator's Guide High Resolution Graphics*, as an optional handout.

PARTICIPANTS

Text: Read Unit 2: *The Fundamental Interactions* for the next session. You have been assigned a particular force to become an "expert" on. Along with the other members of your group, you will present a 5-10 minute mini-lesson to the other participants. Try to think of visual analogies or activities you might include as part of that lesson. Your group's task will also be to present the following table for your force. You may want to complete parts of this table as you read, for your force and others. A few examples have been filled in for clarity. Want to do some additional research? Try looking at *Hyperphysics* at http://hyperphysics.phy-astr.gsu.edu/hbase/HFrame.html.

	Electricity & Magnetism	**Gravity**	**Strong Force**	**Weak Force**
What visible effect does this force have on our world?		Structures, like Earth and solar system		
What particles mediate this force?	Photons			
What property does this force act on?	Electric charge			
Which particles experience this force?			Quarks, nucleons	
Physical range of this force (how far does it extend?)				
Is it attractive or repulsive or both?				
Relative strength				
Other notes				

While you read, consider how you might change your concept map from Unit 1 to include some of the information from this unit. Where do the terms "boson" and "fermion" belong?

Video: Watch the video for Unit 2*.* While watching, consider the following:

- How does the scientific model of nature relate to each researcher's work?
- How does theory affect experiment in these two stories?

Simulation: Download and explore the PhET simulation "Electric Field Hockey" at http://phet.colorado.edu/simulations/sims.php?sim=Electric_Field_Hockey. Try to score a goal. Write a few notes to share during the session. Try to explain this in as many different ways as you can:

- How does the black puck "know" that the red pucks are there?

Make sure to explore what happens when you check the box(es) for "Puck is Positive," "Trace," and/or "Field" and try a few difficulty settings. (*Hint*: "Clear" and "Reset" have two different useful functions).

Unit 2

The Fundamental Interactions

Introduction

> *It is inconceivable, that inanimate brute matter should, without the mediation of something else, which is not material, operate upon and affect other matter without mutual contact... That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance, through a vacuum, without the mediation of anything else... is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it. Gravity must be caused by an agent, acting constantly according to certain laws; but whether this agent be material or immaterial, I have left to the consideration of my readers.*
>
> – Sir Isaac Newton, 1693

If you drop your keys, they fall to earth. But how do the keys "know" that the earth is there? How does an electron "know" that the other one is there? As Newton muses above, what is the mechanism by which things act at a distance? The concept of *fields* has been developed to describe how something can affect another thing without physically touching it, and *field theory* describes how this interaction occurs at quantum scales, via the exchange of *virtual particles*. Among the fundamental forces of nature, however, gravity stands out as a substantial enigma, as will be covered in Unit 3. Additional discoveries about the nature of fields and forces are likely to be made in the future, especially with the experiments at the *Large Hadron Collider (LHC)* that allow scientists to probe particles at energies higher than ever before.

What Will Participants Learn?

Participants will be able to:

1. Describe the mechanism by which two charged objects interact without touching (*action at a distance*).
2. List the four fundamental forces and compare them in terms of key aspects, such as the distances over which they act, the particles they affect, and how those particles are acted on by each force (e.g., *charge*, or *color*).
3. Describe how scientific models provide predictions of what experimental scientists will see, and guide experimental scientists by suggesting promising lines of research.

What's in this Unit?

Text: Unit 2: *The Fundamental Interactions* describes the nature of fields and forces, as well as the four fundamental forces—electricity and magnetism, gravity, the weak force and the strong force. Particles can be distinguished as either matter (*fermions*) or force carriers (*bosons*), which are responsible for the interactions between matter. In field theory, matter particles are described as excitations of fields, and forces are the exchange of virtual particles between matter. Electricity and magnetism behaves differently at tiny distances than at larger distances, and so *quantum electrodynamics (QED)* was developed in order to describe electromagnetism at quantum scales and account for observed measurements. *Quantum chromodynamics (QCD)* describes the interaction of *quarks* through *gluons*, generating the strong force that binds together nuclei. QED and the *weak force* were unified into the *electroweak* interaction, which is compatible with QCD. Only *gravity* remains as an outstanding puzzle—it is not unified with the other three forces, has no quantum theory to explain its effect at microscopic scales, and its force carrier (the hypothesized *graviton*) has yet to be observed. That is the subject of the next unit.

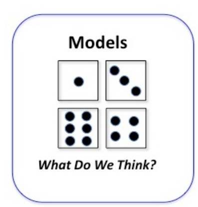
Video: The program for *Unit 2* describes the ATLAS experiment, which measures proton-proton collisions at the Large Hadron Collider (LHC). The high energies of these collisions produce particle interactions never before seen in science, and may provide missing links within the Standard Model as well as evidence for the elusive Higgs boson. Data selection and interpretation at the LHC are very complicated tasks. Srini Rajagopalan is a theorist at Brookhaven National Laboratory working with a group of physicists to generate models that allow them to automatically select the most potentially interesting data from the millions of events that are recorded. Ayana Arce is a physicist at Lawrence Berkeley National Laboratory using simulations to predict what scientists expect to see in this experiment so that it may be compared to the recorded data.

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: Why Don't We Fall Through Our Chair? (10 minutes)
- Activity 1: What Is a Field? What Is a Force? (15 minutes)
- Activity 2: Feynman Theater (20 minutes)
- Activity 3: Force Jigsaw (45 minutes)
- Activity 4: Visual Map of the Forces
- Activity 5: Watch and Discuss the Video (50 minutes)
- Back to the Classroom (10 minutes)

Nature of Science Theme: *Models*. You may wish to display the *Models* icon during the session and remind participants of the central ideas of this theme. Scientists create models, or hypotheses and theories, to make sense of their observations. Thus, a model is a scientific account of nature. A good model is testable and suggests evidence that would support or refute it. When experimental observations do not match the existing model, scientists do and have changed their ideas about nature.



Exploring the Unit

The Hook: Why Don't We Fall Through Our Chair?

<u>Time</u>: 10 Minutes.

<u>Purpose</u>: To identify prior ideas and generate curiosity about the subatomic world.

To Do and To Notice

Facilitate a Think-Pair-Share on the question, "Why don't we fall through our chair?" After participants have discussed for a short time, pose the following clicker question.

Clicker/Discussion Question:

Why don't we fall through our chair?

A. The chair is in the way
B. We're too big to go through the chair
C. We're solid and so is the chair
D. Our electrons interact with the electrons in the chair
E. Something else/More than one

Shortly after the start of the discussion, suggest that participants draw a force diagram, showing that the chair exerts an upward force in order to balance the force of gravity. Probe them, "What kind of force is that?" The "normal force" is accurate, but incomplete. What kind of fundamental force is it?

You may wish to show the animated "Why can't we walk through walls?" at http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/ and discuss as a group.

What's Going On?

The best answer for the clicker question is (D) or (E). We're not simply too big to go through the chair. The atoms of our body and the chair are mostly empty space. Students commonly have the idea that atoms are the smallest piece of a thing, rather than mostly empty space. However, if participants argue that we're too big to *tunnel*[1] quantum-mechanically through the chair, then that is a valid answer. The chair is not just in the way. If gravity exerts a downward force, then the chair must exert an upward force by Newton's second law. What is this force? It's the electrostatic repulsion between our electrons and the electrons of the chair. Answer (C) is also an acceptable partial answer—we're solid. Our atoms interact with each other (as do the atoms of the chair), so that they can't be pushed aside, as would be possible for water or gas.

Neutrinos can pass through walls, and photons can pass through glass, because they don't interact with those materials strongly. An electron on its own can pass through material, but only if it doesn't interact with a nucleon, such as the particles in

[1] *Quantum tunneling* refers to the fact that there is some chance that a particle will tunnel through a barrier due to the probabilistic nature of quantum mechanics.

Rutherford's gold foil experiment. Bound to an atom, however, which is bound to other atoms, electrons simply exert a force against the other electrons in the material.

Explain to participants that the last unit catalogued the different particles that make up the material universe. This unit looks at how those particles interact with each other—the forces between them and how they arise. The interaction of our hand with the wall and our body on the chair is one familiar force (electricity), as is gravity. We'll look at those forces, and less familiar ones, and discuss the mechanisms that make them work.

Activity 1: What Is a Field? What Is a Force?

Time: 15 Minutes.

Purpose: To explore ideas and visuals relating to fields and forces.

Materials:

- "Electric Field Hockey" PhET simulation
http://phet.colorado.edu/simulations/sims.php?sim=Electric_Field_Hockey
(*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.)

Optional Materials:

- PhET "Charges and Fields" simulation
http://phet.colorado.edu/simulations/sims.php?sim=Charges_and_Fields
- Van de Graaff generator
- Mylar balloon
- string

1. Action at a distance

To Do and To Notice

Explain that, of course, things don't have to touch to interact. What types of things interact without touching?

Project the "Electric Field Hockey" PhET simulation on the digital projector. Demonstrate the properties of the simulation yourself, or ask a participant to do so. Leave the "Field" option OFF for now. Explain that this is an aerial view of an air hockey table. The red pucks are fixed once placed. You may wish to start with the simulation in default mode, and move the red pucks to get different effects. Then move to a higher difficulty mode.

- What do the blue lines represent? How can we use these blue lines to answer the question, "How does the black puck 'know' that the red pucks are there?"
- Turn on the "Field" option. Demonstrate how the field responds to the movement and addition of red pucks. Attempt to hit a goal with the simulation in difficulty mode "2".
- What do the field lines represent?
- How are the field lines different from/similar to the force vectors?
- Does the black puck affect the existence of the field lines?
- So, how does the black puck know that the red pucks are there?

What ideas do participants have about how they might use this PhET simulation in their classroom? Brainstorm briefly and write more ideas on the board. Show participants the

PhET website and point out the "Teaching Ideas" listed at the bottom of the link listed above.

What's Going On?

Many things interact without touching, such as wind, electricity, and gravity. The PhET simulation allows us to visualize how electricity acts at a distance.

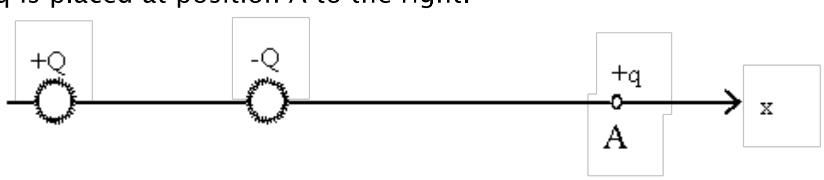
The blue lines are *force vectors*, representing the net force on the black puck from the various red pucks. The *field lines* are a measure of the force that a particle would feel if it were there. They represent the way that an object influences the other objects around it. Both the force and field vectors tell us about how the black puck will move. The field lines permeate all space whereas the force vector only shows us the net effect of the red pucks at the position of the black puck. This field is there even if there's nothing to interact with it, just like we know the earth's gravitational field is there even if we aren't there to feel it. The black puck knows that the red pucks are there because of the presence of this field. Fields explain action at a distance, though we haven't explained how the fields came to exist in the first place.

2. Charges and Fields

To Do and To Notice

Clicker/Discussion Questions: Fields and Forces

Two charges, Q and -Q, are placed along the x-axis as shown. A positive test charge +q is placed at position A to the right.



1. **The test charge feels a force that is**:

   A. Zero
   B. To the right
   C. To the left

2. **If the test charge q is removed, electric field at position A is:**

   A. Zero
   B. To the right
   C. To the left

3. **If a negative test charge is placed at A, it feels a force:**

   A. Zero
   B. To the right
   C. To the left

What's Going On?

Best answers are:

1. (C), to the left
2. the same direction as the force, and
3. (B), to the right, the opposite direction as when a positive test charge was used.

Going Further

Display the PhET "Charges and Fields" simulation. Add charges and select "Show E-field." Watch the electric field change as the charges are moved. Turn off "Show E-field" and use the E-field sensors instead. Since *field = force per unit charge*, these E-field sensors show the force vector that would act on the sensor if the sensor represented a (positive) 1 coulomb charge.

If you have access to a Van de Graaff generator, connect it and charge the Mylar balloon. Show that as you walk around the generator, the balloon string traces out the field lines from the generator. The same may be done with long pieces of tinsel.

Take-home message: Fields are a way of describing how one object influences another without touching it. Fields exist even if there's nothing there to feel them. Later in this session, we'll explore how those fields come to be in the first place.

Activity 2: Feynman Theater

Time: 20 Minutes.

Purpose: Participants will act out the roles of electrons, positrons, and photons to demonstrate the principles of quantum electrodynamics—the quantum theory of electromagnetism that explains the mechanisms by which charged particles interact.

Materials:
- 1-2 tennis balls

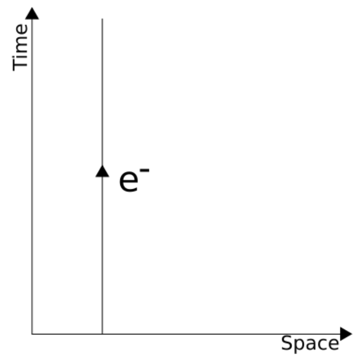
Optional Materials:
- skateboards

1. Feynman Diagrams

To Do and To Notice

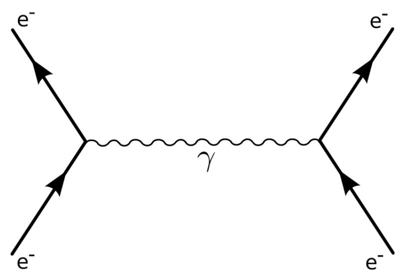
Tell participants that we'll get to gravitational fields in the next session, but now we'll talk about what causes electric fields. Ask participants to share their understanding of this mechanism from the text.

Project or draw the following Feynman diagram without labeling it as a stationary electron. Ask participants, what is going on here? How would you show an electron that was moving through both time and space?



Feynman diagram of a stationary electron

Project the following Feynman diagram showing two electrons interacting by the exchange of a virtual photon. What does the squiggly line represent? How would we label time on this diagram? What do the arrows represent? How is conservation of momentum demonstrated in these graphs?



Interaction of two electrons[2]

What's Going On?

Feynman diagrams represent particle interactions in space and time. Time is the y-direction and space is the x-direction. If something is stationary in space, then its path is vertical. These are called *worldlines* and we'll see them again in Unit 4. If the particle is moving in both space and time, its path is at an angle[3]. (*Note*: These diagrams represent one-dimensional motion in space). The squiggly line represents a virtual photon. A virtual particle is one that exists for such a brief time that we can't really talk about it having a definite velocity or energy. A virtual photon is energy briefly "borrowed" from the energy of the surrounding electric field. The arrows represent momentum, not velocity; Feynman diagrams aren't graphs in the standard sense (i.e., the units of the graph would suggest that the arrows would represent velocity). Thus, conservation of momentum is demonstrated by the vector addition of arrows in the graphs.

[2] Source: © Wikimedia Commons, License: CC ShareAlike 3.0. Author: Papa November, 9 March 2008. http://commons.wikimedia.org/wiki/File:Feynmandiagram.svg.

[3] A 45° angle represents the speed of light on these diagrams. The angle cannot be greater than 45° (i.e., closer to the x-axis than the y-axis). One subtle point about these diagrams: Because quantum particles do not have a well-defined position (they are waves spread out in space), they should not be thought of as small billiard balls moving through space with a definite velocity, as this diagram seems to suggest. Instead, the arrow represents the momentum of a delocalized particle; these diagrams say *nothing* about the position of the particle.

2. Skit

To Do and To Notice

Ask for two volunteers to act out the Feynman diagram showing the interaction of two electrons. You may choose to give them some sort of labels such as “Electron 1” and “Electron 2” with paper or tape. Give them the tennis balls (and skateboards if you have them). Encourage the participants to ask questions and make suggestions. Should the two balls representing electrons be moving or are they stationary? How do they know which way to throw the ball representing the photon?[4] Is the photon thrown once, or multiple times? If one were moving faster than the other, how would the Feynman diagram change? How can we use this to understand why we can’t walk through a wall (but a neutrino can)?

If the group charged with teaching the electricity and magnetism force generated an idea for a similar skit as part of their lesson, you may ask them to present that portion of their lesson here.

Possible discussion questions:

- Are the hockey pucks in the “Electric Field Hockey” simulation exchanging virtual photons?
- So, why can’t we walk through a wall?
- So how do two things interact without touching each other?
- Could two quarks exchange virtual photons? What couldn’t exchange virtual photons?
- How is conservation of mass-energy not violated by the ejection of a virtual photon?
- How are these diagrams related to *Models*?

What’s Going On?

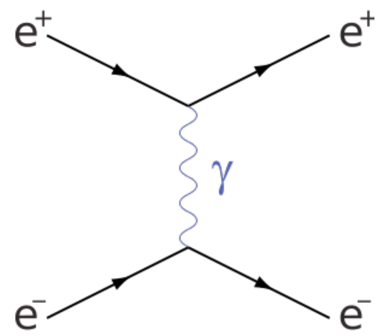
The hockey pucks in the PhET simulation aren’t exchanging virtual particles, unless they’re electrons or protons. The exchange of virtual photons only happens at the quantum level. Instead, the electrons of the hockey pucks are interacting with the field generated by the electrons of the other hockey pucks. We can’t walk through a wall because our electrons are exchanging virtual photons with the electrons of the wall. Things interact without touching each other by exchanging virtual particles across the gap. Thus, we now have a mechanism for understanding action at a distance. Quarks can exchange virtual photons because they’re charged; anything uncharged, like neutrons or neutrinos, can’t exchange virtual particles. That’s why neutrinos can pass through walls. Exchanging virtual photons doesn’t violate conservation of mass or momentum because a photon has zero mass. However, more importantly, a virtual particle doesn’t exist long enough to have a well-defined mass. Feynman diagrams are a visual representation of our mathematical model of particle interactions.

[4] The virtual photon does not really travel from one to the other, and it doesn’t matter which electron emits or absorbs the photon.

3. Going Further: More Complicated Diagrams

To Do and To Notice

You may challenge participants to act out the following Feynman diagram. What is happening? What does a downward pointing arrow represent?



Electron-Positron Scattering[5]

What's Going On?

It may be confusing to consider that a downward arrow indicates backward motion in time. An electron (e^-) moving forward in time, however, is the same as a positron (e^+) moving backward in time. So, you may want to redraw these diagrams with arrows that point in the positive y-direction, indicating forward motion in time. Then this can be understood as annihilation of an electron/positron pair, generating a virtual photon, which in turn generates an electron/positron pair.

Activity 3: Force Jigsaw

Time: 45 Minutes.

Purpose: To learn about the different forces and how they compare to one another.

To Do and To Notice

Ask participants to sit with their group and work together to prepare a 5-10 minute lesson to the class on the force that they were assigned. As part of that preparation, they should complete their column of the table as a small group. They may want to consider creating or showing a Feynman diagram for their particular force and its exchange particle. At the end of the lessons, the class as a whole should have a group version of this table.

Facilitate a discussion among participants regarding the different forces and the similarities and differences between them. Discuss any questions that arise during the mini-lessons and subsequent discussions.

Possible discussion questions:

- What forces hold you together?
- What holds an atom's nucleus together?

[5] Source: © Wikimedia Commons, License: CC ShareAlike 3.0. Author: JabberWok2, 29 November 2007. http://commons.wikimedia.org/wiki/File:Electron-positron-scattering.svg.

- What causes friction?
- Where does the Higgs boson fit into this?

What's Going On?

The forces that hold us together are electricity and magnetism and the strong force. The nucleus is held together by the strong force between quarks in one proton and quarks in another proton. This strong force overcomes the electrostatic repulsion between the protons in the nucleus. Friction is caused by the electric attraction between atoms. The Higgs boson isn't a force carrier in the same sense as the others; but just as electrons interact with the electromagnetic field, particles with mass interact with the Higgs field.

Below is an example of a completed table (copy available in the online resource: *Facilitator's Guide High Resolution Graphics*).

	Electricity & Magnetism	Gravity	Strong Force	Weak Force
What visible effect does this force have on our world? What kinds of objects does it affect?	Atomic and molecular structure; Contact forces	Structures, like earth and solar system	Nuclear structure (or else the nucleus would blow apart from electrostatic repulsion)	Rare beta decay of a neutron into a proton, electron, and an anti-neutrino[6]
What particles mediate this force? *(The boson, or exchange particle)*	Photons	Graviton (not yet observed)	Gluon	Intermediate vector bosons: W+, W-, Z
What property does this force act on?	Electric charge	Mass-energy	Color charge	Weak charge
Which particles experience this force?	All charged particles	All	Quarks	Quarks and leptons
Physical range of this force (how far does it extend?)	Infinite	Infinite	Diameter of a nucleus	0.1% of the diameter of a proton
Is it attractive or repulsive or both?	Either (so can be screened at large distances)	Always attractive (so dominates at large distances)	Attractive	
Relative strength[7]	10^{36}	1	10^{38}	10^{25}
Other notes	Follows inverse square law	Follows inverse square law	Grows stronger at larger distances	Quarks exchanging W or Z boson don't conserve flavor

<u>Take-home message</u>: The four fundamental forces affect objects at different size scales, each acting through different mediating particles. The range of these forces varies greatly, and gravity dominates at large distances because it is always attractive.

[6] Neutrons and protons are made of quarks, so this can also be described as beta decay of quark into lighter quarks.
[7] Depending on the source, participants' values of relative strength may vary from these. Rank ordering is fine. The value depends on the particular particles and definition of "strength." These values are from Wikipedia.com.

Activity 4: Visual Map of the Forces

Purpose: To explore what physical objects are affected by the different forces.

To Do and To Notice

What do these forces affect in the universe? Give participants the following list of words. Ask them to make a drawing, picture, or concept map that links these together appropriately. At what scale (big? small?) are these forces relevant? Discuss as a group.

Earth	Ball	Sun	Molecule
Proton	Neutron	Electron	Quark
Atom	Gluon	Photon	W-boson

What's Going On?

Gravity and electricity and magnetism operate at the largest scales, on objects we're familiar with. The strong force and weak force operate at the smallest, subatomic scales.

Activity 5: Watch and Discuss the Video

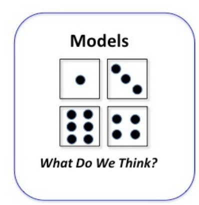
Time: 50 Minutes.

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 does the scientific model of nature relate to each researcher's work?
- How does theory affect experiment in these two stories?

Discuss these questions as a group. Discuss analogies for these researchers' work. How do we do the same thing in our everyday lives?

What's Going On?



Srini Rajagopalan and his team use theory to determine where to look within the data for the most interesting events. Ayana Arce and her team calculate the results that the scientific model should yield, directing scientists in how to compare their data to theory. For example, if we're looking for a good restaurant, we don't start with a systematic search of every city block. Instead, we use models to help us search, such as the theory that more good restaurants are located in Little Italy.

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.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.

Topics and Standards

Forces and Motion. An unbalanced force acting on an object changes its speed, or direction of motion, or both. Any object maintains a constant speed and direction unless an unbalanced outside force acts on it.

Electricity and Magnetism. The nuclear forces that hold the protons and neutrons together in the nucleus of an atom are much stronger than the electric forces between the protons and electrons of the atom. That is why much greater amounts of energy are released from nuclear reactions than from chemical reactions. Electric forces hold solid and liquid materials together and act between objects when they are in contact—as in sticking or sliding friction. Electric forces acting within and between atoms are vastly stronger than the gravitational forces acting between the atoms. At larger scales, gravitational forces accumulate to produce a large and noticeable effect, whereas electric forces tend to cancel.

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

Size and Scale. When describing and comparing very small and very large quantities, express them using powers-of-ten notation. Natural phenomena often involve sizes, durations, and speeds that are extremely small or extremely large. These phenomena may be difficult to appreciate because they involve magnitudes far outside human experience.

Gravity. Gravitational force is an attraction between two masses; the strength of the force is proportional to the masses and weakens rapidly with distance between them. 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.

Nature of Science. A mathematical model uses rules and relationships to describe and predict objects and events in the real world. Mathematical models and computer simulations are used in studying evidence from many sources in order to form a scientific account of the universe. Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models.

Classroom Resources

Concept map of fundamental forces at Hyperphysics http://hyperphysics.phy-astr.gsu.edu/hbase/forces/fforcon.html#c1 and another one at http://en.wikipedia.org/wiki/File:Particle_overview.svg.

What is QCD? An explanatory website, with a small Java applet to demonstrate the attraction of quarks in a proton. http://webphysics.davidson.edu/mjb/qcd.html.

Printable particle and forces wall chart:
http://www.cpepweb.org/cpep_sm_large.html.

The Particle Adventure from Lawrence Berkeley National Laboratory. Interactive website on particle physics, including wall-charts, classroom activities, and explanatory text. http://particleadventure.org/. See particularly, "What holds the world together?" http://particleadventure.org/4interactions.html.

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 can't we walk through walls?"
http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.

"Forces of Nature" Classroom Activities from PBS's *Elegant Universe*. Classroom activities to understand the four fundamental forces.
http://www.pbs.org/wgbh/nova/teachers/activities/3012_elegant_02.html.

"Beyond the 1930's atom" set of classroom activities from The Wright Center for Science Education. A 52-page PDF with a set of activities, student worksheets, quizzes, and other material on the standard model and particle interactions.
http://www.tufts.edu/as/wright_center/products/lessons/pdf/docs/activities/beyond_atom.pdf.

PhET Simulation - Electric Field Hockey. Shows forces and fields on charged "pucks" which players try to shoot into a goal using the properties of electric fields and forces. http://phet.colorado.edu/simulations/sims.php?sim=Electric_Field_Hockey.

Magnetic Oscillators can demonstrate the effects of magnetic fields, creating action at a distance. Below is an example activity from Paul Doherty at the Exploratorium. http://www.exo.net/~pauld/summer_institute/summer_day16magnetism/MagneticOscillators/MagneticOscillators.html.

Feynman Diagrams: The Science of Doodling on the Physics Central website (explore this site for more topics). http://www.physicscentral.com/explore/action/feynman-1.cfm.

Between Sessions

FACILITATOR

You may wish to share the *Classroom Resources* section of the next unit with participants for their homework. *(NOTE:* Unit 3 contains a particularly long set of classroom resources. You may wish to assign each participant to research one or two of the resources and have them report back to the group during *Back to the Classroom.)*

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, and ensure that participants know that they will be expected to present their research during the next session.

PARTICIPANTS

Text: Read *Unit 3: Gravity* for the next session. Pick a topic in the reading that you are particularly curious about, and research one of the following:

- A use of this topic in scientific research or practical or technical applications, or
- A classroom lesson or activity on this topic or related ideas.

Preparatory assignment: In preparation for the next session, please:

1. Plan to give a 1-2 minute presentation on your topic and research during class.
2. Prepare a half-page of notes to guide you during your presentation.
3. Plan to discuss why you chose that topic, and what open questions you have about it.

Video: Watch the video for Unit 3 for the next session. As you watch, consider these discussion questions:

- 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?

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.

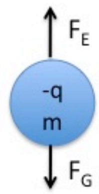
Optional: Taking Einstein's introductory quote literally, calculate the attractive force of two people due to gravity. How does this compare with the gravitational force of the Earth, or an electromagnetic attraction (assuming a 1% difference in charge)?

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

[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.*

<u>Take-home message</u>: 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

<u>Time</u>: 30 Minutes.

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

<u>Materials</u>:

- 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

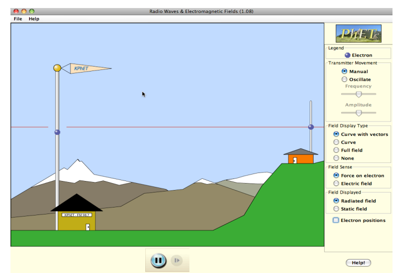
If any participants researched special relativity (specifically, the speed of light) ask them to share their presentation now.

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



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: $F_G = \dfrac{GMm}{r^2}$.

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.

[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

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?

[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*.

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

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

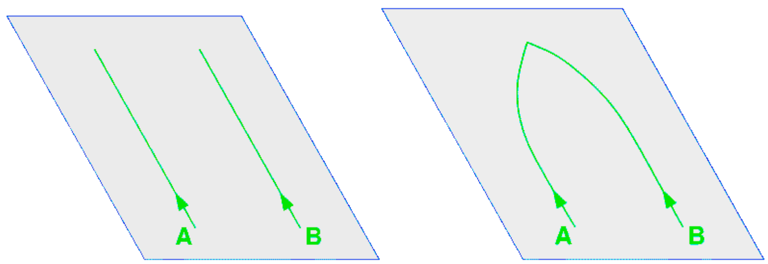
Before the session: Prepare the models. Spandex is available from fabric supply and craft stores. It's best to sew "sleeves" into the edges of the spandex sheet, and slip the dowel into the sleeves. Secure the dowels in a board, as described online at this site[7] so the spandex is stretched taut, but 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.

[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?



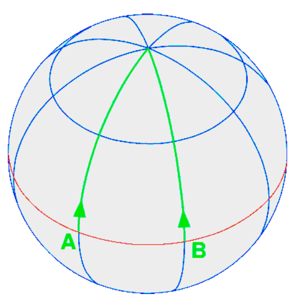
A B

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.

[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.

<u>Take-home message</u>: 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)

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

<u>Materials:</u>

- "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.

[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 $1/1000^{\text{th}}$ 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

[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?

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.

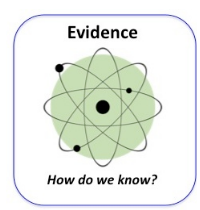
Interactive Lab: *Laser Cooling*. Learn the basics of how to manipulate atoms with light, and cool a hot atomic beam to a few millionths of a degree above absolute zero.

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?

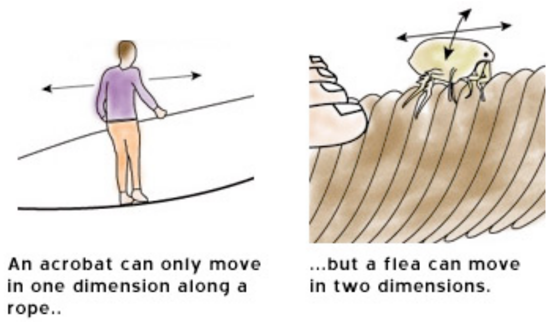
Lay the rope on the ground in a straight line. Ask a participant to walk along the rope. He/she can only move forwards and backwards. Explain that this represents a one-dimensional object, as the person can only move in one dimension—forwards and backwards. Ask another participant to stand on the opposite 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[1]

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?

[1] 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 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.

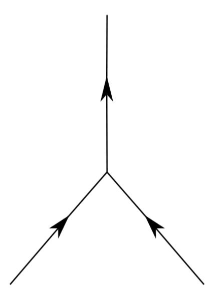
- A single moment in space and time: zero-dimensional (0-D) particle stationary in space and time
- The worldline of a 0-D particle stationary in space but moving forward in time
- The worldline of a 0-D particle moving back and forth (like a mass on a spring) in space over time
- The worldlines of two 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?

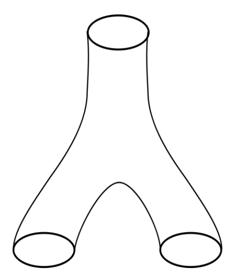
The worldline of a stationary particle, at a particular instant in time, is represented by a single point. A stationary particle that is moving through time is represented by a vertical arrow. A particle moving back and forth is a sine wave moving upwards. Two particles moving towards one another are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



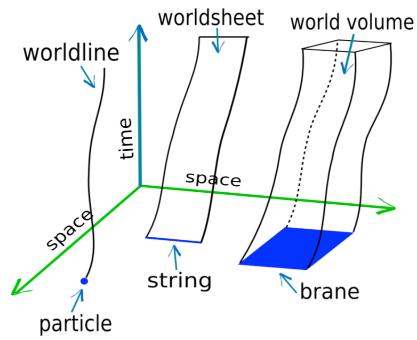
Feynman Diagram: Two particles collide inelastically



The worldsheets swept up by the intersection of two closed strings (called a "pants diagram")[2]

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.

[2] Source: © Wikimedia Commons, License: None. Author: Actam, 29 June 2008. http://en.wikipedia.org/wiki/File:World_lines_and_world_sheet.svg.



Worldline, worldsheet, and world volume[3]

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?[4]

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

[3] Source: © Wikimedia Commons, License: CC ShareAlike 3.0. Author: Stevertigo, 26 April 2005. http://en.wikipedia.org/wiki/File:Brane-wlwswv.png.
[4] Variations of this activity may be found at the Exploratorium at 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.

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.

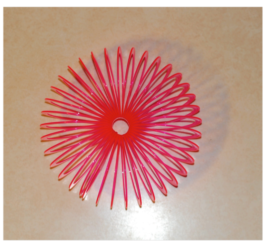
2. String Thing

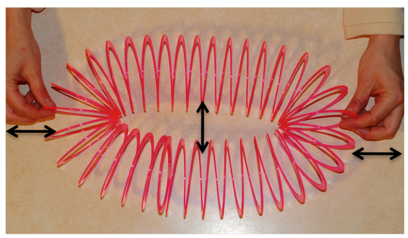
To Do and To Notice

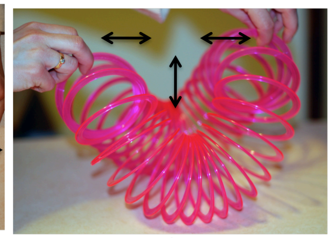
Give each pair of participants a Slinky®. How might they use this as a model of an electron? Using what they learned in the reading, how would they represent a *graviton*? A photon? An electron? How might the graviton differ from the electron? What would a string on a *d-brane* look like?

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 closed string model


A 2D lowest vibrational mode


Another 2-D mode

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?

<u>Optional</u>: 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

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

<u>Time</u>: 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.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.

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.

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.
- Deducting dimensions (on visualizing and understanding extra dimensions) 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.

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.

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.

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.[5] 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. 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?

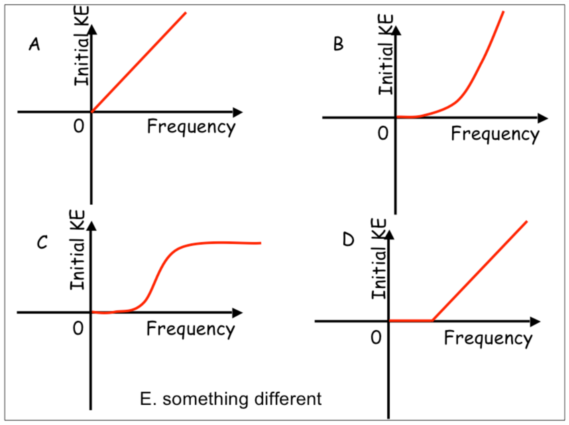
3. Check your understanding.

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.

[5] 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[6]

For a comprehensive study on student understanding of the photoelectric effect, see http://www.colorado.edu/physics/EducationIssues/papers/McKagan_etal/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 . 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.

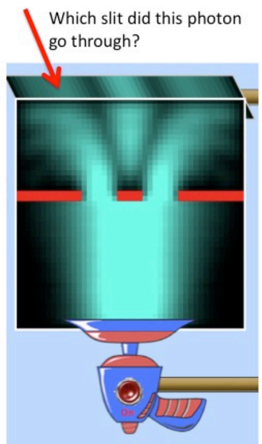
[6] This question and the following questions are from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins and S. McKagan, http://per.colorado.edu/modern.

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



Unit 5

The Quantum World

Introduction

All these fifty years of conscious brooding have brought me no nearer to the answer to the question, "What are light quanta?" Nowadays every Tom, Dick, and Harry thinks he knows it, but he is mistaken.
– Albert Einstein

Our everyday experience with both light and matter turns out to be woefully inadequate for describing how light and matter behave at the scale of atoms. Quantum mechanics told us that light is not simply the stream of electromagnetic waves described by Maxwell, but made of small packets of energy called *photons*. Quantum theory also shows that tiny particles, like electrons, do not have well-defined positions but are instead smeared out in space as waves—their location can only be described probabilistically. In this unit we'll explore these weird aspects of the microscopic world, how it affects the behavior of some human-sized objects, and some cutting-edge applications that have grown out of this elegant theory.

What Will Participants Learn?

Participants will be able to:

1. Describe both the particle and wave behaviors of light and matter, and give examples that display both behaviors at the same time.
2. Provide at least one example for each of the following tenets of quantum mechanics: *quantization, wave-particle duality,* and *the uncertainty principle*.
3. Explain the processes used in cooling and trapping atoms to temperatures near absolute zero.
4. Explain how the probabilistic nature of light and matter waves affects measurement of quantum mechanical phenomena and contrast with classical measurement.

What's in this Unit?

Text: Unit 5: *The Quantum World* covers the field of quantum mechanics and some of its applications. Developed early in the 20th century to solve a crisis in understanding the nature of the atom, quantum mechanics has laid the foundation for theoretical and practical advances in 21st century physics. The unit details the reasoning that led to an awareness of the particle nature of light, including the *photoelectric effect*, *interference effects,* and *blackbody radiation*. The *wave nature of matter* is also explored, including the *de Broglie wavelength* of matter, *interference of matter waves*, *wavefunctions*, and the *Heisenberg uncertainty principle*. Applications to *laser cooling*, *atom traps*, and *atomic clocks* are described.

Video: The program explores how two scientists and their teams are using laser cooling to explore how matter behaves on the atomic level. Laser cooling allows scientists to cool atoms to extremely low temperatures and to trap them within a tiny space. Through this technique Martin Zwierlein and his team at the Massachusetts Institute of Technology produce exotic forms of matter by controlling the interactions of atoms and their external environment. At NIST/Boulder, cooling and trapping of single mercury ions have enabled David Wineland and his team to create what is currently the world's most precise clock, as well as to test some of the fundamental laws of physics.

Video Extra: John Lowe of the National Institute for Standards and Technology (NIST) discusses atomic clocks.

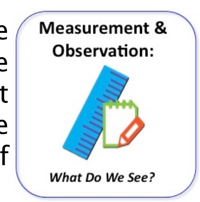
Interactive Lab: *Laser Cooling*. Learn the basics of how to manipulate atoms with light, and cool a hot atomic beam to a few millionths of a degree above absolute zero.

Activities:

- The Hook: How To Make Something Really Cold? (10 minutes)
- Activity 1: Watch and Discuss the Video (50 minutes)
- Activity 2: The Photoelectric Effect (optional)
- Activity 3: The Wave/Particle Nature of Light (35 minutes)
- Activity 4: Matter is a Wave (But What's "Waving?") (40 minutes)
- Back to the Classroom (15 minutes)

(*Note:* There is likely to be a large variation in participants' familiarity and comfort with the topics in this unit. In order to meet all possible needs this unit covers a broad range of material. You may wish to gauge participants' understanding through emailed questions prior to the session. Depending on participants' background experience and preferences, you may wish to expand on *Activity 2: The Photoelectric Effect* (and de-emphasize *Activity 3: The Wave/Particle Nature of Light*), or eliminate *The Photoelectric Effect*. If participants need a review of the photoelectric effect, 15 minutes may be sufficient. If they need to learn it in depth, more time may be needed.)

Nature of Science Theme: *Measurement & Observation*. You may wish to display the *Measurement & Observation* icon during the session and remind participants of the central ideas of this theme. We cannot always trust our direct perception and must confirm our observations via measurement. Thus much, if not all, scientific evidence relies on indirect measurement. A variety of tools allow scientists to probe aspects of the natural world that are beyond our human abilities to perceive.



Exploring the Unit

Before the session: As participants enter, ask them to post their question about quantum theory on the wall or a bulletin board. Encourage them to peruse the questions as they get settled. Tell them to keep their question in mind, and encourage them to speak up about their questions at the appropriate time in the session.

The Hook: How To Make Something Really Cold?

Time: 10 Minutes.

Materials:

- Ping-pong balls (about 15)
- 5 marbles
- An enclosure, such as a hula-hoop

> *(Note:* You may use different types of balls depending on your available materials)

Throw about 10 ping-pong balls into the enclosure and shake so that they move in random directions. Explain that these represent the molecules of a gas.

Ask participants, how can we make this gas hotter? Participants may suggest a variety of mechanisms, such as putting it in an oven or compressing it. These can be modeled by shaking the hula-hoop to make them move faster. Discuss the fact that temperature is a measure of molecular motion, or the kinetic energy of the molecules.

Ask participants, how can we make this gas colder? They may suggest a variety of mechanisms, such as waiting for the atoms or molecules to slow down, putting it in a refrigerator, or the laser cooling from the reading. Defer the discussion of laser cooling. If they suggest waiting for the atoms to slow down and stop (through friction) remind them that frictional forces heat the system. If they suggest the molecules will slow down and stop on their own without friction, recall Newton's laws. If anyone suggests grabbing the ball to stop it, point out that the heat of a hand (or other object) will add energy to that molecule.

Ask, what has to be true for a substance to reach zero temperature? Discuss as a group. Some participants may be confused as to how a substance can be gaseous when it is cold—explain that this is possible at low enough pressure. Molecules are still moving, even if they've been slowed to a near stop in a refrigerator—nothing gets to absolute zero. So, how do we slow them down further? Roll a marble at the moving ping-pong ball to slow it. Now, discuss the idea of laser cooling from the reading. Roll several marbles at the ping-pong balls to represent a laser. Particles of light (photons) hit particles of matter that can only absorb certain energies of light.

You may wish to display some of the applets from Physics 2000 (http://www.colorado.edu/physics/2000/index.pl) on laser cooling, or the *Interactive Lab: Laser Cooling*.

Take-home message: Laser cooling manipulates motion on the atomic scale, and relies on the fact that light is made of photons of particular energies, and the fact that atoms only absorb light of a particular energy.

Explain that in this unit, we will be discussing the particle nature of light and the wave nature of matter, both of which are exactly backwards from what you're used to. In the next unit, we will explore phenomena using laser cooling.

Activity 1: Watch and Discuss the Video

VIDEO

Time: 50 Minutes.

If participants are watching the video in class, have them view it now. You may wish to show the *Video Extra* for Unit 5 (on atomic clocks) here. Remind them of the guiding questions listed in *Between Sessions* from the previous unit.

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

You may wish to display some of the applets from Physics 2000 (http://www.colorado.edu/physics/2000/index.pl) on laser cooling, optical molasses, magnetic trapping, and evaporative cooling to answer participants' questions after the video.

An atomic clock can measure time precisely because it is measuring the period of oscillation of an electron between energy levels, *not* its position. Its energy is very well-defined even though its location is not.

Gather participant responses to Question 2 into different groups: particle nature of light, wave nature of light, particle nature of matter, wave nature of matter. For example, "energy levels of electrons in atoms" would belong in "wave nature of matter." Remark that we don't need quantum mechanics to explain the wave nature of light or particle nature of matter—those can be explained classically. But we do need quantum mechanics to explain the particle nature of light and the wave nature of matter, and we will be exploring those ideas in this unit.

Activity 2: Photoelectric effect (optional)

Purpose: To use thought experiments and simulations to understand the photoelectric effect and how it supported the idea that light was made of quantum packets called *photons*. Participants will compare and contrast classical and quantum predictions for the photoelectric effect with experimental observations. This is recommended for participants who are not as deeply familiar with quantum mechanics and the photoelectric effect, though even those who think they understand this phenomenon may have underlying misconceptions.[1] For those who only need a review, the clicker questions are highly recommended.
Materials:

- Digital projector
- PhET "Photoelectric Effect" simulation (http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect). (*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. Classical frequency dependence

To Do and To Notice

Experiments in the late 1800's showed that if light is shone on a metal, electricity is produced. Let's imagine that this happens because the light "heats up" the metal, giving electrons energy so that they can jump off.[2] How would participants expect:

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

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[1] For a comprehensive study, see http://www.colorado.edu/physics/EducationIssues/papers/McKagan_etal/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 a I-V graph of the experiment, and (d) cannot relate photons to the photoelectric effect.

[2] 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?

(b) The intensity of that light to affect how many electrons jump off the metal?

What's Going On?

Classically, one would expect that the frequency of waves hitting the metal would have no effect on the electrons released from the metal—only the intensity would matter. But we can see from the PhET simulation that the frequency of the light waves hitting the metal affects both the number of electrons released from the metal and how quickly they move. Thus, we need a quantum explanation.

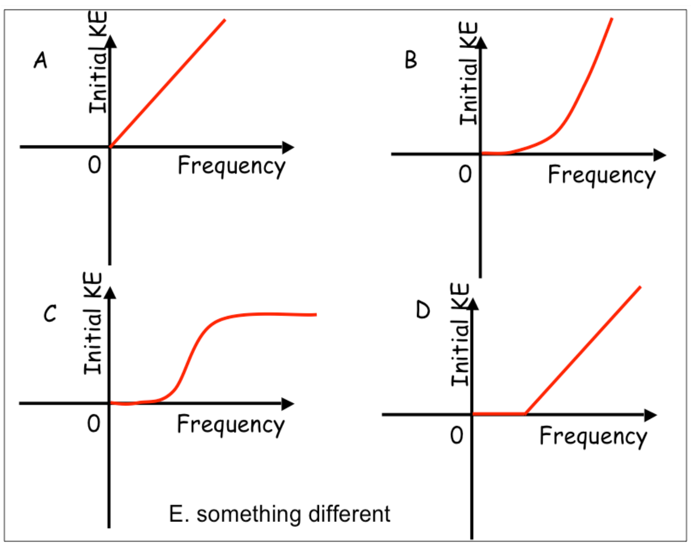
2. Actual frequency dependence

To Do and To Notice

Demonstrate the PhET simulation and its basic properties, or ask a participant to do so. What happens when the light intensity changes? What happens when the light frequency changes? Then, discuss the homework questions as a group. Use each question as a starting point for exploration and discussion of the topics, rather than searching only for a correct answer.

Clicker/Discussion Question: Frequency dependence[3]

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?



What's Going On?

Best answer is (D). Because of the quantized nature of light, one photon can promote only one electron above the *work function* (the amount of energy needed to eject the electron from the metal). You may want to introduce atomic *potential energy well*

[3] 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. This question also appeared in McKagan et al., Am. J. Phys., 77, 87 (2009).

diagrams here if participants struggle with the idea of work functions. What happens when photons of different energies hit an electron in this well?

Thus, using conservation of energy, a complete response is:

- Energy in = Energy out
- Energy of photon (hf) = Energy to eject electron (W) + Kinetic Energy (KE) of ejected electron
- So $KE = hf - W$ (for a single photon; otherwise, $KE = nhf$)
- Thus, until $hf = W$, electrons are not ejected
- After that point, the KE rises linearly with f. Thus, answer (*D)* is correct.

3. Probabilities

To Do and To Notice

Clicker/Discussion Question: Probability of electron ejection

Imagine we're running the photoelectric effect simulation with very low light intensity that uniformly illuminates the surface. We observe an electron only pops out every few seconds. **Why does that particular electron pop out?**

A. Because that is where the light hit the metal
B. That electron had more energy than any of the others so it was the easiest to remove
C. No physical reason, that electron just got lucky and won the "escape from metal" lottery
D. There must be some other physical reason but I am not sure what it is
E. There is a physical reason that is not listed above and I think I know what it is

Prompt participants to think about the "Quantum Wave Interference" simulation.

What's Going On?

Answer is (C). "Uniformly illuminated" means that the probability of a photon being absorbed at every location is the same, but we can't know where that photon will land until it's detected.

Take-home message: The photoelectric effect provides substantial evidence that light acts like a particle and that electrons have fixed energy levels within an atom.

Explain that these ideas of probability and measurement will be explored further in the next activity.

Activity 3: The Wave/Particle Nature of Light

Time: 35 Minutes.

Purpose: To use the PhET simulation "Quantum Wave Interference" to explore the idea that light and electrons are both a wave (that can go through both slits in a double slit experiment) and a particle (that hits the screen at a single location). This is a challenging set of concepts, and we recommend that facilitators look at the summary of common student difficulties on these topics at http://www.colorado.edu/physics/EducationIssues/modern/.

Materials:
- Digital projector
- PhET "Quantum Wave Interference" simulation (http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference).

To Do and To Notice

Show participants the PhET simulation and demonstrate a few key features on the first two tabs (or ask a participant to do so), particularly how both electrons and photons show a double-slit interference pattern indicative of wave behavior. What happens when the particles build up over time? What does this resemble? Focus on the photon interference pattern first.

Ask participants the following series of clicker/discussion questions. Be sure to have them discuss with their neighbors before discussing as a large group.

Clicker/Discussion Questions:[4]

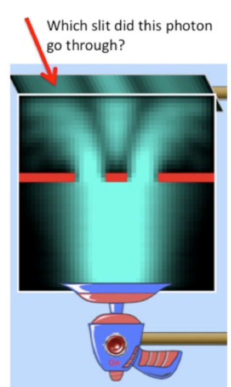
1. **If you shoot a photon through the two slits to hit the screen it:**

   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

Discuss with respect to *Measurement & Observation*.

2. Consider a photon to the left of center as in the image. **Which slit did it go through?**

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



[4] These questions and the following question are from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins, and S. McKagan, http://per.colorado.edu/modern.

Clicker/Discussion Questions continued:

3. **What do you visualize when you think about a photon traveling through space?**

   A. A particle of light with a specific energy traveling in a straight line:

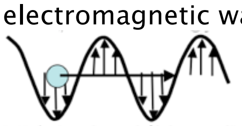
   B. A particle of light with a specific energy traveling along a sinusoidal path:

   C. A weak bit of electromagnetic wave with a specific amount of energy traveling along a straight line:

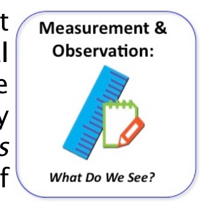
   

   D. A particle of light with a specific energy traveling along side an electromagnetic wave:

   E. None of the above. I think about it in a different way.

What's Going On?



1. Best answer is (D). The nature of physical measurement is fundamentally inexact in the world of quantum mechanics. Randomness is inherent in the natural world. We can predict particle behavior based on probabilities rather than the deterministic equations of classical mechanics. Physical behavior is governed by randomness and probability. Yet, the probability distribution itself *is* deterministic, and can be calculated and predicted with very high degrees of accuracy.

2. Best answer is (C). Light goes through both slits as a wave. But when it interacts with the screen, all the energy ends up in one spot, so it acts like a particle. This is why the interference pattern will show up even if only one photon goes through at a time; each photon interferes with itself. Demonstrate the second tab ("Single Particle") and ask participants to notice what happens when the wave front hits the screen. Discuss as a group.[5]

3. People have many visual models in their heads. Physically, the best answer is (C) which incorporates both the wave view and the particle view, though many undergraduates choose D.[6] A particle is a "chunk" of an electromagnetic wave.

[5] For common questions asked during this simulation, see "Common student difficulties" at http://www.colorado.edu/physics/EducationIssues/modern/.
[6] See college course materials at http://www.colorado.edu/physics/EducationIssues/modern/.

> The energy of a photon is contained in the frequency of oscillating electric and magnetic fields.[7]

Take-home message: Light behaves as a wave, and has a fundamentally probabilistic nature. The bright areas of the interference pattern tell us where a photon is most likely to hit the screen (as a particle) but it goes through both slits (as a wave).

When do we actually need to worry about the particle nature of light? It's only important when our detection system is good enough to see individual photons, such as in the photoelectric effect, the inner workings of lasers, molecular bonding, etc. It doesn't matter for heating and optics.

Activity 4: Matter is a Wave (But What's "Waving"?)

Time: 40 Minutes.

Purpose: Participants will explore the probabilistic interpretation of the wave equation.

Materials:

- PhET "Quantum Wave Interference" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference. (*Note*: You do not need to be connected to the internet to use these simulations You may click "download" to download and run the simulation locally on your machine.)

1. PhET Simulation "Quantum Wave Interference"

To Do and To Notice

Show the PhET "Quantum Wave Interference" simulation and choose "electrons" to be fired from the gun. Demonstrate properties of the simulation as for light waves.

What's Going On?

We know that electrons act like particles. But the fact that they produce an interference pattern also tells us that they act like waves.

2. Probabilities

To Do and To Notice

Tell participants you will now explore the interpretation of these matter waves.

The following is a distribution of all student exam grades in a class. Ask participants, if I pick a student at random, which grade range is he/she most likely to have?

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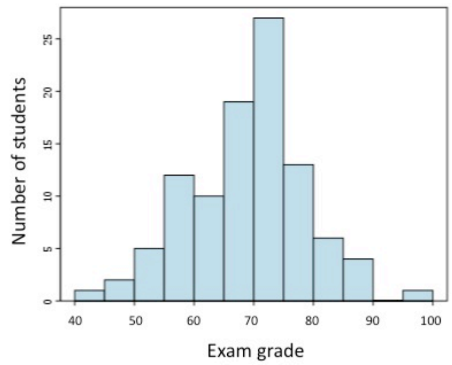
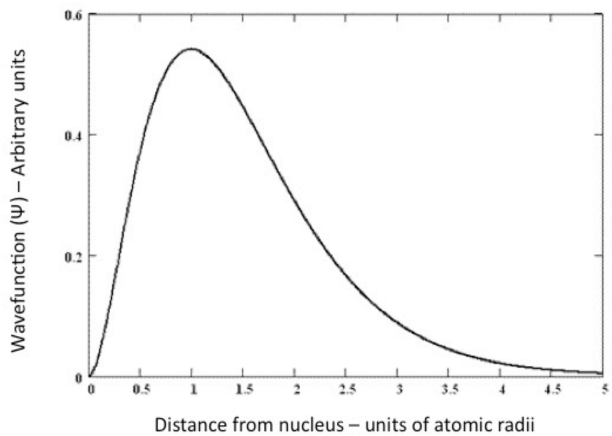
[7] Some participants may be curious how energy only depends on frequency, and not intensity, as a higher wattage light bulb is more intense and puts out more power. The important distinction is between the energy carried by a *beam* of light versus the energy in a single *quantum particle* of light. The energy of a quantum particle (a photon) depends on its frequency. But a beam of light carries many photons, and the energy of the beam is the sum of the energy of each photon. Thus, a higher wattage light bulb emits more photons, each of which carries energy corresponding to its individual frequency, $E=hf$.



Grade distribution
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

The following is the electron wavefunction or probability wave of an electron in the hydrogen atom. Ask participants, if we measure the location of the electron at a random time, how far is it most likely to be from the nucleus?



The n=1 hydrogen wavefunction in one dimension
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

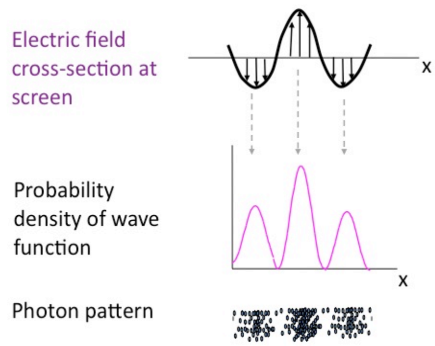
What's Going On?

A student picked at random is most likely to have a grade between 70 and 75. But there is a probability that they will have a grade that is higher or lower than that.

An electron picked at random is most likely to be found at a distance of one atomic radius. But there is also a probability that the electron will be further or closer than that.

If a student or electron is picked at random, there is 100% probability that they will have a grade or location that lies on the curve shown (i.e., with a grade between 0 and 100).

The height of an electron wavefunction represents the probability of finding an electron at that location. This is closely related to the interference pattern for light—the intensity of the pattern on the screen is a measure of the probability of detecting a photon at that location. (In particular, the square of the height of the wave represents the probability but that's not crucial here). Remind participants of the earlier clicker question: "If you shoot a photon through the two slits to hit the screen, it... has a chance of hitting anywhere on the screen, but on average a better chance at hitting where the interference pattern is brightest". Below is a graphical representation of this correspondence between probability and intensity. Discuss the similarities between the two interference patterns and their quantum interpretations.



Photon probability distribution versus intensity

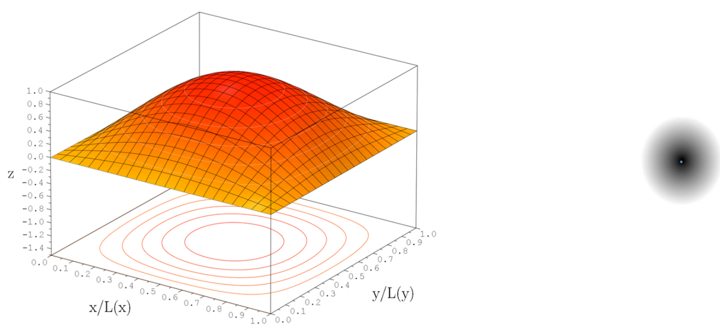
3. Representations of probability

To Do and To Notice

Show participants the n=1 hydrogen wavefunction once again. What does this look like in two dimensions? In three? Discuss as a group. Help participants make the connection between this activity and the spherical shape of the S-orbital.

What's Going On?

Below are some sample images.



The l=0, n=1 hydrogen wavefunction (s-orbital) as a two-dimensional "hump" and a three-dimensional "cloud"

Going Further

Consider the n=2 orbital of hydrogen. Given what participants know about the Bohr model of the atom (i.e., that the n=2 orbital is further from the center of the atom than the n=1), sketch the wavefunction in 1-D, 2-D, and 3-D. The 3-D image should show a spherical shell of high probability at a larger radius. Given what we know about the shape of the p-orbitals in 3-D, (i.e., two lobes like a figure eight), draw the p-orbital on a 1-D graph. It should have two humps on either side of the origin, like camel humps.

4. Measurement and Uncertainty

To Do and To Notice

What does this probabilistic description of electrons mean about the ability of physics to predict results? What about the nature of measurement in physics? How do we answer questions like, "What is the exact position of a particle?" Relate your discussion to the double-slit interference pattern from the PhET simulation and to the Uncertainty Principle.

Consider the *Heisenberg uncertainty* relation. The more precisely we know the momentum (i.e., wavelength) of a particle, the less certainly we know its precise location. Lead participants through the following thought experiment. Imagine a beach on a calm day. A single tall wave comes and crashes on the shore. You know precisely where it was as it approached the shore, and when it reached it. But what was its wavelength? Without a periodic set of waves, it's impossible to talk about the wavelength (and thus momentum, for a de Broglie wave) of the wave. Now imagine a series of about 20 regularly spaced waves, crashing on the shore at equal intervals. These waves have a definite wavelength (and thus momentum). But when did the wave, as a set, hit the shore? The more precisely the wavelength is known, the less precisely the location of the wave is known.

If any of participants' questions from the beginning of class have not been addressed, discuss them now.

What's Going On?

Heisenberg answered the question "What is the exact position of a particle" by saying, "I do not need to answer such a question because you cannot ask such a question experimentally." Such a question cannot be subjected to experiment, and so it is no longer a scientific question. Unless a thing can be measured, it has no place in a theory. Classically, ideas about exact momentum and position of particles are allowed and can be predicted, deterministically. Quantum mechanically, they cannot. Quantum mechanics can only make probabilistic, not definite, predictions. (For further discussion of these ideas, see: *The Feynman Lectures on Physics, Volume 1* and *Volume 3.)*

Take-home message: Matter is a wave, but not the kind of wave that physically moves up and down through space. It is a probability wave, and the height of the wave represents the probability of measuring the particle at that location. The spread of the wave represents the uncertainty in the position of the particle.

Back to the Classroom

Time: 15 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.

Topics and Standards

Energy. Energy appears in many forms (such as kinetic and potential). The total amount of energy remains constant if no energy is transferred into or out of the system. Thermal energy in a system is associated with the disordered motions of its atoms or molecules.

Atoms and Molecules. Atoms are made of a positively charged nucleus surrounded by negatively charged electrons.

Size and Scale. Natural phenomena often involve sizes, durations, or speeds that are extremely small or extremely large.

Waves and Light. Wave behavior can be described in terms of how fast the disturbance spreads, and in terms of the distance between successive peaks of the disturbance (the wavelength). Light acts like a wave in many ways. The wavelength of light varies from radio waves, the longest, to gamma rays, the shortest.

The Mathematical World. Students should be able to estimate probabilities of outcomes in familiar situations on the basis of history or the number of possible outcomes. How probability is estimated depends on what is known about the situation. Estimates can be based on data from similar conditions in the past or on the assumption that all the possibilities are known. The larger a well-chosen sample is, the more accurately it is likely to represent the whole.

Nature of Science. 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. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations.

Classroom Resources

Physics 2000. A great set of clear, interactive tutorials 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 a list of all applets, and "Table of Contents" for an index of all topics. http://www.colorado.edu/physics/2000/index.pl.

PhET Simulations. Interactive simulations and teaching activities for a variety of quantum phenomena and related topics. including: Wave Interference; Quantum Wave Interference; Photoelectric Effect; and Blackbody Spectrum. http://phet.colorado.edu

The Challenge of Quantum Reality, from the Perimeter Institute. An excellent and very detailed teacher's guide with lesson plans, curriculum links, hands-on activities, worksheets, and homework. Includes an excellent activity on the nature of models. http://www.perimeterinstitute.ca/Perimeter_Explorations/Quantum_Reality/The_Challenge_of_Quantum_Reality/.

Workshop tutorials for physics. Short interactive inquiry-based group activities for a variety of topics, including quantum and atomic physics, from the University of Sydney Physics Education Research Group.
http://www.physics.usyd.edu.au/super/physics_tut/contents.html.

Videos on Teachers' Domain about quantum mechanics. Including a segment on whether electrons are particles or waves, the uncertainty principle, and the development of quantum mechanics.
http://www.teachersdomain.org/collection/k12/sci.phys.fund.quan/.

Visual Quantum Mechanics from Kansas State University. Includes research-based interactive visualizations. Instructional units developed as part of the project are available for about $200, though a free sample on light emission is available. http://web.phys.ksu.edu/vqm/software/online/info/summaryOfVqm.html.

Research on Teaching and Learning Quantum Mechanics. A set of nine papers from NARST in 1999 is available for download with good information on student difficulties in learning quantum mechanics. http://web.phys.ksu.edu/papers/narst/QM_papers.pdf.

Measuring Planck's constant. A hands-on activity from the Perimeter Institute to measure Planck's constant (*h*) using LED's and a few simple electronics. http://www.perimeterinstitute.ca/en/Outreach/Plancks_Constant/Measuring_Planck%27s_Constant%3A_Introduction/.

Introductory college level materials in quantum mechanics (and other courses) from the Physics Education Research Group at the University of Illinois. Includes helpful lecture notes and clicker questions (Quantum Mechanics starts on Lecture 20 of the algebra-based materials). Free registration required to download.
http://research.physics.illinois.edu/PER/Materials.htm.

Quantum Physics Labs from the Center for Nanoscale Systems. Several quantum-related labs including the Bohr Model Game, The Phantastic Photon and Light Emitting Diodes, as well as several on wave phenomena, interference, and nanophysics. You can't order the kits if you haven't gone through their institute, but you can use their online lab manuals. http://www.cns.cornell.edu/cipt/labs/lab-index.html.

Public lectures from the Kavli Institute for Theoretical Physics. A variety of public lectures by notable scientists on topics in quantum mechanics. http://www.kitp.ucsb.edu/outreach/public-lectures/past-lectures-talks.

Hands-on activities from the Exploratorium's Paul Doherty.

- Energy levels. Model the energy levels of an atom with a stool or other object, noticing how it will fall to its "ground state" when tilted.
http://www.exo.net/~pauld/activities/energylevelmodel/energylevelmodel.html.
- Bohr Model of an Atom. Model the energy levels of an atom using potential wells and strips of paper.
http://www.exo.net/~pauld/activities/energylevelmodel/bohratom.html.
- Two Slit Interference Model. Model two slit interference with physical representations of waves on strips of paper.
http://www.exo.net/~pauld/summer_institute/summer_day8interference/twoslitinterferencemodel.html.
- Fundamental Frequency. Show resonant frequencies with a phone cord, demonstrating how certain wavelengths can fit on a length of string.
http://www.exo.net/~pauld/summer_institute/summer_day10waves/harmonic_phonecord.html.

Concept map of quantum mechanics at HyperPhysics has summaries of the main ideas of quantum mechanics and how they are interrelated.

- http://hyperphysics.phy-astr.gsu.edu/hbase/quacon.html#quacon

- http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/statcn.html#c1

Good explanations of laser cooling and underlying principles on the Nobel Prize website for 1997. http://nobelprize.org/nobel_prizes/physics/laureates/1997/illpres/.

Videos on new types of atomic clocks developed by NIST http://www.nist.gov/public_affairs/clock/clock.html.

Absolute Zero. An activity guide intended for middle school students that would also be appropriate at the high school level, including demonstrations on superconducting levitation, the meaning of absolute zero, and Bose-Einstein condensation. http://www.compadre.org/portal/document/ServeFile.cfm?ID=8053&DocID=718.

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.

Assign each participant to write a one or two paragraph summary of either Jenny Hoffman's or Debbie Jin's experiment. If possible, allow them to post these summaries in an online forum to spur discussion out of class.

PARTICIPANTS

Text: Read Unit 6: *Macroscopic Quantum Mechanics* for the next session.

Further exploration:

1. **PhET Models of the Hydrogen Atom** at http://phet.colorado.edu/simulations/sims.php?sim=Models_of_the_Hydrogen_Atom. (See also the teacher tips for this simulation).
    a. How is de Broglie's view of the electron different from Bohr's view? What is the purpose of the three different views of the de Broglie electron?
    b. How is Schrödinger's model of the atom different from de Broglie's? You may want to refer to the simulation.

2. **Physics 2000.** Go through the interactive tutorial and applets on Bose-Einstein condensation. Click "what is it" to see all applets, and "table of contents" for a list of topics. The following two links are particularly relevant: http://www.colorado.edu/physics/2000/bec/what_is_it.html, and http://www.colorado.edu/physics/2000/bec/what_it_looks_like.html.

3. **Interactive Lab** associated with this unit: *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.

Video: Watch the Unit 6 program and write a one or two paragraph summary of either Jenny Hoffman's or Debbie Jin's experiment (you should have been assigned to one experiment or the other by the facilitator). In your paragraph, try to imagine you are telling the story of their experiment to someone who is learning about it for the first time. (Even better, actually tell the story of the experiment to a family member or a colleague. Their questions will help you understand the material better.) Be sure to include what they are trying to discover/measure, and how their experiments relate to the topic of "macroscopic quantum mechanics."

Unit 6

Macroscopic Quantum Mechanics

Introduction

A physicist is just an atom's way of looking at itself.
- Neils Bohr

We typically view quantum mechanics as applying to the fundamental particles or fields of Units 1 and 2—not to the objects we find in a grocery store or in our homes. If large objects like baseballs and our dining tables don't behave like waves, why do we bother about their possible quantum nature? More practically, we can ask: If we are supposed to believe that ordinary objects consist of wave-like quantum particles, how does that quantum nature disappear as larger objects are assembled from smaller ones? Or, more interestingly: Are there macroscopic objects large enough to be visible to the naked eye that still retain their quantum wave natures? To answer these questions we need rules for building larger objects out of smaller ones, and means of applying them. These rules are the subject of this unit, and they lead to some surprising macroscopic quantum behavior such as *Bose-Einstein condensates* and *superconductors*.

What Will Participants Learn?

Participants will be able to:

1. Visualize different models of the atom and explain how each model did or did not match experimental observations.
2. Explain how the periodic table is a manifestation of the inner structure of atoms, and how electron energies, spin, and pairing lead to chemical bonding.
3. Describe how quantum mechanics (which operates at the scale of atoms) can have macroscopic effects that are visible to the naked eye. List two or more examples of practical applications of macroscopic quantum mechanics.
4. Compare and contrast the behavior of *bosons* and *fermions*. Explain how fermions can be converted into bosons.

What's in this Unit?

Text: Unit 6 outlines the difference between bosons (integer spin particles) and fermions (half-integer spin particles). The *Pauli exclusion principle* dictates that no two identical fermions can occupy the same quantum state—a fact that leads to the structure of the periodic table as fermions fill up atomic energy levels from the ground state up. Bosons, on the other hand, can occupy the same quantum state, as in a laser, which consists of photons with the same frequency and momentum. Fermionic atoms can be combined to create bosonic atoms, under the proper conditions (extremely cold, low density atoms).[1] This led to the creation of Bose-Einstein condensates (BECs), and new work generating BECs from Fermi gases. These new states of matter exhibit new types of behavior.

[1] Note that fermions combine to create bosons in other contexts without requiring extremely cold temperatures. For example, protons and neutrons are fermions, and combine to create bosonic nuclei and protons; neutrons and electrons are all fermions, but combine to create bosonic atoms.

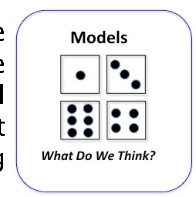
Video: The program investigates one manifestation of quantum mechanics at the macroscopic scale—superconductivity. In order to raise the critical temperature required to achieve superconducting behavior in materials, two researchers are working to understand what's going on inside these materials. Harvard's Jenny Hoffman and her research team are exploring the problem by using a scanning tunneling microscope to unravel the properties of superconductors, atom by atom. Meanwhile, Deborah Jin, a physicist at the National Institute of Standards and Technology, is looking at the problem from a different angle. She and her group are using ultracold gases, which help build models for how superconductors work using simpler systems that can be manipulated at the quantum level. She describes Bose-Einstein condensates (BECs) and her work on *Fermi condensates*.

Video Extra: Wolfgang Rueckner of Harvard University demonstrates the *Meissner effect*, where a magnet will levitate above a superconductor as the superconductor expels all magnetic field lines.

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: Superfluid Coffee (10 minutes)
- Activity 1: Models of the Atom (30 minutes)
- Activity 2: Periodic Chessboard (25 minutes)
- Activity 3: Bosons vs. Fermions (10 minutes)
- Activity 4: Bose-Einstein Condensates (20 minutes)
- Activity 5: Watch and Discuss the Video (50 minutes)
- Back to the Classroom (15 minutes)

Nature of Science Theme: *Models*. You may wish to display the *Models* icon during the session and remind participants of the central ideas of this theme. Scientists create models, or hypotheses and theories, to make sense of their observations. Thus, a model is a scientific account of nature. A good model is testable and suggests evidence that would support or refute it. When experimental observations do not match the existing model, scientists do and have changed their ideas about nature.



Exploring the Unit

The Hook: Superfluid Coffee

Time: 10 Minutes.

Materials:
- Mug of coffee or other liquid
- Video of superfluid helium

Have a cup of coffee or other liquid. Stir it. Notice what happens. It has a single vortex, or whirlpool, in the center, and it gradually comes to rest. How would this behavior change if the coffee cup were filled with superfluid Helium-3? Show a video of superfluid Helium (e.g. http://www.youtube.com/watch?v=2Z6UJbwxBZI). You may also wish to show the *Video Extra* for Unit 6 (on the Meissner effect) here.

Explain to participants: In this unit, we will discuss the surprising behavior of ultracold materials, which allows us to observe quantum effects in things that are large enough for us to see, like a superfluid. In a superfluid, there is no resistance to flow, and rotating liquids show surprising behavior, like many quantized vortices on the surface. (*Note:* Bose-Einstein condensates are superfluids; the difference is that the atoms in Helium-3 interact strongly with each other, so their behavior is much more complicated than in Bose-Einstein condensates which remain gaseous.) First, we'll explore our changing model of the basic constituent of matter: The atom.

Activity 1: Models of the Atom

Time: 30 Minutes.

Purpose: In the last unit, participants learned about the wave/particle duality of light and matter. Now, participants see how Schrödinger's probabilistic description of matter wavefunctions leads to a very different model of the atom, which provides greater explanatory power for experimental observations. This activity extends the ideas in Unit 5.

Materials:

- Optional video from Alice and Bob in Wonderland called, "*How can atoms exist?*" http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.
- Optional handout of different models of the atom from the online resource: *Facilitator's Guide High Resolution Graphics.*

1. Bohr Model

To Do and To Notice

Clicker/Discussion Question: Atomic spectra

Gas atoms can absorb and radiate light

A. Of any frequency or color
B. At any frequency lower than that of the light hitting them
C. Only at precise frequencies or colors
D. In the visible part of the electromagnetic spectrum

CLICKER/DISCUSSION QUESTION

What's Going On?

Best answer is (C). Atoms can only emit and absorb specific frequencies of light. This is because electrons also exist at fixed energy levels in the atom. Draw the *Bohr model* of the atom from the unit. What's wrong with this model? You may wish to show the 1-minute animated short from Alice and Bob in Wonderland called, "*How can atoms exist?*"

2. de Broglie Waves

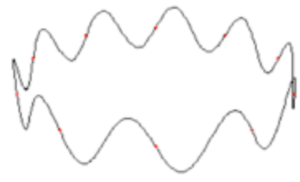
To Do and To Notice

We know that electrons are some sort of wave. How does this lead to electronic energy levels? Imagine a wave that must fit around a ring, as below.

Clicker/Discussion Question: Standing waves on a ring

Imagine a standing wave on a string, but a string with the two ends joined together to create a circle with radius *r*. **What are the restrictions on the wavelength (λ)?**

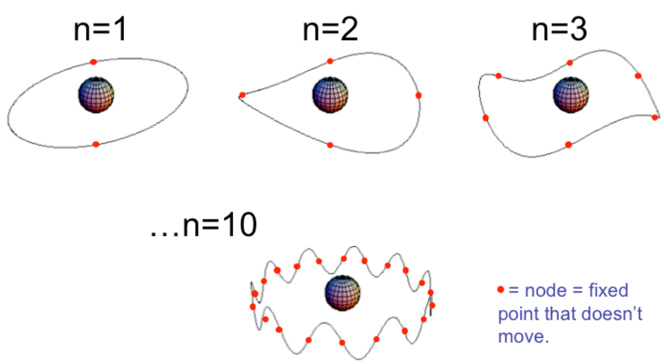
A. r = λ
B. r = nλ n = 1, 2, 3, …
C. πr = nλ
D. 2πr = nλ
E. 2πr = λ/n



What's Going On?

Best answer is (D). For a given orbital radius *r*, the circumference is $2\pi r$, and to get standing waves without destructive interference you need an integer number of wavelengths[2], $n\lambda$. (*Note:* The particular orbital radius itself is fixed by setting the Coulomb potential energy equal to the kinetic energy of the electron).

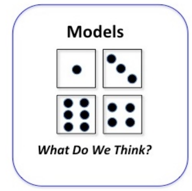
So what would these *de Broglie waves* look like for a single electron atom (e.g., hydrogen)? Thus, de Broglie waves explain energy quantization, at least mathematically. What are the wavelengths of these waves? For photons, $E=pc = hc/\lambda$ gives $\lambda=h/p$. The same relationship between wavelength and momentum can be applied to matter.[3] This is called the de Broglie wavelength: $\lambda=h/p$.[4] Review the models of the atom that we have seen so far.



de Broglie waves for the hydrogen atom[5]

[2] In the absence of any kind of confinement or *boundary conditions*, electron waves can have any energy; they are not restricted to the energy of these standing waves.
[3] Note: The momentum p is different for electrons and photons. For photons, $p=h/\lambda=E/c$ but for electrons and other massive particles, $p=(2Em)^{1/2}$ by using $KE=mv^2/2$.
[4] Note: You may discuss the fact that we don't see everyday objects as waves smeared out in space: As mass increases, the momentum (p) increases and the wavelength becomes incredibly small. Thus, we see everyday objects as located at a definite place in space.
[5] This image is from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins, and S. McKagan, http://per.colorado.edu/modern. For a thorough study of the use of the Bohr model and atomic models in undergraduate settings, and common student difficulties, see S.B. McKagan et al, "Why we should teach the Bohr model and how to teach it effectively," Phys. Rev. ST Phys. Educ. Res. 4, 010103 (2008).

3. Schrödinger Model



To Do and To Notice

Facilitate a Think-Pair-Share:

- What is “wrong” with the de Broglie model of the atom?
- How many historic models of the atom can you come up with? What is wrong with each of them?
- What were your answers to the homework questions on the PhET simulation?
    a. How is de Broglie’s view of the electron different from Bohr’s view? What is the purpose of the three different views of the de Broglie electron?
    b. How is *Schrödinger’s model* of the atom different from de Broglie’s? You may want to refer to the simulation.

Discuss as a group, including the homework questions. Share the schematic on the next page (or your own version of it) with the class and discuss.

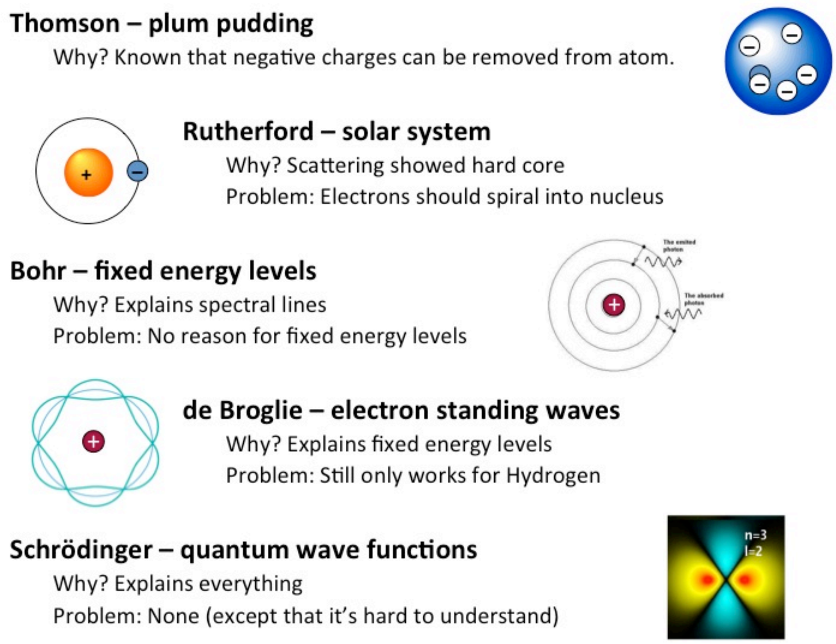
What’s Going On?

Discussion points include:

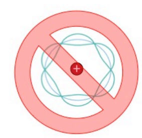
<u>Bohr model</u>: Gives correct electron energies, but postulates fixed energy levels without explaining why the energy levels are fixed. The electron is described as a point particle in space.

<u>de Broglie model</u>: Also gives correct electron energies, and postulates that the fixed energy levels are caused by electrons as standing waves (not an orbiting particle). But these energy levels only work for hydrogen, not for multi-electron atoms, as it is a 1-D model.

<u>Schrödinger model</u>: Also gives correct electron energies, but describes electron as a 3-D probability wave. The quantized energy levels result from boundaries on that wave. Allows us to generalize to multi-electron atoms (as in the next activity).



Models of the atom
(Available in the online resource: *Facilitator's Guide High Resolution Graphics)*



Take-home message: The de Broglie model gives the right answer, but it's the wrong physical model. The electron is not following a circular path around the nucleus. While the energy of the electron is quantized, and the electrons are located in shells (or "clouds"), the location of that electron is probabilistic. Schrödinger's wave equation allows us to calculate the shape of the electron clouds, and the probability of finding the electron at distinct locations within those clouds.

Activity 2: Periodic Chessboard

Time: 25 Minutes.

Purpose: To model the periodic table as a means to compare the Schrödinger model of the atom, quantum numbers, and the nature of fermions to familiar ideas in chemistry. Exploration of the fermionic nature of electrons will then be used to explore the surprising behavior of bosons in the next activity.

Materials:
- Butcher paper
- Colored markers
- 30 small paper or plastic cups
- Copy of the periodic table
- Tape
- Copy of atomic orbital simulation from http://www.falstad.com/qmatom/

To Do and To Notice

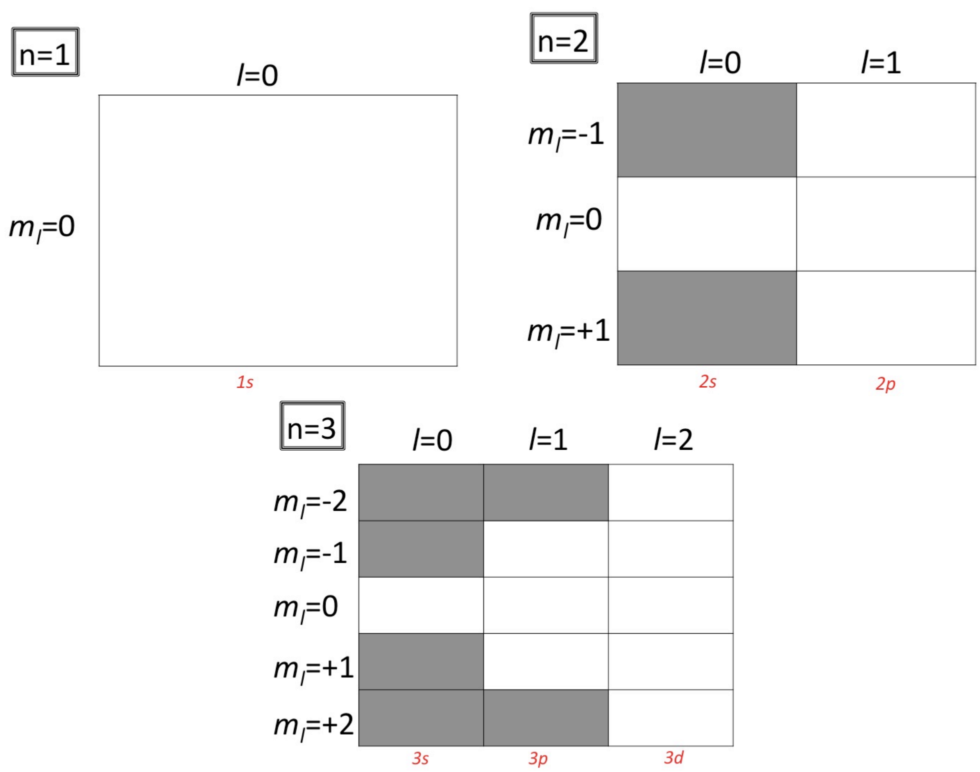
The electronic energy levels in the atoms are solutions to the Schrödinger wave equation, and each one can be uniquely described by four quantum numbers: n, l, m_l, and m_s. This activity will help us link the Schrödinger description of the atom to the chemists' periodic table.

Label three pieces of the butcher paper "n=1", "n=2", and "n=3." Remind participants of the four quantum numbers and their rules:

Name	Symbol	Allowed values
Principal	n	1, 2, 3…
Orbital	l	0, 1, 2…(n–1)
Magnetic	m_l	–l…–1, 0, 1, …+l
Spin	m_s	+1/2, –1/2

As a group, determine the possible quantum numbers available in the n=1, n=2, and n=3 levels. Label the l values along one side and the m_l values along another side. Leave out the m_s values for now. Your final papers may look like the pictures below, or you may choose another layout scheme. Grey squares indicate a quantum number that is not allowed for that level. If you are able, put n=1 on the floor, n=2 on a chair, and n=3 on a table to represent different energy levels.

<u>Optional</u>: You may have participants do this on their own or in pairs and then come to consensus as a group. You may also choose to do only the first two energy levels in the interest of time.



Explain that the cups represent electrons—a right-side up cup is spin = +½, and an upside-down cup is spin = -½. Remind participants that two electrons can't occupy the same quantum state[6] (the *Pauli exclusion principle*). Electrons will fill the lowest energy

[6] Quantum state, wavefunction, and quantum numbers are all different ways of saying the same thing: ψ_{nlm}.

possible without being in the same quantum state. Use a copy of the periodic table and find hydrogen (H), which has one electron.

1. Where should the hydrogen electron be placed on this diagram? It may be in either spin ±½ in the n=1 state.
2. How does this model relate to the observation that hydrogen atoms can only absorb and emit certain frequencies of light?
3. Given that the energy of an electron in hydrogen is $E_n = -13.6\ eV / n^2$ (where 13.6 eV is the ground state energy of hydrogen), how many different electron wave functions have the energy -(1/9) 13.6 eV?
4. Repeat the placing of cups for helium (He), then for lithium (Li), carbon (C), and neon (Ne). What rules dictate the order in which you place these cups? (*Note:* You may wish to make a diagram of the electron configurations for these elements on the board after placing the cups.)
5. In what ways do helium (He), carbon (C), and neon (Ne) differ from one another?

What's Going On?

Discuss the above questions:

1. A ground state electron in hydrogen will be in the 1s level, either ±½.

2. An electron that absorbs a photon is promoted to the next energy level (demonstrate this by moving one of the cups to a higher energy state).

3. This represents the *n*=3 level; A total of 9 states have this energy, or 18 including m_s = ±½.

4. Because two electrons can't occupy the same quantum state, they fill from the "bottom up." Electrons must fill the lowest *n* states, as these represent lower energy values. The lower *l* values fill next, because those allow the electron to remain closer to the nucleus. So the 1s orbital fills first, then 2s, then 2p. (*Note:* This is another way of stating *Hund's rule*.) Let's see why that is. Show participants the visualization of atomic orbitals for hydrogen at http://www.falstad.com/qmatom/. Use the "real orbitals" and start at *n*=1, moving to *n*=2 and *n*=3. Then change the value of *l*. (<u>Optional</u>: The changing color represents the phase of the wave—this is what's "waving." The probability density remains the same while the phase of the wave changes.) The quantum numbers m_l and m_s do not represent different energy values, so electrons can have any of these numbers (but not the same one) as they begin to fill those levels. Thus, any electron is defined by the combination of quantum numbers—*n, l,* m_l, and m_s. Quantum mechanics thus helps explain the periodic table.

5. These elements differ in many ways due to their electron configuration. Helium (He) has a full outer shell, lithium (Li) has one electron in its outer shell, carbon (C) has a half full outer shell, and neon (Ne) again has a full outer shell. These elements differ in many properties, including the *ionization energy*, or energy required to remove an electron. The ionization energy is periodic—it is low for an element with one electron in its outer shell (like Li) and high for an element with a full outer shell (like Ne). As we increase the number of electrons, this pulls electrons closer to the nucleus, so it becomes very difficult to pull electrons away from a noble gas like Ne.

<u>Take-home message</u>: Electrons are described by quantum numbers, and no two electrons in a shell can have the same quantum numbers. This gives rise to the periodic table (which had been described long before quantum mechanics).

Activity 3: Bosons vs. Fermions

Time: 10 Minutes.

Purpose: To explore how bosons do not obey the Pauli exclusion principle, and thus how they behave differently from fermions. Participants will learn how two fermions may be paired to create a boson.

To Do and To Notice

Return to the *Periodic Chessboard.* How would chemistry change if electrons were bosons instead of fermions?

Tape the cups together in pairs. If each electron is spin ½, what then each of these represent spin 0 particles, or bosons. As a group, place the cups to represent helium (He), lithium (Li), carbon (C), and neon (Ne). How do these elements differ from one another now that they're made of bosons?

What's Going On?

Bosons can all occupy the same quantum state (in fact, they like to do so). If electrons were bosons, then they would all occupy the lowest (1s) energy, and have the same quantum state. Helium (He), lithium (Li), carbon (C), and neon (Ne) now would only differ in their mass, total charge, and size. Chemistry would be very boring.

Bose realized that photons with the same energy (or frequency) can have the same quantum state *and* be in the same location. The same is not true of a fermion. If two fermions are in the same physical location (as with electrons in an atom) they cannot have the same quantum state. This is true whether the fermion is an electron or an atom. But we can put several fermions (spin ½) together to make a boson (spin 0). Just as we taped two cups together to make a spin 0 boson, we can put together any fermions (like two atoms) together to make a molecule that is overall spin 0. So, matter can be made of bosons, which will then be able to occupy the same quantum state *and* the same location.[7]

Einstein recognized that *all* bosons should follow Bose's prediction, even bosons made of matter. This is the subject of the next activity.

Take-home message: Bosons can occupy the same quantum state and the same location; fermions cannot. Fermions can be combined into bosons, and show bosonic properties.

Activity 4: Bose-Einstein Condensates

Time: 20 Minutes.

[7] If participants are confused about the difference between fermionic atoms and electrons, consider the following. Two electrons are confined to the same location (e.g., the 1s orbital) by an external force (e.g., the *Coulomb attraction* of the nucleus) but must have different states (e.g., spin of ± ½). Two atoms are confined to the same location (e.g., in a matter trap) by an external force (e.g., by a harmonic oscillator potential) but cannot have the same state (an atom has many more states than just that of spin), unless they are bosons.

<u>Purpose</u>: To explore how the de Broglie wavelength of particles can change with motion and temperature, and how this creates indistinguishable particles.

<u>Materials</u>:
- Marbles and an enclosure (from Unit 5)
- Animation of the Bose-Einstein condensation at http://www.colorado.edu/physics/2000/bec/images/evap2.gif
- Optional: Video "Bose-Einstein Condensate" from the BBC with Dan Kleppner: http://www.youtube.com/watch?v=bdzHnApHM9A&feature=related
- Optional: PhET "Quantum Bound States" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Bound_States

1. de Broglie Wavelengths

To Do and To Notice

Ask participants the following set of questions and have them discuss in pairs. Then, discuss all questions as a group.

Compute the de Broglie wavelength for (a) an electron and (b) a baseball. Choose reasonable values for the parameters in the problem (for example, the approximate speed of an electron in an atom). The mass of an electron is 9.1×10^{-31} kg. Compare these values to the spacing between atoms (which is about 10^{-10} meters). What does this tell you?

Clicker/Discussion Question: Falling stones

A stone is dropped from the top of a building. **What happens to its de Broglie wavelength as it falls?**

A. Increases
B. Decreases
C. Stays the same

What's Going On?

The de Broglie wavelength for both the electron and the baseball is given by $\lambda = h/p = h/mv$. Even if the electron is given a very high speed, its momentum is dominated by its small mass, and its wavelength is longer than that of the baseball[8]. If the speed of the electron is chosen to be around 10^6 m/s, then the wavelength of the electron is close to the interatomic spacing. The wavelength of the baseball will be around 10^{-34} m; much smaller than the size of an atom. Thus, a baseball does not have observable wave characteristics; its wavelength is too small. This is why the quantum nature of classically sized objects can be generally ignored.

As a stone falls, its velocity increases and so does its momentum. Thus, its wavelength decreases. What does this mean for the de Broglie wavelength of objects as they cool down? Their wavelength increases. So, colder objects have larger de Broglie wavelengths.

[8] For a sample calculation, see http://hyperphysics.phy-astr.gsu.edu/hbase/debrog.html#c4.

2. Can You Tell Them Apart?

To Do and To Notice

Remind participants of *The Hook* activity from Unit 5, *How To Make Something Really Cold?* The marbles (representing atoms) are now moving very slowly. Can you tell them apart? Sure. We can tell one marble apart from its neighbor. But let's think about the marbles as quantum particles. Consider their de Broglie wavelengths. Discuss the following questions as a group: What happens to the wavelength of the atom as it cools? What would its wavefunction look like? Can you sketch it? Interpret that graph physically.

Optional: Show the PhET "Quantum Bound States" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Bound_States to demonstrate how energy relates to the number of nodes in the wave function. (Use the first tab, "One Well," and click on different energy levels to see the wave function, or its probability density, in the bottom window. Notice how the wave function broadens if the width of the well is increased. How does that relate to localization?)

Optional: Show the video "Bose-Einstein Condensate" from the BBC with Dan Kleppner (content developer for Unit 5) for a nice visual analogy of Bose-Einstein condensates. http://www.youtube.com/watch?v=bdzHnApHM9A&feature=related.

Show the animation of the Bose-Einstein condensation at http://www.colorado.edu/physics/2000/bec/images/evap2.gif. Before you run the animation, explain: "Electrons in an atom are in a potential well caused by the Coulomb attraction of the nucleus. In the Bose-Einstein condensate, the atoms are in a manmade potential well—a "bowl" of energy. The middle of the image represents the bottom of the bowl. Any atom there is at the lowest possible energy state. Run the animation, and see that a there is a greater density of atoms in the middle (the bottom of the bowl) as the condensate forms. This shows that all the atoms are in the same state—the lowest energy state." Due to common confusion about this image, we recommend that participants make a sketch labeling the x and y axes on this image. The x-axis represents space; the y-axis represents particle density. But there is a hidden variable in the y-axis—energy—such that the middle of the image represents low potential energy.

What's Going On?

As the atom cools, the wavelength of the atom becomes broad. A sketch might look something like the sketch below. The electron is now less localized—it has a probability of being anywhere within the enclosure (though it has a higher probability of being in the center).

Just like electrons within an atom have a lowest possible energy state (the 1s; refer to the *Periodic Chessboard*), atoms within a potential well also have a lowest possible energy state. If the atoms are bosons, then they can all occupy that same quantum state with the lowest energy. The wavefunction depicted above represents the lowest energy quantum state; the next highest energy state would have a node in the middle.

As the wavefunctions of the atoms spread out, they no longer have a well-defined position, and it becomes difficult to tell them apart. They are no longer *distinguishable*—like a photon, these particles have the same quantum state and are in the same location. In the same way that photons in a laser occupy the same quantum state and the same location, these atoms now share the same quantum state. They have become a *superatom*.

<u>Take-home message</u>: As an atom cools, its de Broglie wavelength increases. As a group of atoms cools to absolute zero, their wavelengths overlap and they become indistinguishable.

Activity 5: Watch and Discuss the Video

<u>Time</u>: 50 Minutes.

Have a few participants read their summaries of the experiments in the video and discuss any questions or observations as a group.

If participants are watching the video in class, have them view it now.

How can we apply our understanding to the four applications of supercooled atoms

- Superfluids
- Superconductivity and *Cooper pairs*
- Atomic lasers
- Fermi gases

Superfluids are Bose-Einstein condensates, but harder to manipulate. The atoms in a superfluid are *strongly interacting*—they are much more likely to bump into one another than the atoms in a BEC. This makes them much more complicated to model and to understand.

Superconductors form because electrons pair together as Cooper pairs. Each Cooper pair is a boson, since it is made of two spin ½ particles. Though electrons generally repel one another, they are paired in a superconductor because (a) they are cooled until their wavefunctions overlap and (b) they are confined within a crystal. The electrons in this superconductor flow without resistance. These will be covered in more depth in Unit 8. You may wish to show the *Video Extra* for Unit 5 (on the Meissner effect) here.

Atomic lasers are lasers made of Bose-Einstein condensate atoms. These lasers show interference patterns just as lasers made of light do.

Fermi gases are gases made of fermions. In a BEC, the atoms used are bosons. Debbie Jin and her team try to make fermionic atoms pair up to create bosons (like the fermionic electrons that pair up in a Cooper pair). Those bosons then condense.

Back to the Classroom

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.

Topics and Standards

Energy. The total amount of energy remains constant if no energy is transferred into or out of the system (relevant to spectral lines). Energy appears in many forms (such as kinetic and potential). Thermal energy in a system is associated with the disordered motions of its atoms or molecules.

Electricity and Magnetism. In many conducting materials, such as metals, some of the electrons are not firmly held by the nuclei of the atoms that make up the material. In these materials, applied electric forces can cause the electrons to move through the material, producing an electric current. In insulating materials, such as glass, the electrons are held more firmly, making it nearly impossible to produce an electric current in those materials. At very low temperatures, some materials become superconductors and offer no resistance to the flow of electrons.

Atoms and Molecules. Atoms are made of protons, neutrons, and electrons. Atoms are made of a positively charged nucleus surrounded by negatively charged electrons. An atom's electron configuration, particularity the outermost electrons, determines how the atom can interact with other atoms. Atoms form bonds with other atoms by transferring or sharing electrons. When elements are listed in order by the masses of their atoms, the same sequence of properties appears over and over again in the list.

Waves and Light. Wave behavior can be described in terms of how fast the disturbance spreads, and in terms of the distance between successive peaks of the disturbance (the wavelength). Light acts like a wave in many ways.

The Mathematical World. Students should be able to estimate probabilities of outcomes in familiar situations on the basis of history or the number of possible outcomes. How probability is estimated depends on what is known about the situation. Estimates can be based on data from similar conditions in the past or on the assumption that all the possibilities are known. The larger a well-chosen sample is, the more accurately it is likely to represent the whole.

States of Matter. Different arrangements of atoms into groups compose all substances and determine the characteristic properties of substances. An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.

Nature of Science. 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. Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations. 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, but a close match does not necessarily mean that other models would not work equally well or better.

Classroom Resources

Physics 2000. A great set of clear, interactive tutorials 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 a list of all applets, and "Table of Contents" for an index of all topics. http://www.colorado.edu/physics/2000/index.pl. See in particular the links on elements as atoms, the periodic table, and BECs:

- http://www.colorado.edu/physics/2000/elements_as_atoms/index.html
- http://www.colorado.edu/physics/2000/periodic_table/index.html
- http://www.colorado.edu/physics/2000/bec/index.html

Animation of the Bose-Einstein condensation.
http://www.colorado.edu/physics/2000/bec/images/evap2.gif.

The **Nobel Prize website** for Bose-Einstein condensates has some helpful explanations. http://nobelprize.org/nobel_prizes/physics/laureates/2001/public.html.

Absolute Zero from NOVA. A video program and set of activities related to temperature. http://www.pbs.org/wgbh/nova/zero/. Includes an activity guide intended for middle school students that would also be appropriate at the high school level, including some demonstrations on superconducting levitation, the meaning of absolute zero, and Bose-Einstein condensation.
http://www.compadre.org/portal/document/ServeFile.cfm?ID=8053&DocID=718.

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 *How can atoms exist?*
http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.

PhET interactive simulation on models of the hydrogen atom
http://phet.colorado.edu/simulations/sims.php?sim=Models_of_the_Hydrogen_Atom.

Public lectures from the Kavli Institute for Theoretical Physics. A variety of public lectures by notable scientists on a variety of relevant topics, including Nobel Laureate Wolfgang Ketterle on BECs. http://www.kitp.ucsb.edu/outreach/public-lectures/past-lectures-talks.

A **physical model of de Broglie's atomic model** from Paul Doherty at the Exploratorium. http://www.exo.net/~pauld/activities/energylevelmodel/bohratom.html.

Physics Central **explanatory websites on Bose-Einstein Condensates** http://www.physicscentral.com/explore/action/state-1.cfm,
http://www.physicscentral.com/explore/pictures/cold-atoms.cfm,
and on Fermi gases http://www.physicscentral.com/explore/action/gas-research.cfm.

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.

PARTICIPANTS

Text: Read Unit 7: *Manipulating Light* for the next session.

Video: Watch the video for Unit 7. Using information from the video, and any external sources, consider the following questions and write some notes or short answers to guide you during discussion in the next session:

1. Why is it useful to create a quantum computer? What are the computing problems that it is trying to solve?
2. What are the challenges or barriers to creating quantum computing?
3. In the video, they call this, "spooky action at a distance." What does this mean? How is this different or similar to the "action at a distance" from Unit 2?
4. What do you think about Dr. Hau, and the implications of her team's work?
5. How do these experiments relate to the double slit experiments from Unit 5?
6. How is quantum entanglement consistent with Einstein's theory of relativity, which states that no information can travel faster than light?

Unit 7

Manipulating Light

Introduction

In this odd state, light takes on an almost human
dimension. You can almost touch it.
- Lene Hau, physicist,
discussing her experiments with slow light

Light is central to our lives—it illuminates our way, and provides the warmth we need to live. But it has proven particularly hard to understand. Quantum theory taught us that light acts both as a wave and a particle, giving rise to some surprising behavior (as explored in Unit 5). Light doesn't move like most waves, however. Einstein recognized, in his theory of special relativity, that light has a maximum speed—186,000 miles per second. Recently, scientists have been able to manipulate the properties of light in sophisticated ways. Our increasing ability to affect the movement of light—to slow it down or create *entangled* photons—could lead to completely new types of computer architecture, or applications that haven't yet been imagined.

What Will Participants Learn?

Participants will be able to:

1. Analyze how light of different wavelengths moves through materials using ideas such as *absorption*, *index of refraction*, *phase velocity*, and *group velocity*. Relate this to the particle vs. wave nature of light described in Unit 5.
2. Describe the quantum mechanical concept of entanglement and contrast it with the behavior of classical objects.
3. Give a practical application for quantum entanglement and explain what obstacles must be overcome before this can be exploited in real-world devices.
4. Justify how quantum entanglement is consistent with Einstein's theory of relativity, which states that no information can travel faster than light.

What's in this Unit?

Text: Unit 7: *Manipulating Light* reviews Lene Hau's experiments in slowing light. Ultra-cold atoms of sodium form a *Bose-Einstein condensate (BEC)*. This BEC is hit with a series of laser beams, resulting in the atoms being placed in a *superposition* of two quantum states. This changes the BEC from being completely opaque (because the BEC absorbs incident light and move en masse to a higher energy level) to being transparent at a single frequency. Light at or around this frequency moves very slowly through the BEC because the speed of light depends on the changes in refractive index. Thus, the light pulse is compressed as it moves through the BEC. As a result, the information from the light pulse is contained in a *holographic imprint* in the sodium atoms. If the laser creating these peculiar circumstances is turned off, that holographic imprint remains, essentially allowing light to be stopped in its tracks. The ability to slow light, and store its information in matter, could be important for the emerging field of *quantum computing.* Quantum computers would store information in *quantum superpositions* of

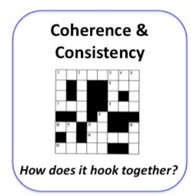
0's and 1's (i.e., these *qubits* can be 0 and 1 at the same time). Additionally, quantum computers will probably use *quantum entanglement*, where the quantum state of one atom is linked to the quantum state of the other one. This is especially important for the field of cryptography, as a change in the quantum state of one atom would easily be observed, providing information as to whether someone had intercepted the message.

Video: The program delves into the cutting edge of our ability to manipulate light to our own ends. Quantum computing uses the probabilistic nature of quantum mechanics to create new computing architectures that enable different types of computing and cryptography. Paul Kwiat and his team at the University of Illinois create photons of laser light that are entangled, which have quantum wave functions that are connected to one another. Such photons—called quantum bits or *qubits*—can serve to encode and process information much faster than in classical computing. Lene Hau, at Harvard University, uses Bose-Einstein condensates (BEC's)—ultracold atoms—to slow and stop light. The atoms in the BEC are all in the same quantum state, the ground state, which allows Lene Hau and her team to imprint a laser pulse on the atoms through some careful manipulation.

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: How Does Light Get Out of a Window? (15 minutes)
- Activity 1: Slowing Light (30 minutes)
- Activity 2: Watch and Discuss the Video (60 minutes)
- Activity 3: Entangled Socks (30 minutes)
- Back to the Classroom (15 minutes)

Nature of Science Theme: *Coherence & Consistency*. You may wish to display the *Coherence & Consistency* icon during the session and remind participants of the central ideas of this theme. Science is not a set of independent facts and formulas (as often seen by students). Rather, scientific findings are accepted as true because they hold together with other ideas and findings. Conflicts between results or between experiment and theory reduce scientists' confidence in either the experiment or the theory.



Exploring the Unit

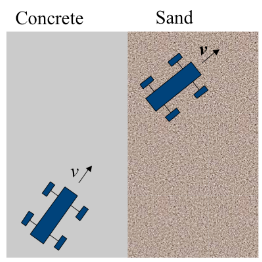
The Hook: How Does Light Get Out of a Window?

<u>Time</u>: 15 Minutes.

Shine a light (such as a flashlight) through a window. Pose the following questions to participants and discuss:
- If light slows down when it goes through the glass, where does it get the energy to speed up?

The total energy of the light beam never changes. It slows down as it travels through the glass because some of its energy goes into "rattling" the atoms of the material, instead of moving itself forward. In a similar way, a car hitting a patch of sand uses some of its energy to move the sand around. Once the car is out of the sand, or the light is out of the glass, more of the energy is available to move it forward, and its velocity increases.

So, when light moves through a material, some of its energy goes into vibrating the atoms of that material. (*Note*: This is not the same as saying that it causes electronic energy transitions in the material). This is also why light bends when it hits a medium with a higher refractive index, as in the analogy with a car hitting sand, shown below: The front right wheel slows first, turning the car at the boundary.



A car moves from concrete to sand
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

Take-home message: Light can move through materials quickly or slowly depending on the index of refraction of that material.

Activity 1: Slowing Light

Time: 30 Minutes.

Purpose: To explore how the speed of light of a material can depend on features of the light itself (such as its wavelength), as well as on properties of the material, and how this leads to different phase and group velocities for light.

Materials:

- Internet access or downloaded simulation at http://webphysics.davidson.edu/applets/Superposition/GroupVelocity.html or http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/sines/GroupVelocity.html)

1. Light Through Glass

To Do and To Notice

Clicker/Discussion Questions:

1. Glass is transparent to visible wavelengths of light, but opaque to ultraviolet wavelengths. **What happens to the ultraviolet light that hits the glass?**

   A. It slows down more than the visible light
   B. It slows down less than the visible light
   C. It bumps electrons in the glass up to a higher energy level
   D. It heats up the glass
   E. Something else/More than one of these

2. Glass is transparent to visible wavelengths of light, but visible light is made of more than one wavelength. **Compared to red light, blue light:**

   A. Slows down more than red light
   B. Is absorbed more than the red light
   C. Heats up the glass
   D. Something else/More than one of these

Recall the particle/wave nature of light. **Which model of light is appropriate in each of these situations?**

What's Going On?

1. Best answer is (E). It bumps the electrons up to a higher energy level (C). This ends up heating up the glass (D), because those electrons then "fall back down" to a lower energy level by releasing thermal energy. So, if a material is *transparent* that means that there are no atomic or molecular energy levels that match the wavelengths of the incoming light.

2. Best answer is (A). Blue light slows down more than red light because the index of refraction depends on the wavelength, or frequency, of the light. This is why blue light is bent more than red light when traveling through a prism, as can be calculated through *Snell's law* ($n_1 sin\theta_1 = n_2 sin\theta_2$) and the fact that $n=c/v$, where n is the index of refraction, θ is the angle from the normal in two media, and v is the velocity of that wavelength of light in the media.

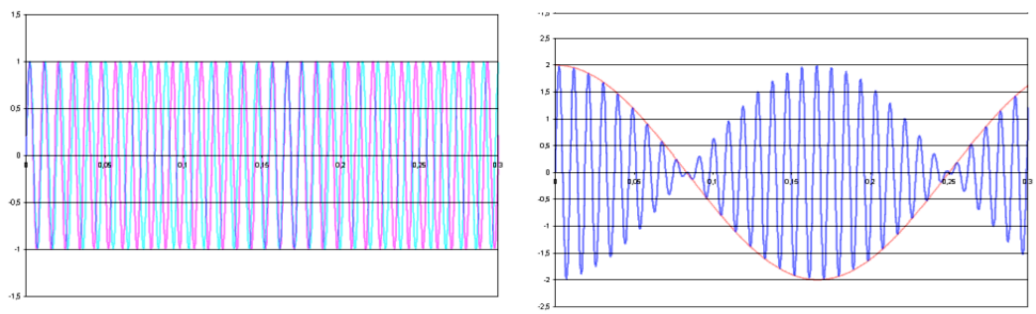
One should consider light as a particle when considering processes like absorption, when atoms in the materials have transitions near that photon wavelength, as for ultraviolet light absorbed by the atoms/molecules in the glass. A wave model for light works when the material is transparent, and so light moves through without interacting with the material, as in question 2.

2. Group Velocity

Open the Physlets applet, Group Velocity Demonstration:
http://webphysics.davidson.edu/applets/Superposition/GroupVelocity.html[1].
Press "Forward." Two sine waves with the same wavelength move at the same velocity.

Now change one of the waves on the applet to have a different wavelength than the other (e.g., change 2.5*sin(**8.0***(x–1.0*t)) to 2.5*sin(**7.0***(x–1.0*t)), then click "Change"). An interference pattern is shown, known as a *beat pattern*.

- What do participants know about beat patterns?
- How would this beat, or wave packet, move if both constituent waves moved with the same velocity?



Two sine waves (110 Hz, magenta, and 104 Hz, blue) sum to form a beat with a new frequency pattern. The envelope is shown in red.
These images are not from the simulation.
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

Test their prediction by pressing "Forward". The wave packet moves at a constant velocity that is the same as the constituent waves.

- How would this wave packet move if both constituent waves moved at slightly different velocities?

Test their prediction (e.g., change 2.5*sin(8.0*(x–**1.0***t)) to 2.5*sin(8.0*(x–**1.5***t)), press "Change" then press "Forward"). The wave packet moves at a different velocity than the constituent waves. Try different values of velocity for each of the constituent waves. What do you notice? Can you make the wave packet go backwards? Slower than the constituent waves? Faster than the constituent waves?

[1] You can check for newer versions of this simulation at http://www.compadre.org/OSP/. Another quality simulation, with fixed phase velocity, can be found at http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/sines/GroupVelocity.html.

Clicker/Discussion Question:

The group velocity is given by $v_g = \frac{c}{n - \lambda \cdot dn/d\lambda}$. **If $dn/d\lambda$ increases, what happens to the group velocity?**

A. It increases
B. It decreases
C. It stays the same
D. It depends on n and/or λ
E. Something else

What's Going On?

Beat frequencies are created by the sum of sine waves with frequencies/wavelengths that are just slightly different. A similar pattern is created by the addition of more than two sine waves. If they are all moving at the same velocity, the *wave packet*, or beat, will also move at that same velocity. If the individual sine waves are moving at different velocities from one another (called *phase velocities*), the wave packet will move at a different velocity (called the *group velocity*). This phenomenon is called *dispersion*. The information carried in a light wave travels at the group velocity. Thus, the group velocity must always be equal or less than *c*, though individual phase velocities may actually be faster than *c*.

Light is made of waves of light with several different wavelengths (even laser light has more than one wavelength, but the range of wavelengths is very narrow). Light traveling through a medium (and not absorbed) travels at different speeds depending on its wavelength, because the index of refraction depends on wavelength. It turns out that the group velocity of the wave packet depends not only on the phase velocity of individual wavelengths of light, but also on how that velocity varies with wavelength of the light.

The best answer to the clicker question is (B)—the group velocity will slow down. If $dn/d\lambda$ is zero, the expression reduces to the standard equation for velocity: $v=c/n$. As $dn/d\lambda$ increases, the denominator gets larger, and thus the group velocity decreases (and becomes negative). So, the more dramatically that the velocity through the material varies with wavelength, the slower the group velocity of the light pulse. This is what Lene Hau did in her experiments—she slowed the group velocity of the light pulse.

3. Slowing Light: The Recipe (optional)

To Do and To Notice

How did Lene Hau do her experiment? The answer is not simple, but here is a model. Stand near three platforms of different heights, like a table (State 3), chair (State 2), and the floor (State 1). Place an object on the floor (like a mug), representing an atom in its ground state. This is where all atoms in a Bose-Einstein condensate would be.

- What happens to the mug if we hit it with the probe laser, tuned to the difference between the floor and the table (States 1 and 3)?
- Recalling the first clicker question from today, what does this imply?

Clicker/Discussion Questions:

1. **What would happen if we only turned on the probe laser (tuned to the difference between the floor and the table, or State 1 and State 3)?**

    A. A single atom moves up to the table (State 3)
    B. All atoms move up to the table (State 3)
    C. Some unknown fraction of atoms move up to the table (State 3)
    D. The light is completely absorbed
    E. The light is completely transmitted
    F. Something else/More than one of these

2. Now we turn off the probe laser. **What happens to the atom (the mug on the floor) if we then hit it with the coupling laser, tuned to the difference between the chair and the table (States 2 and 3)?**

    A. The atom absorbs the coupling laser, and is promoted to State 3
    B. The atom might or might not absorb the coupling laser, it depends on quantum mechanics
    C. The atom does not absorb the coupling laser at all
    D. Something else

3. If the table (State 3) has been split into two levels (one higher and one lower than the original table), **what happens when we turn the probe laser back on (tuned to the difference between State 1 and the *original* State 3)?**

    A. It's all absorbed by the BEC
    B. Half of it is absorbed by the BEC
    C. None of it is absorbed by the BEC
    D. Some unknown fraction is absorbed by the BEC, but we won't know until we measure it
    E. Something else/More than one of these

What's Going On?

Turning on just the probe laser would bump the mug up to the table, or the atom up to State 3. A BEC is completely opaque: It absorbs all incoming light in this way. The challenge of slowing light, in part, was to make the BEC transparent to light.

1. The best answer is (B). A single atom would move up to the table (demonstrate this by moving the mug to the table), had there been only one. However, since this is a Bose-Einstein condensate, *all* the atoms in the Bose-Einstein Condensate will move to the higher level in unison. The first clicker question of today's session showed us that this is indicative of strong absorption of the light. This is why a Bose-Einstein condensate is opaque.

2. The best answer is (C). The coupling laser is not absorbed, the coupling laser is tuned to the difference between the chair and the table. The mug is on the floor, so the coupling laser is the wrong color to lift the mug from the floor to either the chair or to the table. This makes the atoms transparent to the coupling laser. However, participants may remember from the reading that this coupling laser

manipulates the optical properties of the material, so that its index of refraction varies strongly with wavelength. Why this happens is subtle; the presence of the coupling laser actually splits the table into a superposition of two tables—one that is slightly higher than the original table and one that is slightly lower.

3. Best answer is (C). None of the probe light is absorbed. You can't lift the mug from the floor and place it in the space between the two tables; it has to go to either the low table or to the high table. Quantum mechanics tells us that the possibility for absorption of the probe laser by the low table *interferes destructively* with the possibility for absorption of the probe laser by the high table. The two possible pathways conspire to precisely cancel each other out. So, the probe light is not absorbed at all. This is the "dark state" that is referred to in the online text. This dark state makes a holographic imprint of the probe laser as it moves through the material. If the coupling laser is turned off, the split table becomes one table again, and atoms can absorb the probe laser, so the material once again becomes opaque.

Take-home message: If a wavelength of light is absorbed by a material, then electrons jump to higher levels. If a wavelength of light is transmitted through a material, then there are no gaps between electron levels that are equivalent to the energy of that wavelength of light (i.e., where $E_1-E_2=hf$). Wavelengths that are transmitted move at different velocities, but the velocity of the light pulse is different from those individual frequencies. The velocity of the light pulse can be manipulated by changing material properties.

Activity 2: Watch and Discuss the Video

Time: 60 Minutes.

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

1. Why is it useful to create a quantum computer? What are the computing problems that it is trying to solve?
2. What are the challenges or barriers to creating quantum computing?
3. In the video, they call this, "spooky action at a distance." What does this mean? How does this compare to the "action at a distance" from Unit 2?
4. What do you think about Dr. Hau, and the implications of her team's work?

Discuss any questions or comments that participants have about the contents of the video.

1. Why is it useful to create a quantum computer?

There are many reasons that participants may have found, including increased efficiency, the ability to solve complex problems rapidly (because one can operate on a qubit in a multitude of states simultaneously), and quantum encryption (in part because of the ability to detect the presence of a third party attempting to read the encryption key). Key funders of quantum computing are, tellingly, the Department of Defense and the National Security Administration. Simulations are another application of quantum computing: Classical computers can only simulate a few dozen atoms at a time, for example, whereas a quantum computer could simulate complex interactions of various systems (such as what will be found in Unit 8). Richard Feynman was one of the first to propose quantum computers—specifically with the goal of running simulations.

2. What are the challenges or barriers to creating quantum computers?
First, any system for creating a quantum computer must be able to be scaled up. Paul Kwiat's work involved just a few qubits, and required an entire laboratory. A quantum computer that consists of millions of qubits must be of a reasonable size. Because qubits exist in superposition states, accidental measurement of that state will collapse the wavefunction. It's hard to maintain superposition states.

3. What does "spooky action at a distance" mean?
Quantum entanglement is a very different kind of "action at a distance" than that in Unit 2. They are both "spooky" because it appears that information is being transmitted instantaneously through space—either about the quantum state of a particle, or about the motion of an electron. But in the case of electricity and magnetism, one object (an electron) exerts a force on another object (say, another electron) through electromagnetic waves. There is a mechanism by which information is transmitted, with a time delay, from one place to the other. For entangled particles, however, measurement of the quantum state of one particle instantly affects the quantum state of the other particle. Even though they are separate in space, they are entangled, quantum mechanically. This idea will be explored further in the next activity.

4. What do you think about Dr. Hau, and the implications of her team's work?
Dr. Hau is a somewhat inspirational figure, especially as a female scientist, and her success is an example of how much of scientific discovery is due to hard work and perseverance. What ideas do participants have about how her work might lead to practical applications?

Activity 3: Entangled Socks

Time: 30 Minutes.

Purpose: To explore what is meant by quantum entanglement, and how it differs from classical behavior.

Materials:
- Two identical boxes (any size)
- Two different colored socks (such as pink and blue)

1. Entanglement: So What?

To Do and To Notice

Remind participants that in the video, a blue photon split into two red photons of different energy. When measured, they could have any proportion of the energy of the original photon, as long as their total energies equal the total energy of the blue photon. Let's imagine that, instead of any possible energy, one must have 60% of the energy of the blue photon, and the other must have 40%. So, this means that when the energy of one is measured to be 60%, the other must have 40%.

If you don't know quantum mechanics, this doesn't seem surprising. Take out the two socks. Put one sock in one box, and the other sock in the other box. Mix up the two boxes. Give one box to a participant on one side of the room, and the other to a participant on the other side of the room. Ask one to open their box. Now, we know which sock is in the other box, even though we haven't opened it. Why are we not amazed?

Entangled socks[2]

Ask participants to discuss in groups of 2-3:

- Why is this not surprising for socks, but it is surprising for photons? How was our experiment with the socks different from the experiment with photons in the video?

What's Going On?

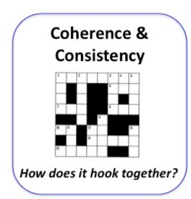
Classically, this experiment isn't surprising at all. Classically, each sock was pink or blue the whole time. But if these were entangled "quantum socks", then both socks together would be in a superposition state of pink and blue. Considering the experiments of Paul Kwiat and his team, the pink sock could represent a photon with 40% of the original photon energy and the blue sock represent one with 60% of the original photon energy.

A particular sock only has a definite color when we measure it, in which case it "chooses" a color (called *collapse of the wavefunction*). If the first sock is measured to be pink, then the second sock must be measured to be blue. This is what the *Schrödinger's cat thought experiment* is referring to. The cat in the box is in a superposition state of alive and dead, as we don't know whether the radioactive source has decayed (killing it) or not. This thought experiment gave rise to the term entanglement. (*Note:* Of course, a superposition of alive and dead is nonsense, which was Schrödinger's purpose in posing the paradox. The interpretation of the thought experiment depends on which interpretation of quantum mechanics one uses.)

Hold up the boxes, and indicate that we now have a photon in each box. Participants should be able to argue that they are an indeterminate color until they are measured. Open one box to show the colored sock inside. What changed at the moment that I opened the box? What do we now know about the other photon? Now is this surprising?

2. Entanglement: Making Sense

To Do and To Notice



Again, in small groups, ask participants to discuss with one another their answers to the last two homework questions, and then discuss as a group.

1. How do these experiments relate to the double slit experiments from Unit 5?
2. How is quantum entanglement consistent with Einstein's theory of relativity, which states that no information can travel faster than light?

[2] Sock image source: © Wikimedia Commons, License: CC ShareAlike 1.0. Author: Ranveig, 21 July 2005. http://commons.wikimedia.org/wiki/File:Fun_socks.png.

What's Going On?

In the double slit experiment, photons went through both slits, but interacted with the screen at a single point. It only became localized when it interacted with the screen, which is a type of measurement. Similarly, the photons have every possible energy before measurement, and only have a specific energy when they are measured.

Entanglement is not in violation of Einstein's theory because no actual information is being transmitted. Imagine that Alice and Bob both have a box with a sock. If Alice opens a box to find a pink quantum sock, she doesn't know whether she opened her box first (so that Bob's quantum sock is destined to be blue) or if Bob opened his box first (so that Alice's quantum sock was destined to be pink). In other words, she can't tell if her measurement resulted in her sock "choosing" to be pink, or if she is learning something new about Bob's sock. So, although the measurement of the color of the sock affects the wavefunction (and thus color) of the other sock, there is no actual information that can be transmitted through this process.

Take-home message: When a photon is in a superposition state, where it has two or more values simultaneously, measurement of the state of that photon forces it to choose one of those states. (This is also true of other quantum particles.) If two photons are created so that they are entangled, the measurement of the state of one photon forces the wavefunction of the other one to collapse, as well.

Back to the Classroom

Time: 15 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.

Topics and Standards

Waves and Light. Visible light is a small band in the electromagnetic spectrum. Light acts like a wave in many ways. Waves can superpose on one another, bend around corners, reflect off surfaces, be absorbed by materials they enter, and change direction when entering a new material. The energy of waves (like any form of energy) can be changed into other forms of energy.

Historical Perspectives. 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."

States of Matter. Different arrangements of atoms into groups compose all substances and determine the characteristic properties of substances. An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.

The Nature of Science. New technologies make it possible for scientists to extend their research in new ways or to undertake entirely new lines of research. The very availability of new technology itself often sparks scientific advances. Investigations are conducted for different reasons, including to explore new phenomena.

Classroom Resources

Description of Lene Hau's work and a brief biographical sketch from Physics Central. http://www.physicscentral.com/explore/people/hau.cfm.

PhET Interactive Simulations on *Quantum Interference*, *Quantum Tunneling,* and *Lasers* are relevant to the topics in this unit. http://phet.colorado.edu.

Simulations/applets on group vs. phase velocity
http://webphysics.davidson.edu/applets/Superposition/GroupVelocity.html
http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/sines/GroupVelocity.html.

A set of interactive Java applets on refraction from the National High Magnetic Field Laboratory. http://micro.magnet.fsu.edu/primer/lightandcolor/refractionhome.html.

A series of brief informative articles on quantum computing and cryptography from the Center for Quantum Computation at the University of Cambridge
http://cam.qubit.org/articles.

Teacher Conferences Talks from the Kavli Institute for Theoretical Physics. Online archives of talks (click on "Online Talk" for audio and slides), geared towards teachers, by leading scientists and educators. Particularly relevant are *Atoms and Lasers* and *Nanoscience and Quantum Computing.* See also the public lectures by notable scientists on a variety of topics, such as Quantum Mechanics and Quantum Information Science. http://www.kitp.ucsb.edu/talks.

Introductory set of lectures on quantum computing by David Deutsch, very clear and informative. http://www.quiprocone.org/Protected/DD_lectures.htm.

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.

Participants will be bringing in examples of emergence for the next unit. You could also assign certain examples to participants to research, if you would like to ensure that there is no overlap in terms of the topics that participants bring to share.

PARTICIPANTS

Text: Read Unit 8: *Emergent Behavior in Quantum Matter* for the next session.

Preparatory assignment:

1. Find a definition of *condensed matter physics.* What kinds of things do condensed matter physicists study? What is "soft" condensed matter? And, most importantly, how do the topics of condensed matter physics relate to emergence? Other useful vocabulary terms to define are: *complexity, complex adaptive matter, phase transition, symmetry breaking, critical point,* and *quantum critical point*.
2. Bring in two examples of emergence—behavior arising from the interaction of many individual pieces. Pictures and/or video are encouraged. Be prepared to explain just what is emergent about what you are showing, and to describe the science behind that example. Two useful websites to start at are http://emergentuniverse.org and http://www.pbs.org/wgbh/nova/sciencenow/3410/03.html.
3. *Optional:* Read the short article "More Is Different" by P.W. Anderson (*Science*, vol. 177, number 4047, pp. 393-296, 1972). Copies are easily available on the internet. This article is sometimes credited with changing the scope of what was then called solid state physics. Dr. Anderson has been called "the most creative physicist in the world" based on research by José Soler.

Video: Watch the video for Unit 8. Compare and contrast what these physicists study with the research in Units 1-5. Is there anything qualitatively different about what they are studying, what questions they ask, and what techniques are they using?

Unit 8

Emergent Behavior in Quantum Matter

Introduction

The reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.
– Philip W. Anderson, "More is Different,"
Science (177), 393–396, 1972.

For a world that obeys the second law of thermodynamics, there is a surprising amount of organization—such as crystal structure in a snowflake or a piece of salt, or life itself. Additionally, many surprising phenomena have been observed that wouldn't have been predicted simply from an understanding of the constituent pieces of that system, such as superconductivity or the intelligent behavior of a colony of ants. A relatively new perspective on physical systems, *emergence* (or *complex adaptive systems* or *complexity*) attempts to understand the macroscopic implications of the interactions between multiple smaller pieces. Biologists are using these techniques in their own fields, as we'll see in the next unit. Physicists, too, are gaining new insights into nature by examining emergent behavior arising from the complex interaction of individual pieces.

What Will Participants Learn?

Participants will be able to:

1. Define emergence as an approach to explaining physical systems compared to the more common reductionist approach.
2. Provide two or more examples of when an emergent approach may be productive.
3. Describe two or more examples of emergent behavior in condensed matter using terms such as phase transition, critical point, states of matter, and jamming.
4. Compare and contrast the methods of constructing scientific knowledge in previous units with those in Unit 8. Outline the types of questions these physicists are trying to answer, and describe their methods.

What's in this Unit?

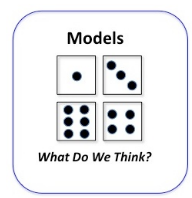
Text: Unit 8: *Emergent Behavior in Quantum Matter* describes the concept of *emergence*, particularly as it applies to the constituent particles, such as atoms or electrons, which make up materials. Variations in the density of these particles are themselves a type of particle (a *quasiparticle*) called a *phonon*. The interactions between these phonons and fields in the materials serve as a sort of glue, causing particles to interact in ways that lead to surprising behavior. Superfluids can be explained in this way: The effective attraction between two atoms cause them to act as one particle with a single wave function at low temperatures, allowing them to flow without resistance. Similarly, superconductivity was finally understood in the *Bardeen-Cooper-Schrieffer (BCS) theory* as a coupling between electrons due to these phonon interactions, allowing them to act as a particle with a single wave function, flowing without resistance. The same techniques can be applied to understand superfluidity in *neutron stars*.

Video: The program follows the work of two physicists—an experimentalist and a theorist—studying systems with emergent properties by modeling their properties in different ways. Paul Chaikin, at New York University, experiments with close-packing using M&M's®. He determines the organizational principles for how these candies interact with one another to determine the behaviors of large collections of particles. By studying this emergent behavior, he creates more simplified models, such as computer programs, combining the reductionist and emergent perspectives. Piers Coleman, from Rutgers University, examines emergent behavior from a theoretical viewpoint. His work focuses on the idea of *critical points*, or the point at which matter moves from one stable state to another (such as the phase transition between liquid and frozen water). Along with an experimental team, Coleman investigates what rules govern the transition of a material, such as a superconductor, from one state to another. In this way, the behavior of many billions of atoms can be explained using simple rules.

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: Who's the Leader? (10 minutes)
- Activity 1: Exploring Emergence (20 minutes)
- Activity 2: Watch and Discuss the Video (50 minutes)
- Activity 3: To See the World in a Grain of Sand (45 minutes)
- Activity 4: Phases, Materials, and Superconductors (15 minutes)
- Back to the Classroom (10 minutes)

Nature of Science Theme: *Models*. You may wish to display the *Models* icon during the session and remind participants of the central ideas of this theme. Scientists create models, or hypotheses and theories, to make sense of their observations. Thus, a model is a scientific account of nature. A good model is testable and suggests evidence that would support or refute it. When experimental observations do not match the existing model, scientists do and have changed their ideas about nature.



Exploring the Unit

The Hook: Who's the Leader?

Time: 10 Minutes.

Purpose: To follow simple rules and see collective behavior emerge.

Materials:
- Images and video of flocking birds or schools of fish

To Do and To Notice

Instruct participants to walk randomly around the room[1]. When they come within one foot of someone else's back, follow that person. What happens?

Eventually, participants should end up walking in a circle. How is this related to emergence? Who led this behavior? How is this different from the instructor telling participants to walk in a circle?

What are some other examples of bottom-up versus top-down behavior?

What's Going On?

While the instructor was the one who set the rules for participants to follow, those rules are what determined the final collective pattern. This is a bottom-up phenomenon, resulting from the individual contributions. If the instructor had instead told participants to walk in a circle, the situation would be an example of top-down rules, rather than bottom-up behavior. The movement of an army, versus the movement of a crowd on a street, is another example of top-down versus bottom-up behavior. See the Teacher's Guide at NOVA's program on emergence at http://www.pbs.org/wgbh/nova/sciencenow/3410/03.html for examples of top-down versus bottom-up behavior and rules as well as a short informative video.

Flocking behavior results from similar types of simple bottom-up rules, regarding the distance and movement of nearest neighbors. Show some striking videos of flocking and schooling behavior.

Going Further

Can you come up with some other examples of patterns that might emerge from simple rules that participants might follow? Try it.

See the Teacher's Guide at NOVA's program on emergence at http://www.pbs.org/wgbh/nova/sciencenow/3410/03.html for more ideas.

Activity 1: Exploring Emergence

Time: 20 Minutes.

Purpose: To share examples of emergence, and collectively come up with a definition of emergence.

To Do and To Notice

Ask each participant to share an example of emergence. As a group, fill in a table with the phenomenon, the individual piece or part that contributes to that phenomenon, and the interaction between those pieces that results in the collective behavior. Examples are given in *What's Going On?* below. Make sure to discuss ant colonies to some degree, as they will be used as an example later.

[1] This activity used with permission from NOVA scienceNOW: Emergence Viewing Ideas. © WGBH Educational Foundation. www.pbs.org/wgbh/nova/sciencenow.

How might we categorize these different types of phenomena? Come up with as many categorical schemes as possible.

Share and discuss definitions of important vocabulary terms from *Between Sessions*: condensed matter physics, soft condensed matter physics, complexity, complex adaptive matter, phase transition, symmetry breaking, critical point, and quantum critical point. Write these definitions on the board. Use these ideas to build a definition of emergence as a group.

What's Going On?

Here is an example list of emergent phenomena.

Topic or Phenomenon	Individual piece	Interactions
Ant colony	Ants	Pheromone trails
Consciousness	Neurons	Neural connections and firing
Crystals	Molecules	Intermolecular forces
Traffic patterns	Cars	People's reactions to car distance or brake lights
Schooling or Flocking	Fish or Birds	Fish/bird reactions to neighbor's distance and movement
City neighborhoods	People	People's and businesses' reactions to a neighborhood's reputation and flavor.
Superconductivity	Electrons	Lattice vibrations called phonons
Slime mold slug	Slime mold spores	Chemical signals
Superfluid	Atoms	Bose-Einstein statistics/quantum attraction
Crowd behavior	People	Rules for social interaction/neighbor distances
Magnetism	Magnetic domains	Magnetic coupling
Heartbeat (synchronicity of pacemaker cells)	Pacemaker cells in heart	Coupled action potentials of pacemaker cells
Synchronicity	Fireflies	Mimicry plus internal pacemaker cells
Liquid crystals	Molecules	Intermolecular interactions
Bose-Einstein Condensation	Atoms or molecules	Quantum mechanical uncertainty resulting in single wave function for all atoms
Color	Atoms	Light and atomic structure
Stock market	Investors	Transactions

There are several categorical schemes that could be used to describe these examples[2]:

- Living/Non-Living
- Biology/Physical Science
- Nature/Human/Non-Living
- Microscopic/Human-sized/Macroscopic

For the purposes of this unit, we will use the categorization of "Living vs. Non-Living." The non-living examples are, almost without exception, from the field of physics known as *condensed matter*. Condensed matter is the study of the physical properties of matter. It used to be called "*solid state physics*," which is the study of solids and other forms of rigid matter. *Soft condensed matter*, on the other hand, is the study of

[2] Several items on the emergence list, and the follow-up activity, adapted from NOVA scienceNOW: Emergence Viewing Ideas. © WGBH Educational Foundation. Used with permission. www.pbs.org/wgbh/nova/sciencenow.

materials which deform under stress, like polymers, liquids, colloids, and granular materials. The written text for this unit focuses on solid state physics, whereas the video touches on both solid state and soft condensed matter. In today's session, we will focus on emergence in condensed matter physics: both solid-state and soft condensed matter. By some accounts, all of condensed matter physics can be considered emergent.

The simplest definition of emergence is the interaction of individual pieces, following simple rules, which leads to collective behavior. There is no leader, or top-down control in such systems—the collective behavior comes from the bottom-up interaction of many individuals. In flocking, for example, each bird is following simple rules: Stay close to your neighbors, but not too close, and avoid predators. From these rules comes surprisingly coherent behavior of the flock as a whole. (*Note*: In particular, non-linear interactions, in which the character of the interaction changes with some parameter, like distance, lead to surprising behavior. In this way, complex behavior is not simply the additive sum of many individual interactions.)

Here is a definition of emergence from the National Academies: [3]

> *Emergent phenomena in condensed-matter and materials physics are those that cannot be understood with models that treat the motions of the individual particles within the material independently. Instead, the essence of emergent phenomena lies in the complex interactions between many particles that result in the diverse behavior and often unpredictable collective motion of many particles.*

Emergence relates to several other key concepts:

> *Complex systems* are systems with many interacting parts. Thus, emergence is essentially the description of the observable phenomena that arise from complex systems. Self-organization is an often-studied feature of complex systems. *Complex adaptive systems* are a subset of complex systems in which feedback is critical.
>
> *Phase transitions* are the transition from one phase of matter to another. This can be a familiar state of matter (such as solid and liquid) or other types of phases (such as *paramagnetic* and *diamagnetic*). When a material changes phase sharply with the varying of some external parameter (as when ice freezes at a clearly defined temperature and pressure), this is called a *first order phase transition.* The properties of materials on either side of a phase transition are emergent. Phase transitions are a key sign of emergent behavior.
>
> Phase transitions usually involve *symmetry breaking*—a change in the symmetry of the constituents. For example, the molecules in a liquid are randomly arranged, and thus very symmetric. The molecules in an ice crystal are very orderly. Since disorder is more symmetric than order (you can look at a liquid from any angle and it will look the same), this is an example of symmetry breaking. Since symmetry breaking would not be predicted from fundamental laws, it is seen as a key aspect of systems that cannot be explained through reductionist means.
>
> At a *critical point*, there is no clear boundary between two phases—the transition between two phases is continuous (a *second-order phase transition*). For

[3] *Condensed Matter and Materials Physics: The Science of the World Around Us*, National Academies Press (2007).

example, a magnetic material that is held near the Curie temperature has properties intermediate between a magnet and a metal. This new, intermediate behavior can be considered a phase of matter unto itself, and thus emergent. A *quantum critical point* is a special class of critical point.

Emergence is a new *model* of the world. Some scientists question the utility of the ideas of emergence and complexity, as they may be too broad to be useful in directing scientific enterprise.

Take-home message: Emergence is a broad concept, spanning the life and physical sciences. It refers to the phenomena observed in complex systems, in which many simple parts together create new (and often self-organized) bulk behavior. In condensed matter physics, it could be said to relate to the bulk of research in that field.

Activity 2: Watch and Discuss the Video

Time: 50 Minutes.

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:

- Compare and contrast what these physicists study with the research in Units 1-5. Is there anything qualitatively different about what they are studying, what questions they ask, and what techniques are they using?

Discuss these questions in terms of *Models*. These physicists' search for rules of interaction, instead of the fundamental building blocks, does affect their scope of investigation. But how? The reductionist techniques from previous units still play a role here, as can be demonstrated, for example, in Dr. Chaikin's use of computer simulations to model the emergent behavior that he sees.

Activity 3: To See the World in a Grain of Sand

Time: 45 Minutes.

Purpose: To use cereal and other materials to investigate self-organization, phases of matter, and critical points in granular materials, or *soft* condensed matter.

Materials:

- Circular fruit-flavored cereal (such as Froot Loops®)
- Rice
- Sugar
- A variety of funnels (1/4" works well)
- Cups
- Shallow containers
  (*Note:* You will use the cereal again in Unit 9, so get plenty.)

Before the session: Experiment with your materials to determine the best amounts and which containers to use.

Ask participants to prepare to be keen observers in this activity. Many of the insights and ideas in this activity are the product of noticing what happens with the different materials. Give each group of 2-3 participants a set of materials, including about 2 cups of each granular material. All activities in this section are done in these small groups, with large group discussion following.

1. Some Sugar in My Bowl

To Do and To Notice

Tell participants to pour the sugar from a cup to a shallow container. What do they notice? Prompt them, after they have explored for a few minutes, to notice (a) what happens to the pile in the shallow container, and how this is affected by the speed with which sugar is poured into it, and (b) what happens to the sugar in the cup as it is being poured, and how this changes with the angle that the cup is tipped. Have them come up with as many observations as possible—anything goes. There are two critical points they might find—what are they? How does this relate to phase transitions? Discuss in small groups and then share ideas as a class.

What's Going On?

When dropped grain by grain into the shallow container, the sugar acts like a solid, and grains bounce from the bottom of the container. When it is poured faster, it acts like a liquid. This is a type of phase transition to liquid-like behavior. A granular material is not a liquid in the standard sense—it belongs to a class of its own due to unusual properties, which are explored in the rest of this activity.

There are two critical points that can be observed in this activity. As the cup holding the sugar tips, the sugar maintains its shape. In this way, it acts like a solid. It doesn't form a level surface because of the force between grains, supporting it into a pile. At some critical angle, it starts to flow, acting like a fluid. Thus, at that critical angle, the solid "melts." This is an example of a continuous phase transition with interesting behavior at the transition. You may notice that the sugar begins to flow, and then stops, in small avalanches. Thus, the sugar near this critical angle exhibits new emergent behavior itself. Another thing to observe is that the sugar does not behave like a normal fluid—as you tip it, only the sugar on the surface flows, and the bulk of the sugar stays in place.

Another critical point can be observed in the sugar pile in the shallow container. This pile acts like a solid. Once the pile is steep enough, the addition of a single grain of sand can either do nothing, or it can cause a collapse of the pile (which can be seen as a "melting" of the solid). The pile will also collapse if you shake it. In this case, the random motion that you cause by shaking it is analogous to the random motion of molecules caused by thermal energy. Shaking the pile increases the "granular temperature," thus "melting" the pile.

The peaked sugar pile, which can be easily prompted to rearrange into a uniformly flat mound of sugar, is an example of a *meta-stable state*. That pile is stable as long as it's not disturbed, but a slight tap will allow it to reach a lower energy configuration (i.e., flat). Meta-stable states will be explored again in Unit 9.

2. Don't Stand So Close to Me

To Do and To Notice

Have participants pour the cereal into a cup. Allow the cereal to mound up slightly above the level of the cup, and try to get one level cup by pushing slightly on the top of the cereal. Then try shaking and tapping the cup. What do you notice?

What's Going On?

As with Paul Chaikin's work on M&M's®, the cereal when poured is rearranged with large gaps between them. Shaking and tapping the cereal allows it to explore other configurations, thus, reaching a more densely packed state. *Close packing* is related to phase transitions because the density of particles is often related to different phases of matter. The interactions between individual particles creates the packing density in different materials—thus, packing density is an emergent phenomenon.

3. We Be Jammin'

To Do and To Notice

Participants can explore the rice for a few minutes, and report on any interesting behaviors. How does it differ from the sugar in terms of how it pours or how the piles collapse? Ask them to pour the rice into the funnel. What do they notice? If the rice does not flow from the funnel, how do they get it started again? How does this relate to critical points? Discuss in small groups and then share ideas as a class.

What's Going On?

Jamming is considered a phase transition from liquid to solid-like behavior—it is a function of the density of the material. When the rice *jams* in the funnel, the physical geometry of the grains is arranged in such a way that each grain is trapped in a cage made of other grains. Unlike a normal solid, where an applied force is distributed throughout the solid, a granular material supports force irregularly. Thus, tapping causes a few key grains to rearrange (generally to be more aligned with one another), starting the flow again. However, flow generally only proceeds for some short period of time, and the material jams again. Similar to the sugar avalanches that began, and stopped, this is a critical point—a gradual transition between two phases.

Participants might notice that the rice and the sugar behave quite differently in the funnel, and when poured into a pile, due to their different shapes. Jamming in a funnel is very dependent on the ratio of the size of the material to the width of the funnel opening. Understanding how material behavior depends on its shape, and what causes jamming, is of particular importance to various industrial applications.

Take-home message: The interactions between individual particles in granular materials result in different phases of behavior similar to the phases of solid, liquid, and gas, and the properties of these materials near the critical points, or boundaries between these different phases, also exhibit interesting behavior. Jamming is related to the transitions between these phases.

Activity 4: Phases, Materials, and Superconductors

Time: 15 Minutes.

Purpose: To discuss different phases of matter in condensed matter physics, and their relationship to emergence.

Materials:
- A pitcher of water
- Circular fruit-flavored cereal (such as Froot Loops®)

- Bowls

1. Phases of Matter

To Do and To Notice

Explain to participants that we are now leaving the world of granular materials and entering other areas of condensed matter physics. The cereal pieces will now represent atoms or molecules. Have participants pour water into a bowl, then add the cereal pieces one by one. What do they notice? In a second bowl, throw a handful of cereal pieces into the bowl all at once. Using a finger, push down the ones that are sticking out of the water so that all lie flat. What do they notice? How do these patterns differ? Discuss with respect to jamming and phase transitions. Example images are given in *What's Going On?* below.

Clicker/Discussion Question:

How many phases of matter have scientists identified?

A. Three
B. Four
C. Somewhere between four and thirty
D. Over a thousand
E. Something else

Discuss as a large group. List all the phases of matter that you can think of—you should come up with at least 6.

What's Going On?

When the cereal pieces are added one by one, the cereal pieces should self-organize into an ordered structure, as in the picture below. This models the slow freezing of molecules to form a typical crystalline solid. When the cereal pieces are added all at once, their organization should be less structured. The cereal pieces (representing molecules) do not have time to arrange themselves into the most energetically favorable configuration.

Crystalline close-packing

Glasslike random packing

This is a model of rapid cooling to form a *glass*. A glass is an amorphous, non-crystalline solid. This is another example of a metastable state. If you shake the bowl, tap the pieces, or move them with your finger, you can achieve the more ordered crystalline pattern—but this more stable state is only achieved by adding energy to the system in this way. The glasslike structure is an example of jamming. The glass is a solid because the molecules are jammed, and need to be jostled in order to flow (much like the rice in the funnel). The glass and the crystalline solid are two different phases of matter.

One fascinating conjecture is that jamming (and unjamming) in the systems from the last activity and this one—rice in a funnel, sand creating a sandpile, and molecules in a glass—are governed by the same type of behavior. This is an area of active research.[4]

The answer to the clicker question is (C): Somewhere between four and thirty. Typically, people consider solid, liquid, gas, and maybe plasma, as the three or four "phases of matter." But as can be seen from the example with the glassy phase, and the list of emergent phenomena at the beginning of this unit, the study of condensed matter physics involves the study of a great many states of matter. Each state of matter can be related to a phase transition, and the properties of each could be considered emergent. Here is a possible list:

- Crystalline solid
- Liquid
- Gas
- Plasma
- Glass
- Insulator/conductor
- Liquid crystal: Isotropic
- Liquid crystal: Nematic
- Liquid crystal: Smectic[5]
- Magnetic materials[6]
- Superfluid/Bose-Einstein condensate
- Superconductors

2. Superconductors

Now we'll consider the topic of superfluids and superconductors. As we saw in Unit 6, at very low temperatures materials may become superfluid. There are three main types of superfluids in nature:

1. Condensed bosonic atoms (i.e., BEC's, helium-4)
2. Condensed, paired fermionic atoms (i.e., Fermi gases, helium-3, neutrons in neutron stars)
3. Condensed, paired fermions (i.e., superconductors, electrons in metals, protons in neutron stars)

The last two can be understood with Bardeen-Cooper-Schrieffer (BCS) theory. We will consider superconductors. These paired electrons are called *Cooper pairs.* To understand Cooper pairs, we'll first use an analogy.

[4] See work by Sid Nagel (University of Chicago) and Andrea Liu (University of Pennsylvania).

[5] Liquid crystals themselves can be described by many more different phases.

[6] Magnetic materials consist of several different types of ordering, such as *ferromagnetism*, *diamagnetism*, and *paramagnetism*.

Clicker/Discussion Questions:

1. **Which of the following represent the individual pieces that contribute to the emergent collective behavior of an ant colony?**

   A. Pheromones
   B. Ants
   C. The queen
   D. The physical location of the colony
   E. Something else/More than one

2. Complete the analogy: ***Ants* are to *pheromones* like *electrons in Cooper pairs* are to _____ in the BCS description of superconductivity.**

   A. The crystal lattice
   B. Phonons
   C. Resistance
   D. Temperature
   E. Something else/More than one

Discuss other open questions about superconductivity from the written unit. How is superconductivity emergent?

What's Going On?

1. Ants (B) are the individual pieces that make up the emergent behavior of a colony. The queen is not a leader—rather, ants interact through simple rules that relate to following chemical trails called pheromones. Thus, pheromones are the means by which the ants interact. (The cereal pieces, on the other hand, interact through cohesion.)

2. The answer is (B): Phonons. Electrons in a superconductor are the individual pieces that give rise to the collective behavior of superconductivity, and they are attracted to one another via phonons. It is surprising that the electrons in a superconductor would be attracted to one another, as they are electrostatically repelled.

   At low enough temperatures, these electrons can interact through the vibrations of (A), the crystal lattice making up the crystal. These vibrations are called phonons. One could argue that (A) is correct, but the most precise answer is (B)—the lattice itself does not attract the electrons to one another, rather, the vibrations of that lattice do that job. (*Note:* The cereal model is not an analogy for superconductivity—superconductors exhibit a different kind of collective ordering.)

Thus, superconductivity is emergent because an understanding of the interaction of individual electrons would not explain the creation of paired electrons (called Cooper pairs). Because the electrons in a Cooper pair are paired, they can move coherently (without bouncing off one another), thus allowing electricity to flow without resistance. The phase transition to the superconducting state is a hallmark of emergence, as is the existence of a critical point (in this case, a *quantum critical point*). Current research examines the relationship between superconductivity and the kind of jamming discussed in granular systems.

Going Further

You may show participants magnetic levitation using the Meissner effect if you have access to a superconducting pellet. See, for example, the *Video Extra* from Unit 6. Also, many videos are available online of superconducting levitation, including a particularly engaging one using a model train: Search the internet for "IFW Dresden levitating train".

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.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.

Topics and Standards

Energy. Chemical energy is associated with the configuration of atoms in molecules that make up a substance. Some changes of configuration require a net input of energy whereas others cause a net release.

Electricity and Magnetism. At very low temperatures, some materials become superconductors and offer no resistance to the flow of electrons.

States of Matter. A system usually has some properties that are different from those of its parts, but appear because of the interactions between those parts. Atoms may link together in well-defined molecules, or may be packed together in crystal patterns. Different arrangements of atoms into groups compose all substances and determine the characteristic properties of substances. An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.

Systems. A system usually has some properties that are different from those of its parts, but appear because of the interaction of those parts. Most systems above the molecular level involve so many parts that it is not practical to determine the existing conditions, and thus the precise behavior of every part of the system cannot be predicted. Even in some very simple systems, it may not always be possible to predict accurately the result of changing some part or connection. As the number of parts in a system grows in size, the number of possible internal interactions increases much more rapidly, roughly with the square of the number of parts.

Nature of Science. Scientists formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models. A mathematical model uses rules and relationships to describe and predict objects and events in the real world. The usefulness of a model can be tested by comparing its predictions to actual observations in the real world. But a close match does not necessarily mean that other models would not work equally well or better. 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. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations. 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.

Classroom Resources

Emergent Universe. A project of the Institute for Complex Adaptive Matter, this beautiful website explores many aspects of emergent phenomena with compelling visual examples. Includes examples of emergent phenomena. Click on "Unlocking the Universe" for interactive games and a comic book. http://emergentuniverse.org.

Teachers' Conferences from the Kavli Institute for Theoretical Physics. Online archives of talks (click on "Talks" for audio and slides), geared towards teachers, by leading scientists and educators. Particularly relevant is *High Temperature Superconductivity: What is it?.* http://www.kitp.ucsb.edu/outreach/teachers/conferences.

Gallery of Computation. A collection of artwork from a computer programmer who creates his pieces by writing algorithmic programs that result in sometimes surprising images. http://complexification.net/gallery/.

Hands-on activities from Jill Johnsen at the Exploratorium on self-assembly (using Cheerios) and a BB model of grain boundaries demonstrating close packing. http://www.exo.net/~jillj/.

Emergent e-labs collaborative site for creating teaching activities on emergence. Contains labs and educational materials on superconductivity. https://sites.google.com/site/edusupernet/.

Music of the Quantum: Short discussions of emergence from leaders in the field (sponsored by ICAM). See particularly the sections on "Emergence & Transformation" and "Soft Matter" (soft condensed matter). http://musicofthequantum.rutgers.edu/.

Why do Complex Phenomena Emerge from Simple Ingredients? Book chapter, in *Condensed Matter and Materials Physics* from the National Academies Press (2007). This excellent (and free) online textbook provides an undergraduate-level primer on all the important topics in this unit, such as superconductivity, Fermi liquid theory, quantum critical points, complexity, and their relationship to emergence. http://www.nap.edu/openbook.php?record_id=11967&page=30.

The Institute for Complex Adaptive Matter Outreach and Education page includes many resources, such as a wiki devoted to teaching ideas of emergence, and an online encyclopedia devoted to emergence. http://icam-i2cam.org/index.php/outreach/

Lectures for children from the Santa Fe Alliance for Science, many on topics related to emergence and complexity. Look especially for titles with the word "complex". Video quality is mixed, but talks are easy to locate. http://www.sfafs.org/science_cafes.asp.

Superconductors.org. A basic resource page on superconductors, including explanatory articles and links to tutorials and images. http://www.superconductors.org/.

Concepts in Complex Systems. A nicely organized, clear set of explanatory pages on the concepts related to complexity and emergence. http://necsi.org/guide/concepts/.

WNYC Radio Lab: Emergence. A charming and provocative radio episode on emergent phenomena. http://www.wnyc.org/shows/radiolab/episodes/2005/02/18.

NOVA scienceNOW episode on emergence and complex patterns. Includes a 12 minute video appropriate for the classroom,
http://www.pbs.org/wgbh/nova/sciencenow/3410/03.html.
Includes a teacher's guide and viewing ideas here:
http://www.pbs.org/wgbh/nova/teachers/programs/3410_03_nsn.html.

Absolute Zero from NOVA. A video program and set of activities related to temperature. http://www.pbs.org/wgbh/nova/zero/. Includes an activity guide intended for middle school students that would also be appropriate at the high school level, including some demonstrations on superconducting levitation. http://www.compadre.org/portal/document/ServeFile.cfm?ID=8053&DocID=718.

The Game of Life. Here you can play online a simple version of John Conway's famous Game of Life, where simple local rules give rise to a variety of complex behavior. http://psych.hanover.edu/JavaTest/Play/Life.html.

Hyperphysics concept map of superconductivity, including BCS theory. A helpful organization of key concepts.
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/supcon.html#c1.

A teacher's guide to superconductivity for high school students. A rather old (1994) but still useful guide on the fundamentals and applications of superconductors, homework questions, and experiments using superconducting pellets.
http://www.ornl.gov/sci/htsc/education.html.

Interesting books and articles: "The Complexity Complex" from *University of Chicago Magazine*, http://magazine.uchicago.edu/0212/features/index.html; S. Nagel, "Physics at the Breakfast Table—or waking up to physics," American Journal of Physics, 67:1, 1999; S. B. Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* (Scribner, NY, 2001); and S. H. Strogatz, *Sync: How Order Emerges from the Chaos in the Universe, Nature, and Daily Life* (Hyperion, NY, 2004).

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.

PARTICIPANTS

Text: Read Unit 9: *Biophysics* for the next session.

- Write down one or two questions that you have in each area.
- Bring a "gem" to the next session on each topical area—an interesting or relevant idea, activity, or observation that you'd like to share.

- How could you expand your concept map from Unit 1 to include these topics?

Video: As you watch the video for Unit 9, consider the following questions:

- As you watch, mark things that you've seen or heard about before. Why are they showing up here in biology?
- What are some other examples of the results of one field informing another field?
- What are some things that one has to consider when working with biological systems that one doesn't have to worry about in non-biological systems?

Exploring Further: Do the interactive tutorial activity "Protein Folding" at http://molit.concord.org/database/activities/225.html (but not reports or writing activities).

Unit 9
Biophysics

Introduction

There is still much lack of knowledge about this advanced level of organization of matter we call 'life', and its novel non-material consequences. However, at this stage, it is simply 'lack of knowledge', and not 'discrepancy' with the present concepts of physics
– Manfred Eigen, biophysicist and 1967 Nobel Laureate

Biologists operate in a very different domain than physicists—they study microscopic structures and particles, deep inside the body, buffeted by collisions with millions of other microscopic particles within the cellular soup. How can the ideas and approaches of physics be used in such a complex environment? This unit addresses how physicists have provided key insights and techniques in the world of biology, helping to push the frontiers of both science and medicine. Many of the concepts of *emergence*, introduced in Unit 8, apply to these topics in the biological realm.

What Will Participants Learn?

Participants will be able to:

1. Recognize how the tools of physics do and do not apply in biological systems and describe some of the limitations of these tools in biology.
2. Explain how protein folding is consistent with the physical principles of *entropy* and *energy landscapes*, and how these principles have been useful in explaining/describing these biological processes.
3. Describe the concept of a *fitness landscape* in evolution and use it to explain the evolution of one or two different *genotypes* (e.g., sickle cell anemia or beak size).
4. Describe how the brain is fundamentally different from a computer.

What's in this Unit?

Text: Unit 9: *Biophysics* covers four main areas where physics has informed the practices of biology, in increasing size scale: DNA, protein folding, evolution, and the mind and consciousness. DNA contains the genetic code, and contains a huge amount of information—more, in fact, than is needed to determine the structure of the organism. Quantifying the information in a strand of DNA is a topic of study within physics. DNA codes for the sequence of amino acids in a protein, but the actual folded structure of that protein depends on a wide array of variables. Physicists have contributed the concept of *free energy landscapes*, and *local minima*, to help understand how proteins choose from the many possible folded configurations. The diversity of the genetic code is closely tied to how particular genomes affect an organism's fitness level—i.e., the process of evolution. How organisms evolve in response to stress can be understood, in some part, with an application of physics principles. Finally, the study of computation has provided some insights into the mind and memory—though the limitations of this approach highlight how the mind and consciousness are fundamentally different from a computer, representing an emergent phenomenon.

Video: The program covers two medical treatments that have been inspired by research in physics. Vinothan Manoharan and a team at Harvard University study *self-assembly*—a topic of Unit 8. Since viruses appear to create their outer shell (called a *capsid*), the study of how this self-assembly occurs could be advantageous in fighting disease. Harald Paganetti, of Massachusetts General Hospital and Harvard Medical School, works on *proton therapy*, which uses radiation to destroy cancerous cells in a more targeted fashion than traditional radioactive treatments. Proton radiation research is directly borrowed from physicists' particle accelerators.

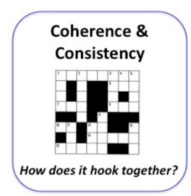
Interactive Lab: *Laser Cooling*. Learn the basics of how to manipulate atoms with light, and cool a hot atomic beam to a few millionths of a degree above absolute zero.

Activities:

- The Hook: Big Forces at Small Distances (15 minutes)
- Activity 1: Life and the Second Law (15 minutes)
- Activity 2: Breakfast Proteins (30 minutes)
- Activity 3: Fitness Landscape (15 minutes)
- Activity 4: Watch and Discuss the Video (50 minutes)
- Activity 5: Pulling it Together (15 minutes)
- Back to the Classroom (10 minutes)

(*Note:* The video for this unit is not closely tied to the content of the written text. Thus, you may choose to assign the video and discussion questions for homework. If you choose to show the video in class, you may wish to drop the second half of *Activity 1: Life and the Second Law* in the interest of time.)

Nature of Science Theme: *Coherence & Consistency*. You may wish to display the *Coherence & Consistency* icon during the session and remind participants of the central ideas of this theme. Science is not a set of independent facts and formulas (as often seen by students). Rather, scientific findings are accepted as true because they hold together with other ideas and findings. Conflicts between results or between experiment and theory reduce scientists' confidence in either the experiment or the theory.



Exploring the Unit

The Hook: Big Forces at Small Distances

Time: 15 Minutes.

Purpose: To introduce the idea that different forces (namely, *collisional* and *thermal forces*) dominate at the microscopic scale rather than at the familiar macroscopic scale.

Materials:

- A heavy ball and a light ball (e.g., steel ball and a ping pong ball)
- Digital projector
- PhET simulation "Gas Properties"
  http://phet.colorado.edu/simulations/sims.php?sim=Gas_Properties

(*Note*: You do not need to be connected to the internet to run these simulations. Choose “Download” to save to your computer.)

To Do and To Notice

Roll the light ball across the floor. What happens? What affects how far it rolls? What might stop it? Roll the heavy ball across the floor. Why does it roll further?

Project the PhET simulation “Gas Properties.” Select “Light Species” for the *Gas in Pump*. Pump the handle a small amount, so a few (5 or fewer) red balls enter the chamber. What do participants notice about their behavior? Does it look similar to the ball rolling across the floor?

Then pump the handle about twice, so that there are many light gas molecules in the chamber. It’s difficult to follow the motion of these molecules with the eye, so add 3 or 4 heavy gas molecules using the manual controls on the right. What do participants notice about the behavior of these blue molecules? Add more red molecules with the pump and increase the pressure, and notice how the behavior of the blue molecules becomes more erratic. How easy would it be to “throw” a blue molecule from one side of the chamber to the other?

What’s Going On?

The heavy ball rolls further than the light ball because of its greater mass. It is slowed, and eventually stopped, by friction—both with the table, and with the molecules of the air. Our intuition is useful in answering these questions.

Our intuition is less useful when we look at microscopic objects. The isolated red gas molecules in “Gas Properties” are mainly affected by their own momentum, as were the rolling balls. Once many molecules are added, however, they begin to show Brownian motion due to the multiple collisions. As the number density of the red gas molecules is increased, their behavior becomes increasingly erratic. This is the experience of microscopic sized objects, such as proteins and DNA, which exist in a sea of water molecules inside the human body. When a ball is thrown across the room, it collides with air molecules, but its motion is mostly dictated by its own weight and momentum. When a blue molecule is thrown across the chamber, however, its motion is mostly dictated by collisions with other molecules. Its momentum only affects its behavior for a fraction of a second. Thus, forces like *viscous drag* are very important for objects in the cell.

Below is a list and description of important forces at this size scale.

Force	**Sample calculation**[1]
Collisional and thermal	Collisions are equivalent to thermal energy. The force due to a collision is given by $F = \Delta p/\Delta t = \Delta(mv)/\Delta t$. If struck by a water molecule (average v = 600 m/s, average m = 30×10^{-27} kg) once per second, F=36×10^{-12} pico Newtons (pN). The effects of random collisions drives Brownian motion. Due to the large number of collisions, the overall force is relatively large (~500 pN on a typical protein). Similarly, if a protein were accelerated forward, it would only move forward under that force for a fraction of a second before hitting another object (or being slowed by drag, see below).
Viscous	Drag forces are also relatively larger on small objects, due to the greater ratio of drag to momentum as an object's mass decreases. DNA would come almost immediately to a stop. For a similar reason, it takes 10 hours for a protein to move a distance of 100 mm in a spinning centrifuge. Drag increases with the size and shape of the object; for a typical protein at typical speeds the viscous force is about 480 pN.
Electrostatic	A charged particle experiences a force $F=qE$ in an electric field. Due to the small electric charges of, for example, an ion, these forces are usually only a few pN. The atoms on a protein chain, however, experience high electric fields due to their proximity, resulting in forces up to 100 pN between atoms in a protein. This is important in protein folding, later in the session.
Elastic	Proteins and DNA both have stiffness; this stiffness may be demonstrated by grabbing and dragging the optical trap apparatus on the bottom of the screen. If "show DNA force" is checked, the restoring force will be shown. For a typical motor protein, this force might be about 1 pN for a stretch of 1 nanometer.
Gravity	Gravity is negligible for these small masses. A protein mass is about 166×10^{-24} kg, giving a gravitational force of only 1.6×10^{-9} pN. This is 11 orders of magnitude smaller than viscous forces!

Take-home message: Biological molecules are suspended in liquid, and experience thousands of collisions each second. Because of their small mass, these collisions affect the momentum of the particle much more than most external forces (such as electricity, or mechanical forces).

Activity 1: Life and the Second Law

Time: 15 Minutes.

Purpose: To explore how entropy relates to biological systems, both in terms of protein folding and the existence of life itself. Molecular collisions leading to Brownian motion explains why the DNA strand in the PhET simulation "Stretching DNA" moves erratically, and entropy explains why it folds when released from the trap. (*Note: Part 2* is self-contained and may be eliminated in the interested of time.)

[1] Sample calculations from J. Howard, "Mechanics of Motor Proteins and the Cytoskeleton" Sinauer Press, 2001.

Materials:

- Latex gloves (enough for every one or two participants)
- Digital projector
- PhET simulation "Stretching DNA"
  http://phet.colorado.edu/simulations/sims.php?sim=Stretching_DNA
  (*Note*: You do not need to be connected to the internet to run these simulations. Choose "Download" to save to your computer.)

1. Dancing DNA

To Do and To Notice

Project the PhET simulation "Stretching DNA." Explain that what is shown is a strand of DNA—a biological polymer. Proteins are also biological polymers, so similar behavior would be seen if this were a protein. The pushpin represents one end of the DNA molecule that is pinned in place. The yellow ball represents a dielectric bead, which is held in an optical trap just like the molecules of a Bose-Einstein condensate (BEC) in Unit 6 and 7. Demonstrate that the ball may be moved, stretching the DNA. What do participants notice about the behavior of the strand of DNA? What forces might be responsible for the behavior that they see? Discuss briefly before presenting the clicker question.

Clicker/Discussion Question:

What do you think are the three most important forces on the strand of DNA (not including the force from the optical trap)?

1. Gravity
2. Elastic stretching
3. Thermal/collisions
4. Viscous drag
5. Electricity and magnetism

A. 1, 3, 4 (gravity, thermal, viscous drag)
B. 2, 3, 4 (elastic, thermal, viscous drag)
C. 1, 3, 5 (gravity, thermal, electricity and magnetism)
D. All of them are important
E. Something else

How does the behavior of the DNA strand differ from, say, a string sitting in a glass of water?

What's Going On?

Because of its size, DNA is affected by very different physical forces than more familiar objects. The best answer to the clicker question is (B). Make sure that participants understand that (a) gravity is negligible and (b) thermal/collisional effects are important at this scale. This is why the DNA strand shows such erratic behavior whereas a string in a glass of water sits perfectly still, to our eye. The string's mass is much more significant with respect to the water molecules. The DNA's erratic behavior can also be explained in terms of entropy, as described below.

2. Entropy and Life

To Do and To Notice

Ask participants for a definition of the *second law of thermodynamics*, and write it on the board. Facilitate a Think-Pair-Share.

- What is *entropy*?
- Is life consistent with the second law of thermodynamics?

Ask participants to put on the latex glove and stretch the latex rapidly against their skin. What do they notice?

Clicker/Discussion Question:

> **If the latex glove gets warm as it is stretched, what must be true of the entropy of the glove as it is stretched?**
>
> A. It increases
> B. It stays the same
> C. It decreases
> D. The heat of the glove isn't related to its entropy
> E. Something else

Return to the PhET "Stretching DNA" simulation. Turn off the power on the optical trap, releasing the yellow molecule. What happens to the DNA strand?

Think-Pair-Share

- How can this be explained in terms of entropy?

What's Going On?

The second law of thermodynamics includes the following principles:

- Thermal energy flows from high temperature to low temperature
- The total entropy (or microscopic disorganization) of a system increases during an irreversible process

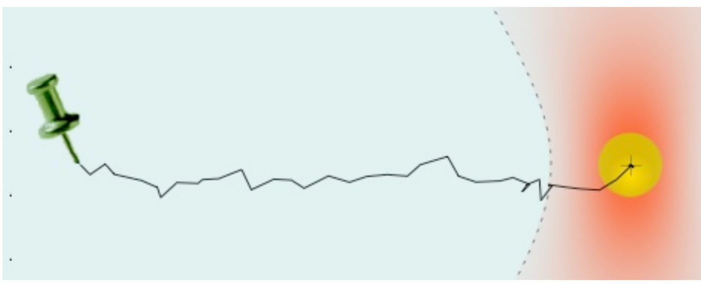
Life might appear to violate the second law because life is a highly ordered, low entropy state. But entropy only increases in isolated systems. Living things are not an isolated system; they exchange matter and energy with their environment. Living things spend a lot of energy to maintain a state of not being in equilibrium with their environment. If an organism is in thermal equilibrium with its environment, it is probably dead. In order to stay alive and maintain their high degree of order (and thus low entropy), life increases the overall entropy of the universe. Thus, the entropy of the universe (a closed system) does increase, and life does not violate the second law.

As the entropy of a system increases, its thermal energy increases, and less energy is available for doing work. This can be illustrated by considering an ice cube. As it melts, it absorbs heat from the environment. Melting represents an increase in entropy, as the highly-ordered crystal becomes a disordered liquid. Freezing represents a decrease in entropy, as the disordered liquid becomes an ordered crystal.

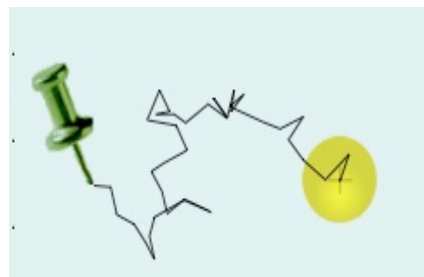
If the latex glove gets warm as it is stretched, then its entropy must be decreasing. Heat flows from the latex during this decrease in energy, like heat flows from water as it freezes into ice. This means that the stretched latex is more ordered than the unstretched latex. Latex is made of polymers, a type of molecular rubber band that is not unlike DNA or a protein. A coiled or folded polymer is less ordered (and thus has higher entropy) than a stretched polymer.

Because both DNA and proteins are polymers, the demonstrations with the PhET simulation on DNA would equally apply to proteins. Thus, the proteins fold because this is a more disordered, high entropy state. In this way, entropy explains why things happen—objects seek a high entropy state.

The different ways that a polymer can fold, or different configurations of the polymer, are called different states of the polymer. Statistically, high entropy means that there are more states. Liquid water has more states than solid ice because the molecules can rearrange themselves in many different ways (each rearrangement is one state). Thermal energy, or collisions with other molecules, "bumps" the polymer into different configurations. Similarly, collisions between water molecules "bump" them into different positions. This allows the polymer, or water, to explore many different states.[2]



Stretched DNA or protein
Low entropy; high order



Folded DNA or protein
High entropy; low order

Take-home message: Coiled or folded polymers are in high entropy, disordered states. Thus, a protein will fold, when left to its own devices, because systems tend towards high entropy. The way that it folds—the particular folding pattern that it chooses—is enabled in part by the thermal energy from collisions with surrounding molecules.

Activity 2: Breakfast Proteins

HANDS-ON ACTIVITY

Time: 30 Minutes.

Purpose: To create an analogy for how DNA codes for protein structure, including the role of RNA. Participants explore how the sequence of amino acids relates to the folded structure of the protein, and the huge array of folding possibilities.[3]

Materials:

- Fruit-flavored donut-shaped cereal (such as Froot Loops®)
- Chenille stems
- String
- Scissors
- Pencil
- Paper

[2] These are complicated ideas, and not every participant will understand the concept of states.
[3] Activity used with permission: "Breakfast Proteins," © Julie H. Yu, Exploratorium, 2010. http://exo.net/~jyu.

Before the session: Using letters to correspond to the different colors of the cereal (i.e., Y=yellow, R=red), write down a template for the cereal chain as follows: BRYBRYPRPYP. Tape this piece of paper in the corner of the room and section off this area with some string. Put some scrap paper and pencils next to this area.

To Do and To Notice

Tell people that the instructions to make their cereal chain are in the corner of the room. Since the instructions are taped down, they can use the scrap paper to help them remember them.

Place a cup of cereal and chenille stems in the main part of the room. People must construct their chains in this area.

In groups of 2–3:

- Compare the finished cereal chains. Is everyone's the same?
- Find the best folding pattern for the cereal chain assuming that "red wants to touch red." Is there only one folding pattern that accomplishes this?
- Going further: Which of these folding patterns is the lowest energy (and thus most likely)?

In the whole group:

- Field participants' questions and invite them to share their "gems" on the topics of the genome, proteins, free energy landscapes, and related topics from *Between Sessions* homework.

Clicker/Discussion Questions:

1. Imagine that a protein consists of ten segments. Each segment can fold in one of two ways. **How many different configurations are possible for the protein as a whole?**

   A. 2
   B. 12
   C. 20
   D. 200
   E. 1024
   F. Something else

2. The online text discussed the concept of *free energy landscapes*. **Which of the following have similar free energy landscapes?**

   A. An electron in empty space AND a ball rolling down a funnel
   B. An electron next to a proton AND a ball rolling down a funnel
   C. An electron in empty space AND a ball on the floor
   D. An electron next to a proton AND a ball on the floor
   E. More than one of these/Something else

Discuss as a group.

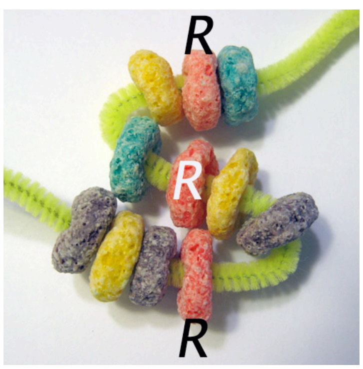
- How does the concept of free energy landscapes relate to protein folding?
- Where is the physics in this activity?

What's Going On?

Making the cereal chain is a model of protein synthesis from DNA. The initial template represents a portion of DNA (called a *gene*) that sits in the nucleus of the cell and gives instructions for how proteins are made. (Variations on each gene, such as a change in one letter, would be called an *allele* of that gene.) In order to get this information to an area where proteins can be made, it must be copied into RNA, which is very similar to DNA but has a different form. This is represented by the hand-written notes on the scrap pieces of paper. The copying process is called *transcription*. Just like in the cell, a single DNA template can give rise to many RNA transcripts. These transcripts move from the nucleus of the cell into the cytoplasm where ribosomes use the information to assemble proteins from amino acid subunits in a process called *translation*. In the cell, the genetic code dictates which amino acid residues correspond to a given DNA sequence, but in the cereal chain it is usually obvious that the letters in the instructions correspond to the color of the cereal. Each participant's cereal chain represents a protein.

The folding of a protein depends on the properties of the amino acids and sidechains (such as electric charge, hydrophobic or hydrophilic) that make it up. How a protein folds is important because this determines its function in the body. Alzheimer's and mad cow diseases are both caused by the misfolding of a single protein, as is sickle cell anemia.

The protein formed here can fold one of three main ways, given the rule that red must touch red.



Configuration #1: Line

Same as Configuration #1, but fold top part onto bottom part so that all three reds are touching

Configuration#2: Twisted line.

Configuration #3: Triangle

Configuration #2 is considered lower energy because (a) the three red pieces of cereal are all touching, unlike Configuration #1, and (b) there are no sharp kinks in the structure, as in Configuration #3. You can imagine why this would be lower energy if you consider the three red cheerios as connected by rubber bands. Configuration #1 stretches the rubber band and so would be at a higher potential energy than Configuration #2. Participants can experiment with protein chains and folding at The Molecular Literacy Project: http://molit.concord.org/database/activities/225.html.

1. Answer is (E); 1024. The number of possible folding configurations for any protein is huge. Scientists can't predict the folding of a protein from its amino acid sequence, in part, because there is a huge array of different folding possibilities. In this activity, if each protein segment can fold in one of two ways, then when two segments are strung together, the whole protein can fold in four ways ($4=2^2$). If three are strung together, the protein can fold in 8 ways ($8=2^3$). If ten are strung together, they can fold in 1024 ways ($1024 = 2^{10}$). Thus, the

number of combinations grows exponentially with the number of segments. In reality, each protein segment can fold in more than two ways, and the number of combinations is immense.

2. Answer is (E); More than one. Both (B) and (C) represent similar energy landscapes. Option (B) represents a flat landscape, and option (C) represents an energy minimum (see figure below). The ball seeks the lowest elevation by rolling down the funnel. This may not bring it to the lowest possible elevation—there may be a deeper funnel a few feet away. Similarly, biological structures try to minimize their potential energy, but not all states are accessible. Proteins find the best folding that they can by minimizing their energy within the local energy landscape. Thus, protein foldings represent *local minima*, or *metastable states* (recall the sand pile of Unit 8). Finding a local minima is more efficient than trying every possible folding configuration by trial and error, as in the Traveling Salesman problem (see *Activity 5*).

Rough energy vs distance diagram for a ball on a funnel or electron near a proton. "Distance" would be replaced with "folding configuration" for a protein energy landscape.

Physics comes into play in many areas of this activity, for example:

- Informatics of the genome
- Bonding between amino acid base pairs
- Intramolecular forces between different parts of the protein chain
- Entropy (See *Activity 1*)
- Energy landscapes

Thus, these biological systems are consistent with physical principles, even if physics is as yet insufficient to explain them in detail (see the quote for this chapter).

<u>Take-home message</u>: DNA codes for protein synthesis. The amino acid sequence of the protein dictates its folded structure. The protein folds to minimize its energy, but there are so many different possible folded structures (due to different combinations of the folding of the subunits of the proteins) that it's impossible for the protein to find the lowest-energy structure by trying all of them. The concept of energy landscapes, from physics, helps explain why proteins can find the lowest energy folded structure quite quickly. Thermal energy nudges a protein into different folded configurations, allowing it to explore the local energy landscape and find the local minimum. Folding is important because the protein function depends on its folded structure—an idea critical for evolution.

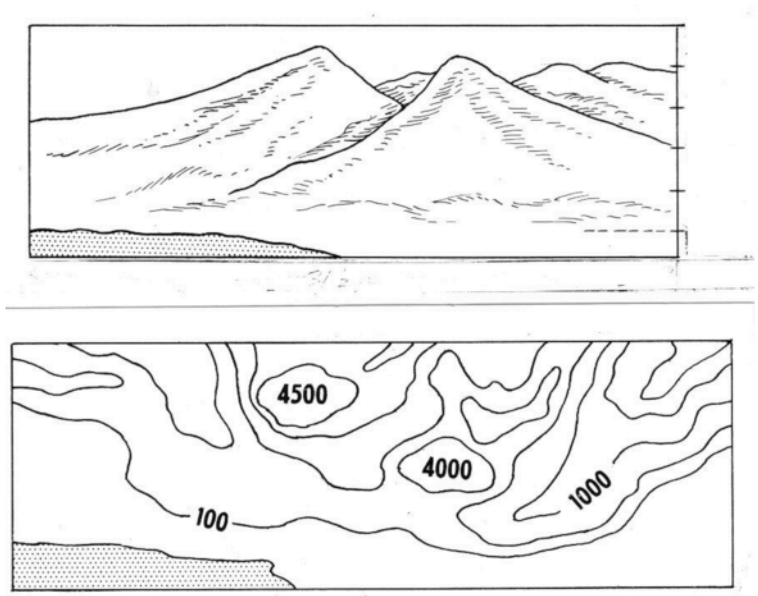
Activity 3: Fitness Landscape

Time: 15 Minutes.

Purpose: To explore the idea of fitness landscapes: How the evolution of a species is related to movement on that landscape, and how the landscape itself can depend on external factors.

To Do and To Notice

Show participants a copy of a topographic map, as below.



Topographic map as an analogy for a fitness landscape[4]
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

This can be used as an analogy for a fitness landscape, in which the goal of species evolution is to seek a maximum of fitness. A finch with a long beak that can pick up smaller seeds is more fit (in terms of that particular trait) than its brother bird with a broader beak that has more trouble picking up seeds—that bird would be at a higher point on one of the mountains than its brother with the broader beak.

As a group, list the features of *free energy landscapes* and *fitness landscapes* in two columns on the board. What types of things does each landscape affect? Which is the best place for an object to be, a hill or a valley? What types of factors move an object up or down on the landscape?

Think-Pair-Share:

1. What are some other examples of processes that would push a species uphill?
2. What are some processes that would push a species downhill?

[4] Source: © Wikimedia Commons, License: None. Author: Pearson Scott Foresman. http://commons.wikimedia.org/wiki/File:Contour_map_%28PSF%29.png.

3. Sickle cell anemia is caused by a genetic mutation that causes a single protein to misfold, making blood cells sickle-shaped. Sickle cell anemia reduces life expectancy. People with sickle cell anemia are less likely to get malaria. How might the fitness landscape for the sickle cell mutation depend on geographic location?
4. Going Further: People who survived the plague called the “Black Death” had a particular genetic mutation that protected them from getting the disease. Before the Black Death, this mutation had no effect on their fitness. Explain this using the concept of fitness landscapes.

Field participants’ questions and invite them to share their “gems” on the topics of evolution and fitness landscapes from *Between Sessions* homework.

What’s Going On?

Free energy landscapes and fitness landscapes are similar concepts, with key differences:

	Free energy landscape	**Fitness landscape**
Things affected by the landscape	Proteins and molecules	Generations of organisms, or genomes
It’s best for those things to move to…	Valleys	Peaks
The factors affecting movement on the landscape	Charge, hydrophobicity, etc.	Finding things to eat, reproducing, resistance to disease, etc.

1. Species can be pushed uphill by a variety of factors. The introduction of antibiotics both puts *selection pressure* on bacteria which are immune to the antibiotic, and *mutation pressure* on bacterial populations to develop immunity to the antibiotic.

2. Species can be pushed downhill by genetic mutations that are maladaptive. Possible discussion point: What type of role do rare mutations from, say, radiation, play in these landscapes (imagine Godzilla as a fictional example). Lack of genetic diversity can also lead to a downhill movement, as the species does not have enough diversity to adapt to its environment.

3. In Africa, sickle cell anemia protects against malaria, so it is adaptive. That genotype will be a peak on the fitness landscape. In Europe, sickle cell anemia is, instead, a valley, representing its maladaptivity.

4. Before the Black Death, the landscape for that particular gene was flat. With the arrival of the Black Death, which killed a large percentage of Europe’s population, a sharp peak in the fitness landscape appeared, showing the strong selection pressure for people with this genotype.

<u>Take-home message</u>: One can consider a species to be under the effects of a variety of forces, or stresses, or pressures, similar to a physical object. The opposing forces of mutation, selection, inbreeding, and crossbreeding must balance in order for an organism to be static in terms of its evolution. Thus, the concepts of (a) equilibrium, (b) opposing forces or pressures, and (c) locally stable but non-optimized states, are useful concepts from physics that apply to biology, further demonstrating the coherence of scientific disciplines.

Coherence & Consistency

How does it hook together?

Activity 4: Watch and Discuss the Video

Time: 50 Minutes.

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.

- As you watch, mark things that you've seen or heard about before. Why are they showing up here in biology?
- What are some other examples of the results of one field informing another field?
- What are some things that one has to consider when working with biological systems that one doesn't have to worry about in non-biological systems

Discuss the video with participants, focusing on the discussion questions.

The perspectives of physics relate to questions of biology in a wide variety of ways. If you examine the table of contents of an introductory Biophysics textbook, you will see many familiar concepts from introductory physics (e.g., energy, forces, bonding, heat and energy transfer), chemical physics (e.g., reaction rates, diffusion) as well as from more advanced or modern physics (e.g., neural networks) and physical techniques (e.g. x-ray, nuclear magnetic resonance, optical tweezers, atomic force microscopy).

String theory is another example of one field informing another, as the mathematics developed for this physical theory has proven useful for various branches of mathematics. The physics of superconductors has been important for developing the branch of medical imaging called *magnetic resonance imaging*, or MRI.

Biological systems are, in many ways, messier than physical systems. One has to consider the rather complicated chemical and physical environment of most biological processes. As discussed in *The Hook* activity, the energy scale of interactions in biological systems is quite different from that in many physical systems. As seen in the video, for medical research one also has to be aware of side effects of treatments. This is not a concern in physics (except when considering the safety of technicians and scientists).

Activity 5: Pulling it Together

Time: 15 Minutes.

Purpose: To see how the different aspects of this unit relate to one another, and discuss the highest level of organization—consciousness and the brain.

Materials:
- *Find the Highest Note* http://www.exploratorium.edu/exhibits/highest_note/
- Related files at http://asa.aip.org/demo27.html)
- *Optional*: Traveling salesman route through Germany from online resource: *Facilitator's Guide High Resolution Graphics*

1. Consciousness and the Mind

To Do and To Notice

Use the auditory illusion *Find the Highest Note*. (Let the cursor hover over each key to play the sound. This can be slow to load—be patient or use the non-interactive "Shepard Scale" version at http://asa.aip.org/demo27.html). Be sure to play the "continuous" version at that website as well—it's quite striking. Ask participants, "What do you notice?" Use this activity, and the online text, to discuss the question:

- How is the brain different from (and similar to) a computer?

Field participants' questions and invite them to share their "gems" on the topics of consciousness and the mind from *Between Sessions* homework.

What's Going On?

In *Find the Highest Note*, each key is actually a collective of notes spaced by an octave. The volume of the different notes in the chords changes as you go around the keyboard, creating the illusion of a never-ending staircase of sound.[5] This, and any other illusion, can show how our perception of the world is different from what is actually there. See also *The Hook* activity from the Introductory Unit. Thus, our mind is different from a computer in that it does not simply process what is there. The complex interactions of many neurons give rise to surprising behaviors, like reasoning or consciousness.

2. What's Complexity?

To Do and To Notice

Think-Pair-Share:

- Where would you place each of the topics from this unit (DNA, protein folding, evolution, and the mind) on your concept map from Unit 1? Do they belong here? Do they need a new concept map?
- Describe the complexity in each of these areas. That is, what are the basic building blocks in each system, and what are the interaction forces or pressures that are resulting in complex behavior?
- How does the Traveling Salesman problem relate in each case?
- How do these types of complexity, or emergence, differ from the types of emergence we saw in Unit 8? Is there something qualitatively different about them, or not?

What's Going On?

In many ways, these ideas require their own **concept map,** and one could organize them hierarchically. However, all the things listed in this unit are made of the "matter particles" identified on the concept map, and they interact through the "force particles" or *bosons*. Thus, one could argue that, for example, protein is made of "matter particles" which interact using the "force particles" but in a very complex manner giving rise to new behavior.

[5] More on this activity here: http://www.exo.net/~pauld/summer_institute/summer_day1perception/find_the_highest_note.html.

We can identify the individual constituent pieces, and their interactions, for each of the topics in this unit:

Topic or Phenomenon	Individual piece	Multiple possibilities for individual pieces	Interactions
DNA/Genome	Amino acids	Sequence of amino acids	Mutations
Protein folding	Amino acids	Many folded structures	Between amino acids and between amino acids and environment
Evolution	Genes and alleles of genes	Many different genotypes	Between organism and environment (fitness)
The mind	Neurons	Many different network structures	Connections between neurons

The "Traveling Salesman" problem is a famous optimization problem. Given a list of cities and the distances between each of them, how can a salesman find the optimal route that minimizes the total distance but visits each city only once?

An optimal tour through Germany's 15 largest cities – the shortest out of exactly 43,589,145,600 (14!/2) possibilities[6]
See the online resource: *Facilitator's Guide High Resolution Graphics*

Solving this problem by trial and error requires a huge amount of time (and hundreds of cities can take years to solve computationally). When there are multiple possibilities for any outcome (such as the number of ways that a protein can fold, the different genotypes that might be adaptive in an environment, or the different paths through which neurons could connect together in a network), nature cannot use trial and error to find the optimal solution. Instead, it finds a good solution based on local variables (See energy or fitness landscapes).

These examples of emergence, or complexity, are similar to those in Unit 8 in that the interaction of many small parts gives rise to new behavior. However, in the previous chapter, one could argue that if we knew a little bit more, we could indeed predict that behavior. We know something about the mechanistic interactions between those parts, we just don't know how to solve a problem with that many pieces. In this unit, we have much less understanding of the fundamental processes and interactions that are giving rise to that emergent behavior.

[6] Public domain image: http://en.wikipedia.org/wiki/File:TSP_Deutschland_3.png.

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.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.

Topics and Standards

(*Note:* See "The Living Environment" at http://strandmaps.nsdl.org/ to explore standards and benchmarks, and common misconceptions, related to biology.)

Forces and Motion. The change in motion of an object is proportional to the applied force and inversely proportional to the mass ($F=ma$). An unbalanced force acting on an object changes its speed or direction of motion or both. Any object maintains a constant speed and direction unless an unbalanced force acts on it.

Energy. Energy appears in many forms (such as kinetic and potential). Thermal energy in a system is associated with the disordered motions of its atoms or molecules. Chemical energy is associated with the configuration of atoms in molecules that make up a substance. Some changes of configuration require a net input of energy whereas others cause a net release. In any system of atoms or molecules, the statistical odds are that the atoms or molecules will end up with less order than they originally had and that the thermal energy will be spread out more evenly. The amount of order in a system may stay the same or increase, but only if the surrounding environment becomes less ordered. The total amount of order in the universe always tends to decrease.

Electricity and Magnetism. Electric forces acting within and between atoms are vastly stronger than the gravitational forces acting within and between atoms.

Size and Scale. Natural phenomena often involve sizes, durations, or speeds that are extremely small or extremely large.

Nature of Science. There are different traditions in science about what is investigated and how, but they all have in common certain basic beliefs about the value of evidence, logic, and sound arguments.

Classroom Resources

Configuration Space. Learn the meaning of configuration space and how to model it as a surface with the Robot interactive. The accompanying text chapter provides background on this topic.
http://www.learner.org/courses/mathilluminated/interactives.

Foldit protein folding game. Solve protein folding puzzles along with other online players. Players' results actually contribute to biological science by providing researchers with algorithms and recipes for protein folding. http://fold.it/portal/.

Folding@home. A distributed computing project from Stanford University, where you can donate your computer cycles to solving protein folding problems. Includes some general information about protein folding. http://folding.stanford.edu/English/Science.

myDNA. DNA teaching activities, including scavenger hunt, the DNA code, and the genome. http://www.dnai.org/teacherguide/guide.html.

WNYC Radio Lab: Emergence. A charming and provocative radio episode on emergent phenomena, including a piece on the emergence of consciousness. Definitely worth a listen. http://www.wnyc.org/shows/radiolab/episodes/2005/02/18.

Self-assembly with nanomanufacturing. Scaffolded interactive java simulation activity using models of biological self-assembly.
http://molit.concord.org/database/activities/231.html.

DNA to Protein Synthesis interactive java simulation activity, using a model of gene transcription and translation through protein folding.
http://molit.concord.org/database/activities/245.html.

PhET Stretching DNA simulation.
http://phet.colorado.edu/simulations/sims.php?sim=Stretching_DNA.

Chaos and complexity. Resources for students and teachers. A series of tutorials (mostly concise summaries of the science) regarding different aspects of chaos and complexity in a variety of fields, including psychology, economics, and biology. http://www.societyforchaostheory.org/tutorials/.

Mathematics Iluminated. Video program and online text chapter devoted to this topic. http://www.learner.org/courses/mathilluminated/interactives.

Emergent Universe. A project of the Institute for Complex Adaptive Matter, this beautiful interactive website explores many aspects of emergent phenomena with compelling visual examples. Click on "The Fibril Connection" for an exploration of protein folding and Alzheimer's disease and how amyloid structures (a self-organization of individual proteins) relates to emergence. See especially "Explore Renegade Proteins".
http://emergentuniverse.org.

Bioquest. Community resources for problem solving in biology. A resource-rich website with curricular material on biology, with modules, case studies, and other hands-on learning. See in particular their "resource" section. Helpful for teachers looking for in-depth resources on biological applications. http://bioquest.org/.

Biocomplexity centers and organizations. The "Resources & Links" section includes a list of many centers engaging in biocomplexity research. Most do not have specific educational materials, but if one of these organizations is nearby, they may serve as a useful resource. http://biocomplexity.indiana.edu.

Materials for teaching biocomplexity from the Science Education Resource Center (SERC). A set of (rather old) documents related to biology, geology and complexity that could be useful in designing curricula or assessments.
http://serc.carleton.edu/NAGTWorkshops/biocomplexity/teaching.html.

Two great books on these topics: S. B. Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* (Scribner, NY, 2001); and S. H. Strogatz, *Sync: The Emerging Science of Spontaneous Order* (Hyperion, NY, 2004).

Between Sessions

Facilitator

Give participants one of the following values of an orbital radius to be used in the following simulation. They will find the velocity required to make a circular orbit for this radius. Not every value of radius needs to be assigned to a participant—if you have fewer participants than radii, select a well-spaced subset of the following values to assign: 30 – 50 – 90 – 115 – 120 – 140 – 150 – 167 – 175 – 200.

Participants

Text: Read Unit 10: *Dark Matter.* Make notes of any questions that occur as you read. You may wish to reconsider changing your concept map from Unit 1 to account for dark matter (and, optionally, dark energy).

Preparatory Assignment:
Download the PhET "My Solar System" simulation at
http://phet.colorado.edu/simulations/sims.php?sim=My_Solar_System.
Use the sun and one planet pre-set.

1. **Make the planet orbit the sun in a circular orbit.** Write down the settings you used.
2. **What happens when you reduce the velocity of the orbiting planet?** If you increase it? Write a few sentences describing what you see and the underlying physical principle. In particular, how does the magnitude of an object's velocity affect its orbit?
3. **Find a velocity that makes the object escape into outer space.** Now, try to find a way to keep it in orbit, *without changing its velocity or radius.* How did you do it?
4. **Explore the relationship between orbital velocity and radius.** How must you change the speed of an object to keep it in orbit when you reduce its orbital radius? Why?
5. **Find the velocity required to make a circular orbit for the value of orbital radius the instructor assigned to you.** Use the following values: M1=200, M2 = 1. Bring your results to the next session.

Video: As you watch the video for Unit 10, keep the following questions in mind. You may want to make some notes to aid you in discussion during the session.

1. What is the evidence for the existence of dark matter that is observed or would be observed in each experiment? Since we can't see dark matter, what observables would provide a clue to their existence?
2. What do we know about the nature of dark matter or about what makes up dark matter?

Unit 10

Dark Matter

Introduction

The Universe is made mostly of dark matter and dark energy, and we don't know what either of them is.
– Saul Perlmutter, astrophysicist

In Units 1 and 2, we explored the most basic constituents of the universe—quarks, electrons, neutrinos, bosons, and the exotic particles created in accelerators. In this unit we learn about *dark matter* that, along with *dark energy* (the topic of the next unit), makes up 96% of the matter and energy in the universe. Several lines of evidence from diverse fields point to the existence of dark matter, but scientists are still unsure of the nature of this mysterious substance and it has yet to be observed directly. We know that it exists, but don't know what it is. The quest to observe and characterize dark matter is a major focus of both particle physics and astrophysics.

What Will Participants Learn?

Participants will be able to:

1. Compare and contrast dark matter with normal matter in terms of its basic properties and distribution in the universe.
2. Describe at least the following two of the lines of evidence for the existence of dark matter.
    a. Describe the relationship between orbital radius and velocity for bodies in the solar system and compare to that of stars orbiting in galaxies.
    b. Describe the effects of gravity on light traveling from distant places in the universe and compare "gravitational lenses" to traditional optical lenses.
3. Explain how two principles of the nature of science, *Evidence* and *Coherence & Consistency*, justify scientists' claim for the existence of dark matter based on data and evidence from multiple fields.

What's in this Unit?

Text: Unit 10: *Dark Matter* outlines the evidence for the existence of dark matter, including *galaxy cluster rotation* (Zwicky), simulations of the development of galaxies over time (Ostriker and Peebles), rotation of stars around galaxies (Ford and Rubin), the fluctuations in the *cosmic microwave background (CMB)*, and the synthesis of elements in the Big Bang. Alternative hypotheses (such as *modified Newtonian dynamics (MOND)* are discussed. The text also explores the search for the particles that make up dark matter—in particular, *axions*, *weakly interacting massive particles* (*WIMPs)*, and *massive compact halo objects* (*MACHOs)*. What is the nature of these hypothesized particles and objects, and what data would provide evidence for their existence?

Video: The program examines the research of two scientists who are searching for dark matter in two different directions. Doug Finkbeiner of the Harvard-Smithsonian Center for Astrophysics is exploring the cosmos, examining CMB radiation. The glow from the

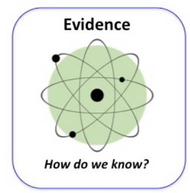
Big Bang has been redshifted such that astronomers observe it not as visible light, but as a microwave "glow". In order to see this background radiation, the radiation emitted from various sources in our galaxy must be subtracted. He found that the total radiation emitted from our galaxy was greater than the sum total of emission from known sources, such as gas and dust. This *haze* may be due to the annihilation of dark matter particles and antiparticles. Rick Gaitskell, of Brown University, is looking in another direction; instead of looking outwards to the sky, he is conducting an experiment deep inside the Earth for evidence of dark matter. In an abandoned mine, an elaborate experiment has been constructed to detect energy emitted from a collision of a WIMP traveling to the Earth from outside our galaxy, with a xenon nucleus.

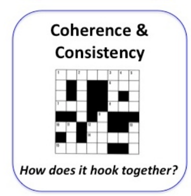
Interactive Lab: *Evolution of Large Scale Structure in the Universe.* Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.

Activities:

- The Hook: More Than We Can See (10 minutes)
- Activity 1: PhET "My Solar System" Simulation (30 minutes)
- Activity 2: Gravitational Lensing (20 minutes)
- Activity 3: Watch and Discuss the Video (50 minutes)
- Activity 4: How Do We Know that Dark Matter Exists? (20 minutes)
- Back to the Classroom (20 minutes)

Nature of Science Themes: *Evidence* and *Coherence & Consistency*. You may wish to display the *Evidence* and *Coherence & Consistency* icons during the session and remind participants of the central ideas of these themes. How do we know what we know? Measurements 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 support 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. Science is not a set of independent facts and formulas (as often seen by students). Rather, scientific findings are accepted as true because they are coherent and consistent—they hold together with other ideas and findings. Conflicts between results or between experiment and theory reduce scientists' confidence in either the experiment or the theory.





Exploring the Unit

The Hook: More Than We Can See

Time: 10 Minutes.

Purpose: To identify how dark matter relates to the other types of matter and energy in the universe.

Materials:

- Visualization of the Sloan Digital Sky Survey
- Example concept map from the online resource: *Facilitator's Guide High Resolution Graphics* (optional).

To Do and To Notice

Show a dynamic visualization of the universe based on the Sloan Digital Sky Survey data (SDSS) indicating the structure of galaxies and clusters in the universe. For example, you might choose one or more of the following videos:

- "Mapping the Universe" (a visual "zoom out" from the earth based on SDSS data): http://video.google.com/videoplay?docid=-8252705102362324792&q=sdss# and at http://astro.uchicago.edu/cosmus/projects/sloanmovie/
- "A Walk Through the Universe" (a visual "fly through" of the universe based on SDSS data) http://www.vimeo.com/4169279
- "The Known Universe" (a visual "zoom out" from the Earth to see SDSS and CMB data and then back in to Earth) http://www.amnh.org/news/2009/12/the-known-Universe/ or at YouTube.

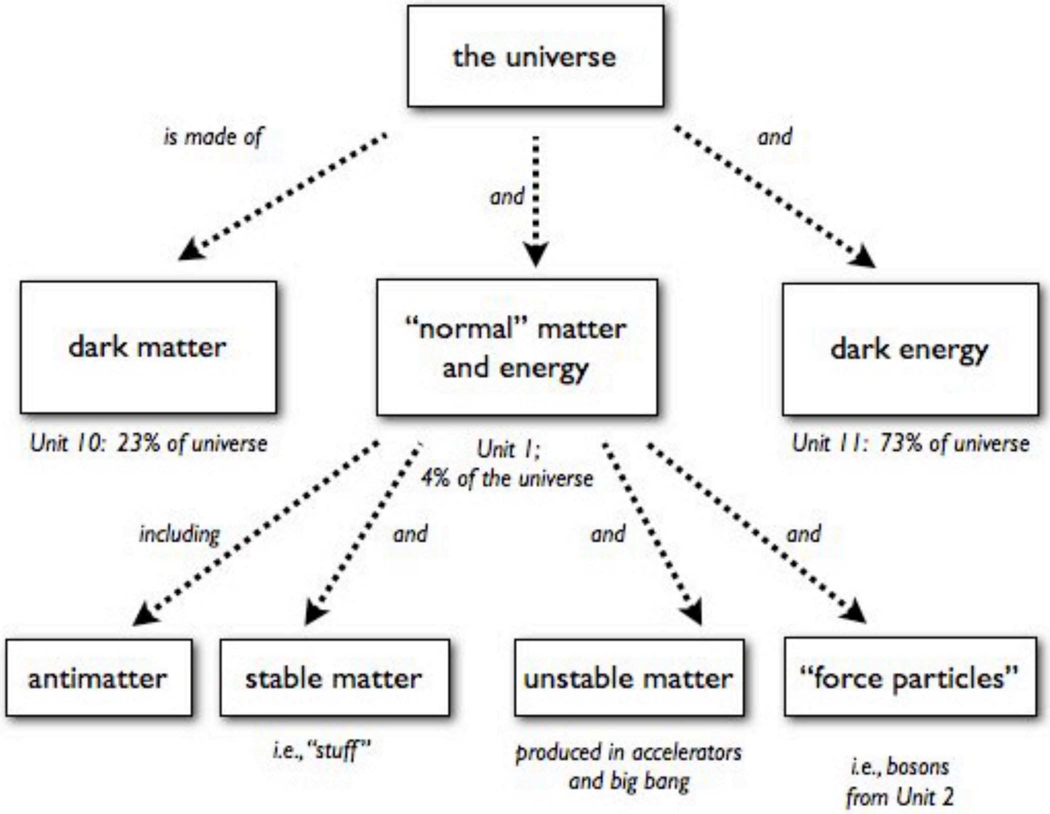
What are participants' reactions? What else is there in the universe than what we see here? How can you know that something is there if you can't see it? How can you know that something has mass if you can't see it? Emphasize ideas about nature of science, and explicitly elicit participants' ideas about dark matter. Discuss why dark matter is called "dark".

Ask participants to draw the next higher level (that which supercedes *matter* and *force* particles) on their concept map from Unit 1. What else exists other than the *particle universe* that formed the top level of our concept map in that unit? Where do dark matter and dark energy belong? After they have created their own, show them the example concept map on the next page and discuss all concept maps as a group.

What's Going On?

The structure seen in the universe in the SDSS data could not have arisen just from what we see (the luminous matter). Dark matter is one of the things that we can't see in this data (as are dark energy and other forces). There are a variety of things that we know exist but can't see. For example, you can feel the effect of air molecules when you sit in front of a fan. But there are ways that we can measure the existence of these things by, for example, seeing how they affect things around them.

According to our current understanding, normal matter and energy comprises only 4% of the total matter and energy in the universe. Dark matter comprises 23%. Dark energy, which is the topic of the next unit, comprises another 73%.



Example concept map
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

Activity 1: PhET "My Solar System" Simulation

Time: 30 Minutes.

Purpose: To explore the relationship between orbital velocity, radius, and the mass generating the gravitational attraction for orbital motion.

Materials:

- Tennis ball on string
- PhET "My Solar System" simulation at http://phet.colorado.edu/simulations/sims.php?sim=My_Solar_System (*Note:* Your computer does not need to be connected to the internet to run this simulation; select the "Download" option to download locally to your computer.)

To Do and To Notice

Discuss the results of participants' experiments with the PhET "My Solar System" simulation from the homework while demonstrating on the digital projector.

1. **Demonstrate a circular orbit.** (*Note:* Use the following settings: mass body 1 = 200, mass body 2 = 1, x-position body 2 = 120, y-velocity body 2 = 130. Check "Show Grid" and "Tape Measure" and check that the orbit is circular using the gridlines and the tape measure.)

2. **Ask participants what they found when they reduced/increased the orbiting object's velocity.** Demonstrate that the orbit changes shape as velocity is gradually increased/decreased, and the orbiting object can crash into the sun (if the velocity is too low) or escape into space (if the velocity is too high). Discuss the relationship between a planet's velocity and its orbit. Note that the velocity in question is the *orbital (*or *angular) velocity* rather than *linear velocity* and briefly discuss the difference between the two.

3. **Ask participants how they kept the planet in orbit when the velocity was increased beyond the escape velocity.** (*Note:* It works to either increase mass 1, or mass 2. Emphasize increasing mass 1—mass 2 is very small in most systems.) Discuss the relationship between this experiment and dark matter—i.e., that the observation of high orbital velocities (for galaxies in clusters, or stars/gas in galaxies) did not match the observed mass at the center. Thus, the mass at the center must be larger than observed to keep the object in a *bound* orbit. This also means that, by observing an object's orbit, the mass responsible for that orbital motion (mass 1) can be deduced.

4. ***Optional:* Swing a ball on a string so that it traces a circle in the air**. Ask, "What do I need to do to make this ball move faster?" Discuss with participants how this is similar (and different) to the results with the PhET simulation. The muscle power required to make the ball's orbit speed up is analogous to the additional mass (and thus the extra pull of gravity) at the center of the solar system, making the planet's orbit speed up.

5. **Discuss participants' experimentation with orbital velocity and radius**. To keep an object in orbit when the orbital radius is decreased, the velocity must be increased to keep the planet from crashing into the sun. The sun has a stronger effect on the planet because of the reduced distance. To balance the increased gravitational potential energy for a smaller orbit, the kinetic energy must be increased.

6. **Use participants' planetary data from their homework to create a plot of velocity (y-axis) versus radius (x-axis).** You may wish to use a database (such as Excel) and its graphing tools. Below are the correct values with mass 1 = 200, mass 2 = 1.

Radius	Speed
30	260
50	200
90	150
115	132
120	129
140	120
150	116
167	110
175	108
200	100

   You will obtain a curve where velocity drops with increasing radius.

7. **Show participants Vera Rubin's data for galactic rotation**, in the text. Why was this data surprising, given the results of the PhET experiment? How is this curve

evidence for the existence of dark matter? How does this relate to *Evidence*? Is there another way to account for this data?

8. **Discuss results with participants.** Some possible points of discussion:

   a. **Galactic rotation**[1]. How do these results differ from the rotation of stars around a galaxy? The PhET simulation deals only with masses that are discrete—the mass of a galaxy is spread out in space. How do we use what we learned about gravity in Unit 3 to account for these two different situations?

   b. **How is dark matter distributed?**

What's Going On?

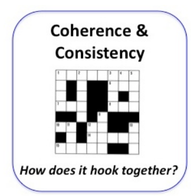
An object of a given mass will stay in a circular or elliptical orbit only for a particular velocity—too fast, and it will fly off into space; too slow and it will crash into the object it is orbiting. If the velocity is faster than this optimal velocity, then the mass of the central object must increase in order to keep the orbiting object in orbit. This balances the increased kinetic energy with an increased gravitational attraction. Similarly, the closer that an orbiting object is to the central object, the larger the gravitational attraction, and the faster the orbital velocity. This is what was plotted in the graph of *v* versus *r*. For those who are interested, velocity grows with $1/\sqrt{r}$: Assuming a circular orbit generated by a centripetal acceleration produced by gravity,

$$F = ma = \frac{GMm}{r^2} = m(\frac{v^2}{r})$$

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

$$v = \sqrt{GM/r}$$

Vera Rubin's data didn't follow this curve—stars moved faster than they should have given their orbital radius. One way to explain this is that there is additional mass that the stars are rotating around. This is related to *Coherence & Consistency* because this conjecture is consistent with other laws of physics, such as the laws of gravity. The laws of gravity, instead, could be modified to account for these observations. Mention Modified Newtonian Dynamics (MOND), but this theory has not been as successful as dark matter in explaining a variety of observations.



This PhET simulation only shows discrete bodies orbiting other discrete bodies (like the Sun). In a galaxy, the matter of the galaxy is distributed through space, and not concentrated in one point. This is important because the matter inside an object's orbit exerts a gravitational pull on that object (the matter outside its orbit has no effect[2]). Stars further away from the center of the galaxy are further from the mass, but in turn are orbiting more mass (both dark and normal). This extra mass is just enough to counter the extra orbital distance, so the relationship between velocity and radius is essentially constant.

[1] *Galactic rotation* refers to the orbit of stars and gas around galaxies. *Galaxy cluster rotation* refers to the orbit of galaxies within clusters. Both exhibit velocities faster than expected, suggesting the presence of dark matter.

[2] This is Newton's Law of Universal Gravitation, or "Gauss' Law for Gravity."

How is dark matter distributed? Dark matter is densest at the center of a galaxy, becoming less dense further away. Galaxies are embedded in a *dark matter halo* that extends beyond the boundary of the galaxy. While there is some dark matter in the solar system, its effect is dwarfed by the sun's gravitational pull. Thus, the results from the PhET simulation are valid for the solar system. If all dark matter were similarly concentrated at the *center* of galaxies, instead of spread out through space, Vera Rubin's graph would have mimicked the one found in the PhET simulation.[3]

Take-home message: Astronomers infer the existence of dark matter by the fact that stars orbit galaxies faster than they should given the gravitational pull of the galaxy. This is similar to the results from the PhET simulation.

Activity 2: Gravitational Lensing

Time: 20 Minutes.

Purpose: To demonstrate how gravitational lensing affects light reaching our telescopes.

Materials:

- One or several wine glasses with a curved bottom, as shown[4]
- Latex sheet model from Unit 3
- A heavy object (a stapler will do)
- A tennis ball
- Graph paper
- *Optional*: Images of light bending by a lens and light bending by gravity from online resources

Before the session: Experiment to find the best-sized dot to make on the graph paper for your particular wine glass.

1. Light bends by refraction

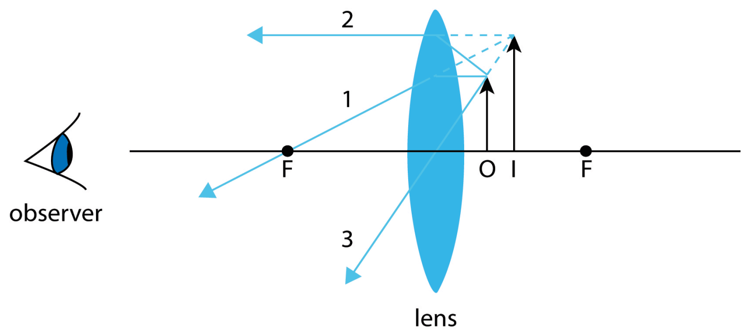
To Do and To Notice

Make a large dot on the graph paper. Have participants put the wine glass over the graph paper and observe how it distorts both the grid of the graph paper, and the dot. If the dot is centered below the wine glass, they should view a ring. If it is not centered, they should see arcs. Experiment with and without liquid in the glass, with varying distances of source and lens, and by moving the lens from side to side. This can also be done as a demonstration for the class by using an overhead projector or illuminating the wine glass with a light source and projecting the image on the wall or floor.

Remind participants that light is bent when it passes through materials, as when a pencil looks bent when it is in a cup of water. This is also how lenses work. Draw the following lens diagram on the board (or use the PhET simulation "Geometric Optics" http://phet.colorado.edu/en/simulation/geometric-optics). How would the image

[3] We don't recommend discussing initial *rise* in Vera Rubin's graph, which is arguably an artifact of the measurement techniques.
[4] Source: © Wikimedia Commons, License: None. Author: Will Murray, 23 December 2006. http://commons.wikimedia.org/wiki/File:Wine_Glass_%28Red%29.svg.

change if the object extended both above *and* below the center line? How would the image change if the object were a cross, centered on the center line?



Light is bent by a lens, forming an image
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

What's Going On?

If the object extended above and below the center line, the image would also extend above and below the center line. If the object were a cross, the image would also be a cross. Thus, an object that extends in all directions in the x-y plane (such as a dot on a piece of paper) would create an image that is a disk. Since the center of the wine glass is very thick, the dot on the paper turns into a ring.

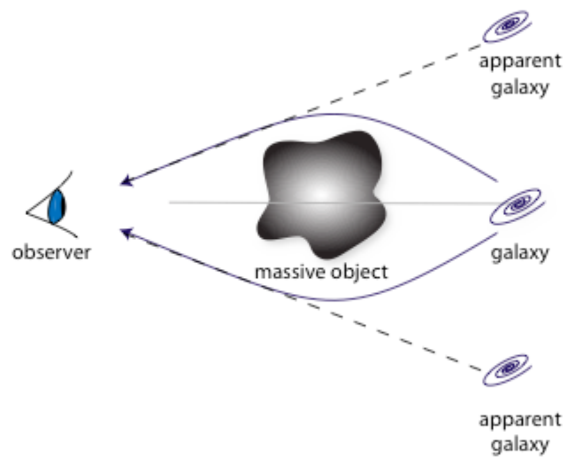
2. Light is bent by gravity

To Do and To Notice

Remind participants of what they learned in Unit 3—we know that light is bent by gravity—but only a little bit, or else flashlight beams would curve dramatically towards Earth. Have four participants hold the latex sheet at the corners, with the heavy object in the middle. Roll the tennis ball across the sheet, and ask participants what they notice. The ball curves towards the heavy object just as light curves when traveling around a heavy mass. However, since light is moving much faster than the tennis ball, it only curves when traveling by very massive things.

Draw the following diagram on the board, without the apparent galaxies. Explain that this is how light is bent by a galaxy. Ask participants, "Where does it appear that the galaxy is located?" Based on their responses, draw the dotted lines showing the location of the apparent galaxies. As with the wine glass experiment, help participants visualize that if the diagram is extended in all dimensions, the two apparent galaxies turn into an apparent galaxy ring, called an *Einstein ring.*[5] Brainstorm: How is a gravitational lens different from an optical lens?

[5] For participants who are curious, the wine glass demonstration is a good approximation of gravitational lensing because light passing near a massive object is deflected by an angle that is related to $1/r$, where r is the distance from the center of the object to the nearest point where the light passes it by. A wine glass is thicker at the center and thinner at the edge, and its thickness is approximately related to $1/r$, where r is the distance from the center. Thus, the wine glass deflects light in a similar fashion to a massive object.



Light is bent by a massive object, forming apparent galaxy images
(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

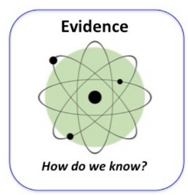
What's Going On?

So even though we can't see dark matter, we can detect it through its effects on light traveling to us from distant galaxies and clusters. When we see a warped image, we can infer something about the lens that has warped it.

A gravitational lens is different from an optical lens in several ways:

- Both bend light, but bend it in different ways (the resulting image is different)
- The effective curvatures of the two lenses are different
- In a gravitational lens, a ring (rather than a disk) is the image resulting from a point of light
- A lens bends light at the interface only; a gravitational lens bends it continuously
- A gravitational lens shows us an apparent image that is similar to a virtual image in a lens—we perceive the location of the image based on light rays that appear to be emanating from that point

Going Further



Show participants images from Hubble resulting from gravitational lenses in space. How do these images relate to the theme of Evidence?

- http://hubblesite.org/newscenter/archive/releases/1996/10/image/a/. Note that all the images of the blue galaxy look somewhat similar. These are the same galaxy, much as shown in the drawing, above. Note that this page has a good explanation of how the images from Hubble are analogous to the wine glass experiment.

- For those who want more, see the following links. Which of these images show an object that is directly on the other side of the gravitational lens? Which show an object that is well off-center of the lens?
  - http://hubblesite.org/newscenter/archive/releases/exotic/gravitational-lens/2004/08/results/100/
  - http://hubblesite.org/gallery/album/exotic/gravitational_lens/pr2003001e/titles/true/
  - http://hubblesite.org/newscenter/archive/releases/2009/25/image/ao/

Show participants the image of the Bullet Cluster from the text or at http://hubblesite.org/newscenter/archive/releases/exotic/dark%20matter/2006/39/image/a/. This is an image of a collision of two galaxy clusters. From standard observational techniques, astronomers measured the normal (luminous) gas from the two clusters, shown in pink.

Ask participants, what would you expect to happen if two groups of people were walking towards each other on a narrow street and the two groups collide?

> Answer: Two groups of people would slow and stop, just like the two galaxy clusters (shown in pink) have run into one another and slowed[6].

Ask participants to imagine that each group of people was accompanied by a group of butterflies, flying at the same speed as the people are walking. What happens to the butterflies when the people bump into each other?

> Answer: The groups of butterflies will continue to fly forward, not bumping into one another, and thus not slow. Using gravitational lensing, astronomers were able to deduce the total matter present in the two clusters. The total matter (shown in blue) has passed through the collision without interacting, like the butterflies in the analogy. This dark matter has bypassed the point of collision, as expected for a weakly interacting form of matter. This is considered key evidence for dark matter. Ask participants if there are other analogies that they can imagine for what they see in this image.

Activity 3: Watch and Discuss the Video

VIDEO

Time: 50 Minutes.

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

Discuss the video with participants, focusing on the evidence for dark matter from each experiment.

Key evidence for dark matter in each experiment:

- Finkbeiner: He found extra emission in WMAP, called the WMAP haze, possibly created by dark matter annihilation.
- Gaitskell: If he sees light emission, then the amount and position of that light will be a clue to the presence of dark matter, created in collisions between dark matter and normal matter. (*Note:* The interaction between dark matter particles from space and a nucleus here on earth can be modeled by rolling 10 tennis balls towards a single golf ball—only rarely will a tennis ball hit a golf ball).

[6] Note: Galaxy collisions don't generally involve actual *collisions*. Rather, the two galaxies interact gravitationally, and slow down.

Activity 4: How Do We Know Dark Matter Exists?

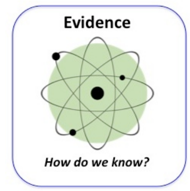
Time: 20 Minutes.

Purpose: To discuss how the multiple pieces of data provide a consistent and coherent set of evidence for the existence of dark matter.

To Do and To Notice

Discuss the following questions as a group:

1. How do we know that dark matter exists? As a group, create a list of the evidence and discuss in light of the theme of *Evidence*.
2. What would Finkbeiner and Gaitskell's experiments add to this evidence?
3. What do we know about the nature of dark matter?
4. What evidence would you want to see that would prove to you that dark matter exists?



What's Going On?

1. How do we know that dark matter exists?

- **Galaxy rotation** (Rubin). The speed of stars orbiting in galaxies is too large—they must be embedded in dark matter.
- **Galaxy cluster rotation** (Zwicky). The speed of galaxies orbiting in clusters is too large—they must be embedded in dark matter.
- **Gravitational lensing.** The distortion of light tells us that there are objects we can't see.
- **Cosmic microwave background** (CMB). The CMB is an image of how "lumpy" the regular matter in the universe was shortly after the Big Bang. These concentrations of matter acted as gravity sinks, drawing more matter to them. However, the lumps we see in the CMB are too small to have had enough gravitational force and attract the matter to see the galaxies and structure we see today (from the Sloan Digital Sky Survey, see *Hook*). If this normal matter were accompanied by dark matter, however, these early lumps would have had enough gravitational attraction to create the universe we see today. If you've ever made rock candy, you know that the sugar needs something to cling to (the string) in order to grow into crystals. In the case of the universe, the "seeds" for structure is the lumps in the CMB.
- **Galactic simulations** (Ostriker and Peebles). The observed structure of galaxies only emerges if a uniformly distributed invisible mass was present as they evolved.
- **Particle physics** ("Big Bang nucleosynthesis"). From the ratio of different elements in the universe, cosmologists can determine the abundance of normal matter in the universe (4%). Since other measurements tell us that dark matter is 23% of the mass-energy of the universe, it must be some new, exotic form of matter (not just normal matter that's not glowing).

2. What would Finkbeiner and Gaitskell's experiments add to this evidence? These observations are more direct and less inferential, and the logical or causal chain is (perhaps) shorter than in other observations. Their experiments, if positive, give additional evidence for the existence of dark matter. These experiments would also give us new information about the nature of dark matter.

3. What do we know about the nature of dark matter? Brainstorm as a group. Below are some possible answers.

- Dark matter is the primary source of gravity in the universe.
- Dark matter is by far the most abundant form of matter in the universe.
- A variety of pieces of evidence suggest that dark matter exists.
- Dark matter does not emit, block, or scatter light.
- Dark matter is an exotic form of matter (not just normal matter that doesn't emit light).
- Our models suggest that dark matter is probably one of three things—axions, WIMPs, or MACHOs.

4. What evidence would you want to see that would *prove* to you that dark matter exists? Brainstorm as a group. Some participants may feel that the existence is already proven. Some may argue that nothing can ever be proven beyond a doubt. Discuss the nature of evidence and proof in science.

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. Facilitate a discussion with participants:

- **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

Forces and Motion. Gravitational force is an attraction between two masses; the strength of the force is proportional to the masses and weakens rapidly with distance between them. Gravity is the force that keeps planets in orbit around the sun. If a force acts towards a single center, the object's path may curve into an orbit around the center. The change in motion (direction of speed) of an object is proportional to the applied force and inversely proportional to the mass.

Energy. The total amount of energy remains constant if no energy is transferred into or out of a system. In order for the total energy to remain constant (and equal to zero) when a planet (or other orbiting object) moves closer to the mass generating the gravitational pull, the kinetic energy of the planet must balance the increased gravitational potential energy; thus, the planet's velocity must increase.

Size and Scale. When describing and comparing very small and very large quantities, express them using powers-of-ten notation. Natural phenomena often involve sizes, durations, and speeds that are extremely small or extremely large. These phenomena may be difficult to appreciate because they involve magnitudes outside our experience.

Waves and Light. For an object to be seen, light must be emitted by or scattered from it. Visible light is a small band in the electromagnetic spectrum.

The Universe. The universe is estimated to be over 10 billion years old and to have originated in the Big Bang. Some distant galaxies are so far away that their light takes several billion years to reach the Earth—therefore, they are seen as they were that long ago in the past.

The Solar System. Gravity is the force that keeps planets in orbit around the sun.

Nature of Science. The selection of appropriate measurement and observation tools is important in answering a particular experimental question. For some of these observations, increasingly sophisticated technology is used to learn about the universe. Mathematical models and computer simulations are used in studying evidence from many sources in order to form a scientific account of the universe. 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. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations. Observation, evidence, and logic are important in the interpretation of experimental results.

Classroom Resources

PhET interactive simulations, and accompanying teacher-created activities, at http://phet.colorado.edu.

NASA's *Imagine the Universe* teachers' site with lesson plans and more: http://imagine.gsfc.nasa.gov/docs/teachers/teachers_corner.html. See the "resources" section for a list of topics on dark matter: http://imagine.gsfc.nasa.gov/docs/resources/resources_a.html#dark_matter.

The Mystery of Dark Matter teacher's guide and games from the Perimeter Institute. Excellent and very detailed lesson plans, hands-on activities, sample calculations, conceptual questions, and curriculum links. Don't miss the simple but fun dark matter video game. http://www.perimeterinstitute.ca/Perimeter_Explorations/The_Mystery_of_Dark_Matter/The_Mystery_of_Dark_Matter/.

Astronomy activities, including dark matter, from NASA and Sonoma State University: http://universe.sonoma.edu/activities/.

Galactic rotation activity from the University of California at Irvine Observatory Astronomy Outreach Program: http://www.physics.uci.edu/~observat/astro_activities_teachers.html.

Universe Adventure online interactive textbook about cosmology from University of California at Berkeley, with teacher activities on the Big Bang and Cosmic Background Radiation: http://universeadventure.org/index/teachers.htm.

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/.

NOVA's scienceNOW feature on Dark Matter, with teacher's guide and lesson plans: http://www.pbs.org/wgbh/nova/teachers/viewing/0301_01_nsn.html.

Galaxies and Dark Matter—1 hr video lesson, including demonstrations, lecture, and discussion questions. http://blossoms.mit.edu/video/fisher/fisher-watch.html.

Gravitational Lenses. Three teaching activities on gravitational lenses:

1. R. M. Ros (2008), Gravitational lenses in the classroom, *Phys. Educ.* **43**(5), 506-514
2. M. Falbo-Kenkel and J. Lohre (1996), Simple gravitational lens demonstrations, *Phys. Teach.* **34**(9), 555-558.
3. Exploratorium, http://www.exo.net/~pauld/activities/astronomy/gravitationallens.htm.

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.

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.

PARTICIPANTS

Text: Read Unit 11: *Dark Energy.* While you read, think about how astronomers measure and observe the universe. Make a list of the following items that you notice as you read:

1. Measurement tools used by astronomers (e.g., telescopes)
2. The measurements that each tool allows astronomers to make (e.g., the shape and position of objects in the sky).

Video: While watching the video for Unit 11, focus on the following questions:

1. How do we know that dark energy exists? In particular, what are the logical chains suggesting, in each experiment, that dark energy exists?
2. What are the researchers' premises?
3. What did they observe?
4. What did they conclude?

Interactive Lab: You may wish to explore the Interactive Lab associated with this unit: *Evolution of Large Scale Structure in the Universe.* Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.

Unit 11

Dark Energy

Introduction

Because dark energy makes up about 70% of the universe, it dominates over the matter content. That means dark energy will govern expansion and, ultimately, the fate of the universe.
- Eric Linder, astrophysicist

In the last unit, we learned about dark matter, an unseen form of matter that would account for the gravitational attraction that has pulled material in the universe together into the kinds of large-scale structures that astronomers have observed. In this unit, we learn about evidence for an unseen *repulsive* component of the universe—*dark energy*, which would account for the surprising fact that not only is the universe expanding (as first observed by Edwin Hubble, leading to the Big Bang theory), but that the expansion is *accelerating.* However, the exact nature of this dark energy—which accounts for a whopping 73% of the universe—is still a mystery.

What Will Participants Learn?

Participants will be able to:

1. Describe and explain how astronomers use *luminosity* and *redshift* to measure the distance and speed of celestial objects.
2. Describe, using pictures, graphs and/or words, what astronomers mean by an *expanding* universe. Describe several different ways that the expansion could change over time (e.g., decelerate, accelerate, remain constant) and what this means for the fate of the universe.
3. Explain how observations logically suggest the presence of *dark energy*. Describe dark energy in terms of its observed effect on the universe, and contrast with dark matter.

What's in this Unit?

Text: In Unit 11: *Dark Energy* we learn how astronomers came to their current understanding of the structure of the universe, particularly by measuring aspects of celestial bodies such as *luminosity* and *velocity* (through observation of *redshift*). Edwin Hubble observed that distant galaxies were moving away from us faster than nearby galaxies, constructing the *Hubble diagram* of distance versus velocity, showing that the universe was expanding. But how is this expansion changing over time? Because most *standard candles* for judging distance from the earth were relatively close, previous measurements of the universe's expansion were over a somewhat small range of distances. New measurements from *Type 1a supernovae* have allowed astronomers to judge the distance and velocity of objects much further from the earth, and thus much further back in time. These observations provide evidence that indeed the expansion of the universe is not constant or slowing, but instead accelerating. *Dark energy* is the proposed agent of this acceleration—a repulsive type of energy that could be thought of as an “anti-gravity force” unlike anything yet known to us. Dark energy accounts for 73% of the mass-energy in the universe. Additionally, from the *cosmic microwave background (CMB)*, we can infer the *geometry* of the universe (measurements indicate that it is flat)—this, in turn, provides information about the *density* of the universe.

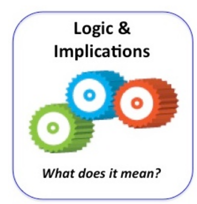
Video: In this program we hear from two researchers who are investigating the effects and origin of dark energy. Robert Kirshner, at the Harvard-Smithsonian Center for Astrophysics is investigating what this dark energy may be. He studies distant supernovae to gain a better understanding of how this force has shaped our universe over time, leading to the conclusion that the universe is accelerating. At Princeton University, David Spergel is looking back even further in time, into remnants of light emitted only 300,000 years after the Big Bang, searching for clues about dark energy. His work with the cosmic microwave background radiation has provided information about the geometry of the universe (suggesting it is flat), providing information about its density. These two research threads allow scientists to conclude that the universe is composed of about 73% dark energy.

Interactive Lab: *Evolution of Large Scale Structure in the Universe.* Experiment with different initial conditions to see what structures form, and try to build a universe similar to the one we live in today.

Activities:

- The Hook: The Night Sky Is Dark (10 minutes)
- Activity 1: Touch the Sky (15 minutes)
- Activity 2: How Far Away Is It? (15 minutes)
- Activity 3: How Fast Is It Moving? (15 minutes)
- Activity 4: The Universe is Expanding (15 minutes)
- Activity 5: Looking Back in Time (optional)
- Activity 6: Watch and Discuss the Video (20 minutes)
- Activity 7: The Fate of the Universe (15 minutes)
- Back to the Classroom (15 minutes)

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.



Exploring the Unit

The Hook: The Night Sky Is Dark

<u>Time</u>: 10 Minutes.

<u>Materials</u>:

- Optional video: “*Why Is it Dark at Night?*”

http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/

To Do and To Notice

Ask participants, what do you see when you look up at the night sky? Make a list of participants' observations, making sure that at least one of them is that the sky is dark between little points of light (the stars). Draw the night sky on the board. Ask them, "What are some ways that the stars might be scattered in the universe so that we would see something like this?" Prompt them to come up with as many models as they can. Discuss as many as you like—below are three common models.

Model 1: The universe is a black ceiling with a bunch of little lights stuck on it.
Are there problems with this model?

Model 2: The stars are spread out through space, which extends infinitely.
Are there problems with this model?

Model 3: The stars are spread out through space, with an "edge" to that space.
What does this model imply?

You may wish to show the 1-minute animated short from Alice and Bob in Wonderland called, "*Why Is it Dark at Night?*" http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.

What's Going On?

Model 1: Using this model, we wouldn't expect the stars to move relative to each other, but we see that they do.

Model 2: If this were true, the entire night sky would be bright. Imagine you're standing in a thick glade of trees. If the glade has no end, you will see tree trunks everywhere. But if the glade has an end, you can see the space beyond the trees—which you see as daylight between the trunks. Similarly to a glade of trees, the universe looks very similar in all directions. If the universe were infinite, we would see stars (and thus light) everywhere we looked, with no space between them. This is true even though more distant stars are fainter (just like distant trees look smaller)—there are more stars at larger distances, balancing out their faintness. Another analogy: snowflakes block our view of a mountain, even though the furthest ones are very small. For more information, look up "Olbers' Paradox"—the Wikipedia entry is useful.

Model 3: This is the current model. Beyond this edge, there are either no stars, or their light has not yet reached us. The fact that the night sky is dark tells us that the universe has an edge in time, before which it did not exist.

Activity 1: Touch the Sky

Time: 15 Minutes.

Purpose: To digest the content of the reading, and consider how astronomers make use of the limited measurement tools available for them.

Lead into this activity from *The Hook* by noting that the simple observation that "the night sky is dark" provides deep information about our universe, even though we have no way of directly observing most portions of the universe.

To Do and To Notice

Ask participants to get out their lists from the reading, and create a master list of "measurement tools" and "measurements" as a group. Consider how the challenges of measurement in astronomy are similar/different to those of particle physics.

What's Going On?

Many of the problems of astronomy are problems of measurement. Astronomers can't physically touch the objects of their study, as they are too far away. Particle physicists can't physically touch the objects of their study, as they are too small. Note that some things that astronomers measure (such as spectra) could be viewed as a measurement in its own right, or as a tool for measuring other things (such as Doppler shift). Several of these measurement tools will be investigated in the next activities.

Possible measurement tools:

- Naked eye observations
- Telescopes
- Photographs
- Spectra of celestial objects (could also be considered a measurement)
- Standard candles

Possible measurements:

- Location and shape of objects
- Luminosity
- Distances, using luminosity and "standard candles"
- Velocities (towards/away from earth) using Doppler shift of spectra
- Changes in luminosity, location, and shape over time

Activity 2: How Far Away Is It?

<u>Time</u>: 15 Minutes.

<u>Purpose</u>: To explore one of the above measurements—luminosity—as a tool to measure distance. This is important in understanding the expansion of the universe.

<u>Materials</u>:

- Optional light meter

To Do and To Notice

If there are two identical light bulbs in a dark room, how do we tell which is furthest away? Ask participants for their answers. Among the answers should be "the one that is less bright is furthest away." Tell participants that the power of a light source (like a star) is spread out equally over a sphere around the star. Thus, the intensity is given by the power divided by the area of a sphere surrounding the object ($Power/4\pi r^2$).

Clicker/Discussion Question:

If a star's total power is 100 W and you measure an intensity of 0.001 Watts/m^2, how far away is the star?

A. 0.001 m
B. 10 m
C. 90 m
D. 315 m
E. 1120 m

What did we need to know to figure out the star's distance? How could we get this information? Discuss as a group.

What's Going On?

Answer to the clicker question is (C): 90 m. You may want to discuss the unreasonableness of these numbers for the power and distance of a star! What kind of object would produce these numbers? (Answer: light bulb.) If a teacher has a light meter, they can demonstrate this type of power law to students in a classroom.

In order to figure out the distance of the star, we needed to know its intensity (which we can measure), and its total power. How can we know the power of a star? We use *standard candles*—an object that belongs to some class of objects that all have the same (and known) brightness. If the power of a star is known, then measured intensity (power/area) will allow the distance to the star's host galaxy to be calculated. This is similar to calculating the distance to a neighbor's house by measuring the brightness of the 100W bulb on the neighbor's porch.

Take-home message: Astronomers use intensity of celestial objects to determine their distance.

Activity 3: How Fast Is It Moving?

Time: 15 Minutes.

Purpose: To explore one of the above measurements—redshift—as a tool to measure velocity. This is important in understanding the expansion of the universe.

Materials:

- Football or other ball with embedded buzzer, or a buzzer on a string
- The PhET "Wave Interference" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Wave_Interference. (*Note*: You do not need to be connected to the internet to use the simulation. You may download it locally to your computer.)
- *Optional*: PhET "Sound" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Sound.
- *Optional*: Online "Doppler Shift" simulation. http://scatter.colorado.edu/STEM-TPSoft/.

To Do and To Notice

See the Doppler. Use the PhET "Wave Interference" simulation. Choose the "Water" tab. Demonstrate the basic features of the simulation, such as the ability to adjust the frequency and amplitude of the waves. Choose low frequency and high amplitude waves. You may now use the mouse to grab the faucet slowly, and observe the resulting pattern of the waves, such that they are higher frequency in front of the faucet. Discuss as a group and ensure that participants understand that objects coming towards us have a higher frequency, and objects moving away have a lower frequency. You may also use the "Sound" simulation (http://phet.colorado.edu/en/simulation/sound), with speakers connected to the computer, and move the person to hear the Doppler Effect. You may also use the online applet "Doppler Shift" (http://scatter.colorado.edu/STEM-TPSoft/).

Explain that the same process occurs for light—light is lower frequency (redder) if an object is moving away, and higher frequency (bluer) if an object is moving towards the observer. What other activities do participants use to show the Doppler Effect?[1]

If astronomers know the frequency of light originally emitted by a star, then we can measure how much the frequency is shifted when it reaches earth. But how do we know what frequency of light was originally emitted? What possible frequencies/colors of light could be produced by a star? Talk to the group and make some suggestions.

Clicker/Discussion Question: Frequencies emitted by a star

1. **What characteristic frequencies of light could a star produce that astronomers might be able to know in advance (in order to then measure how much it is Doppler shifted)?**

   A. The colors of light found in the sun, because all stars are the same color as the sun
   B. The color of light found in that particular type of star: Each type of star gives off all its light at a particular wavelength
   C. The particular colors of hydrogen atoms in the stars
   D. The particular colors of neon atoms in the stars

CLICKER/DISCUSSION QUESTION

[1] Other standard demonstrations of the Doppler Effect include whirling a buzzer on a string overhead in a circle, or throwing a ball with a buzzer back and forth from the front to the back of the room. Can you tell if the object is moving towards or away from you? Think about cars at the Indy 500 – what do you hear when cars come towards you? When they go away?

Clicker/Discussion Question: Redshifted hydrogen

2. This image shows the hydrogen spectrum—it plots the lines of hydrogen spread out by wavelength.

The following four spectra represent the spectra measured from celestial objects. **Which one is moving away the *fastest?***

A. 

B. 

C. 

D. 

What's Going On?

1. Best answer is (C): Astronomers use the spectrum of hydrogen in order to calculate the redshift of the star. Answer (D) would work but there is very little neon in stars.

2. Best answer is (B): This spectrum is the most redshifted of all the spectra, indicating a star that is moving away the fastest.

So, now we know how to measure the velocity of objects (but only towards/away from the earth). In fact, we can use the amount the colors have shifted to calculate[2] an exact speed (towards/away) from us (v), using the change in wavelength ($\Delta\lambda$), the original wavelength (λ), and the speed of light (c): $\frac{\Delta\lambda}{\lambda}=\frac{v}{c}$.

Take-home message: Astronomers use the spectrum of hydrogen, and its redshift, to determine the speed of a star relative to the earth.

Activity 4: The Universe is Expanding

Time: 15 Minutes.

Purpose: To explore what it means to say that the universe is expanding.

Materials:

- Balloons
- Paper
- Tape
- Transparencies and overhead projector, and image from http://www.exo.net/~pauld/activities/astronomy/ExpandingUniverse.html (optional)

[2] This formula is only correct for velocities (v) much less than the speed of light.

- Digital image of expanding dots from online resources (optional)
- Hubble Plot and Closed/Open Universe plot (from the text)

To Do and To Notice

Ask participants, “How could Hubble calculate recessional velocity of a galaxy? How could he calculate the distance of the galaxy from the earth?” Show participants the Hubble Plot from the text, showing recessional velocity versus apparent distance. What do they notice? What could cause this behavior, such that distant galaxies are receding more quickly? Solicit responses.

Use one or more of the following visual models to help participants visualize why things move further apart from one another in an expanding universe.

- **Balloon Universe.** Stick paper dots on a balloon, randomly. Blow it up and watch the dots on the surface move further apart. [3] The space and time of the universe are modeled by the “skin” of the expanding balloon, and light can only travel on the surface of the balloon. Imagine you lived in a galaxy on the surface of the balloon; as the balloon expands, would all the other galaxies appear to move towards you or away from you?
- **Moving people.** Using the analogy from the text regarding desks in a classroom, ask participants to stand one meter from one another. Then ask them to move so that they are all two meters apart from one another. How far away is your neighbor from you now? (*Answer:* 2 meters). How far away is your neighbor’s *neighbor*? (*Answer*: 4 meters). So what?
- **Expanding dots.** Show how all points in an expanding universe see all other points moving away from them, and thus no one point is at the center, using presentation software and a digital projector[4]. See online resource: *Facilitator’s Guide High Resolution Graphics.*

What’s Going On?

Edwin Hubble used redshift (Activity 3) to calculate the speed of galaxies, and luminosity (Activity 2) to calculate the distances of galaxies from the earth. Hubble noticed two things:

1. Nearly all galaxies were moving away from us.
2. The further away a galaxy, the faster it was moving.

This implied that the universe was expanding.

The visual activities serve to demonstrate that the universe appears to expand out from all points, even though no single point is the center of the expansion. Thus, all galaxies are moving away from us, on Earth, even though Earth is not the center of the expansion. The moving desks activity serves to illustrate that things that are further away are moving faster in an expanding Universe.

Take-home message: The universe is expanding, which means that all objects are moving further apart from one another. There is no center from which the universe is expanding.

[3] See http://www.exo.net/~pauld/activities/astronomy/universalballoon.html for an example of this activity, and http://solar.physics.montana.edu/tslater/plunger/expand.htm for relevant discussion questions. Inspired by work by Colin Wallace at the University of Colorado at Boulder.

[4] If you have an overhead projector, see the following link for a variation using transparencies: http://www.exo.net/~pauld/activities/astronomy/ExpandingUniverse.html.

Activity 5: Looking Back in Time (optional)

Purpose: To understand how looking at distant objects—such as supernovae or the cosmic microwave background—is equivalent to looking back in time. This helps prepare participants for understanding of the video.

Materials:

- Drawing paper
- Optional, "*Is That Star Really There?*" from Alice and Bob's Adventures in Wonderland http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/

To Do and To Notice

Participants imagine what a city would look like if it took light ten years to travel each city block—three blocks away, you can see people in the bell-bottoms of the 1970's; fourteen blocks away, the city did not yet exist. Use the "City Universe" activity at http://www.exo.net/~pauld/activities/astronomy/cityUniverse.html.

You may want to introduce this topic with the 1-minute animated short, "*Is That Star Really There?*" from Alice and Bob's Adventures in Wonderland.

What's Going On?

Because light takes time to reach the Earth, we are observing the universe as it was, not as it currently is. Thus, observational astronomy offers a glimpse back in time.

Activity 6: Watch and Discuss the Video

Time: 20 Minutes.

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.

After the video, discuss each experiment and the logical chains described by each scientist as to how their results suggest that some repulsive force exists in the universe. Field and discuss any questions. For example:

KIRSCHNER

Premise 1: Fainter supernovae are further away.
Premise 2: The more red-shifted supernovae are moving faster.

Observation 1: Distant supernovae are more red-shifted than closer supernovae.

Conclusion 1: Distant supernovae are moving faster → universe is expanding (Hubble's Law).

Observation 2: Highly red-shifted supernovae are further away than expected by Hubble's Law.

Conclusion 2: The expansion of the universe is speeding up. (And this could be related to the cosmological constant).[5]

SPERGEL

Premise 1: The cosmic microwave background (CMB) radiation represents a snapshot of the density fluctuations in the early universe, when it was 400,000 years old.
Premise 2: The angular size of the hot and cold spots in the CMB should be 1 degree because that's how far light could travel from the Big Bang up to 400,000 years.

Observation 1: The observed size of the hot and cold spots in the CMB is 1 degree.

Conclusion 1a: The universe is flat, because light traveling in a straight line in Euclidean space will yield spots of the same apparent size as their actual size.

Conclusion 1b: The Universe has a density of 1 (characteristic of a flat universe).

Observation 2: The pattern and temperature of the temperature variations in the CMB.

Conclusion 2: The pattern produced indicates that the universe has a flat geometry, and thus a particular density (the critical density).

Conclusion 3. Because there is not enough dark and normal matter to account for this calculated density, there is a deficit of 73%, consistent with the presence of dark energy causing the universe to accelerate.

Possible concluding discussion questions:

- What if the rules of physics (e.g., the propagation of light) are different very far away/very long ago? What would that mean? How do we know that the same rules apply here as there?
- Why can't we just say that there's dark matter we don't see and dark energy that we don't see, and that their effects cancel each other out (and thus we can ignore them)?

Activity 7: The Fate of the Universe

Time: 15 Minutes.

Purpose: To explore what the expansion of the universe implies about the ultimate fate of the universe—the "big chill" versus the "big crunch."

[5] This logic is not made explicit in the video—you may want to return to the balloon activity to help participants understand this conclusion. For those who are interested, the additional redshift of distant supernova is due to the *expansion of space* rather than additional motion of those supernovae: http://www.exo.net/~pauld/activities/astronomy/expansionoflight.html.

To Do and To Notice

Clicker/Discussion Question:

How do we know that the universe's expansion is speeding up?

A. We measure for a long time and see that galaxies are speeding up
B. We look back into the past different amounts of time, to see how the expansion changes with time
C. Neither/Something else

If we shoot a rocket straight up from earth, what different things can happen to it? What basic features determine which it will be?

Facilitate a discussion, helping participants make the connection between this analogy and the two possible outcomes for the universe (the "big chill" or the "big crunch"). Show the plot of open versus closed universes from the text. What are the parallels with the rocketship trajectories, above?

Now, what if we shot a rocket up from the earth and it zoomed away from earth at an ever-increasing rate? What could cause that?

What's Going On?

The answer to the clicker question is (B), as can be discerned from the video. It's not possible to measure for a long enough period of time to see the change in rate of expansion.

The rocket would have two possible trajectories:

A. It could fly off into space. This happens if its velocity (the escape velocity) overwhelms the force of gravity.
B. It could go up a distance, then turn around and crash back to earth. This happens if the force of gravity overwhelms its velocity.

Option A is analogous to the "big chill" in which the acceleration of the universe continues forever, with dark matter too weak to reverse the expansion.

Option B is analogous to an eventual contraction of the universe—the "big crunch"—in which dark matter is strong enough to reverse the expansion.

If the rocket, instead, zoomed away from Earth at an accelerating rate, this would be surprising. This would require some sort of anti-gravity force acting on the rocket—like dark energy.

Take-home message: The expansion of the universe is accelerating, which doesn't make sense if the only thing causing the expansion was the energy from the Big Bang. Dark energy acts as an anti-gravity force, increasing the expansion of the universe.

Back to the Classroom

Time: 15 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. Facilitate a discussion with participants:

- **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

Forces and Motion. Gravitational force is an attraction between two masses; the strength of the force is proportional to the masses and weakens rapidly with distance between them. All motion is relative to whatever frame of reference is chosen, for there is no motionless frame of reference from which to judge all motion.

Size and Scale. When describing and comparing very small and very large quantities, express them using powers-of-ten notation. Natural phenomena often involve sizes, durations, and speeds that are extremely small or extremely large. These phenomena may be difficult to appreciate because they involve magnitudes far outside human experience.

Waves and Light. The observed wavelength of a wave depends on the relative motion of the source and the observer. Visible light is a small band in the electromagnetic spectrum.

The Universe. Because the light seen from almost all distant galaxies has longer wavelengths than comparable light on earth, astronomers believe the whole universe is expanding. The Big Bang theory suggests that the universe began 10-20 billion years ago in a hot dense state.

Nature of Science. Mathematical models and computer simulations are used in studying evidence from many sources in order to form a scientific account of the universe. 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. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations. Observation, evidence, and logic are important in the interpretation of experimental results.

Classroom Resources

The **Sloan Digital Sky Survey teachers' page** at http://cas.sdss.org/dr5/en/proj/teachers/basic/ includes a lesson plan regarding the expansion of the Universe, including creation of students' own Hubble plot.

The **Universe Adventure** online interactive textbook about cosmology from University of California at Berkeley: http://www.universeadventure.org/. Teachers' page with lesson plans at http://www.universeadventure.org/index/teachers.htm.

A full **Supernova Educator Unit** from NASA and Sonoma State University at http://xmm.sonoma.edu/edu/supernova/index.html.

Wilkinson Microwave Anisotropy Probe (WMAP) teachers' page on the cosmic microwave background, with classroom activities and an inflatable WMAP globe: http://map.gsfc.nasa.gov/resources/edresources1.html.

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 "*Is that star really there?"* and *"Why is it dark at night?* "
http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.

NASA's *Imagine the Universe* teachers' site at
http://imagine.gsfc.nasa.gov/docs/teachers/teachers_corner.html.

- The Fall-Off of Light, and Hubble's Law and the Doppler Shift
  http://imagine.gsfc.nasa.gov/docs/teachers/lessons/swift_grb/how_far.html
- Roy G. Biv: the relationship between color and wavelength
  http://imagine.gsfc.nasa.gov/docs/teachers/lessons/roygbiv/roygbiv.html

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/.

From the **Exploratorium's Paul Doherty**, a variety of activities on the expansion of the Universe: Balloon Universe, Circle Universe, City Universe, City Universe Size, Doppler Model, Expanding Universe, Expansion of Light, and Sound Circles at http://www.exo.net/~pauld/site_map.html.

Determining Red-Shift in a Receding Star from PBS.
http://www.pbs.org/deepspace/classroom/activity2.html.

PhET simulations on waves, Blackbody spectra, and Doppler Effect, and accompanying teaching activities. http://phet.colorado.edu.

What the WMAP! Article on the Cosmic Microwave Background and cosmology on Physics Central. http://www.physicscentral.com/explore/action/wmap-1.cfm.

Singing' the Black and Blues. A discussion activity from NASA on "why the night sky is black" with explanations suitable for high school students.
http://spaceplace.nasa.gov/en/educators/bluesky_blacksky.pdf.

Teacher Conferences Talks from the Kavli Institute for Theoretical Physics. Online archives of talks geared towards teachers, by leading scientists and educators. Particularly relevant are *The State of the Universe* and *Forging the Elements and Probing the Universe with Stars.* See also the public lectures by notable scientists on a variety of topics. 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.

Between Sessions

FACILITATOR

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

PARTICIPANTS

Review your notes and other course materials to remind yourself of earlier topics. Be prepared to answer the following questions in the next session:

1. **Prepare a presentation slide: Which topic or idea was your absolute personal favorite?** Consider the topics you found the most intellectually stimulating or that sparked your curiosity, regardless of whether you might use it in the classroom. Why was it your favorite? Prepare a slide to present to the group for the next session.
2. **How do some of the topics, research studies, or nature of science themes relate to one another?** Brainstorm: How might you start to organize these into a coherent framework?
3. **Pick at least two topics that you might use in your classroom.** These "topics" don't need to be the subject of an entire unit (such as "dark energy") but can be a subtopic within that unit (such as "the expansion of the universe.") Think about how you might approach using these topics with your students. Where might they fit within your curriculum, and what teaching approaches might you use?
4. **Identify at least two challenges to using materials in the classroom**. You may identify (a) the challenge(s) you anticipate in using one of the two topics you chose, above, or (b) one or two topics that you *didn't* choose to include and what barriers you anticipate would prevent you from using that topic in your classroom.

Review Unit

Introduction

What we call the beginning is often the end. And to make an end
is to make a beginning. The end is where we start from.
– T.S. Elliot

In the preceding eleven units we have gone on a journey of the very small to the very large, covering topics from particle physics, to the world of atoms and light, finally exploring living things and then the enormous scale of the cosmos. How do all these areas of research relate to one another? How do the nature of science themes act as a lens to help us understand how these diverse fields relate to the scientific enterprise as a whole? This unit will serve as a review of previous units by looking for connections between the different topics covered by the course as a whole.

What Will Participants Learn?

Participants will be able to:

1. Construct an organizational framework in order to explore connections between the majority of topics and ideas in previous units, including the nature of science themes.
2. Choose at least two topics they would like to use in classroom instruction, and generate an action plan for incorporating them into the existing curriculum.
3. Evaluate one or two challenges or barriers to using topics from this course in the classroom, and generate ideas on how to reduce those barriers.

What's in this Unit?

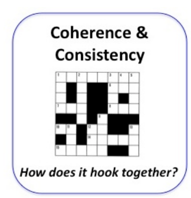
Text: There is no online text accompanying the Review Unit.

Video: There is no video accompanying the Review Unit.

Activities:

- The Hook: A Few of My Favorite (Physics) Things (20 minutes)
- Activity 1: How Does It Hook Together? (1 hour)
- Activity 2: Planning for the Classroom (1 hour)
- Activity 3: Continuing the Conversation (optional)

Nature of Science Theme: *Coherence & Consistency*. You may wish to display the *Coherence & Consistency* icon during the session and remind participants of the central ideas of this theme. Science is not a set of independent facts and formulas (as often seen by students). Rather, scientific findings are accepted as true because they hold together with other ideas and findings. Conflicts between results or between experiment and theory reduce scientists' confidence in either the experiment or the theory.



Exploring the Unit

The Hook: A Few of My Favorite (Physics) Things

Time: 20 Minutes.

Purpose: To share favorite topics or ideas from the course, helping to serve as a review of the material and to share the intellectual stimulation that each participant derived from the material.

Ask participants to take a few minutes to present their pre-prepared slide and describe the idea or topic that was their favorite or that they found most stimulating, regardless of whether they might use it in the classroom. Write each on the board as they describe it. Why was it their favorite? Are there common favorite themes and ideas? (*Note*: In groups of larger than 8 participants, we recommend this activity as a Think-Pair-Share).

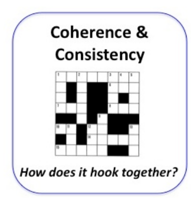
Activity 1: How Does It Hook Together?

Time: 1 Hour.

Purpose: To create an organizational framework and explore connections between topics, ideas, concepts, and nature of science themes throughout the course.

Materials:
- Butcher paper
- Index cards
- Markers
- Digital camera
- *Optional*: Handouts of recommended concept-mapping terms

Concept Mapping (20-30 minutes)
Ask participants to gather in groups of 2-3 and arrange themselves around the room. Together, they will create an organizational framework to search for connections between different topics and ideas in the course, which will be photographed at the end of the activity. One of the best tools for this type of exploration is a concept map, but they may choose any tool that suits them. They may write words and phrases directly on the butcher paper or chalkboard, or we recommend writing them on the index cards and then arranging them on butcher paper or a chalkboard, and indicating the connections between them.



- Below is a list of candidate words and phrases from the course.
- Participants may search the *Glossary* in the online materials for additional items, or add ones from their own memory.
- They may wish to use their concept map from Units 1 and 10 as a jumping-off point and/or review the *What Will Participants Learn?* section of each unit.
- Ask them to pay particular attention to the theme of *Coherence & Consistency*; how do these topics and ideas hook together?
- Do they notice topics that don't hook together, that are incompatible?

Gallery Walk (20-30 minutes)
After about 20-30 minutes, even if they are not finished with the task, ask participants to stop work for a gallery walk—or poster session—of all groups' concept maps. Each small group will invite the group as a whole to visit their corner of the room, where they

will explain their map or organization, including any connections that they found particularly surprising or interesting. Are there common organizational structures? Are there any topics that are left on the fringes of most concept maps? For topics/ideas that are incompatible (e.g., emergence and particle physics), is this a problem? Do we need a wholly consistent science, or is a science that is consistent, piecewise, sufficient?

Finish Concept Maps (10–20 minutes)
After the gallery walk, participants may return to their own concept map to add connections or make modifications based on what they saw during the gallery walk.

At the end of the activity, take pictures of the finished concept maps with the digital camera so that images may be shared with participants.

Highly recommended terms to include:

Nature of Science Themes

Measurement & Observation	Evidence	models	Logic & Implications	Coherence & Consistency

Unit Content

Particle physics	Electrons	Quarks	Atoms	Strong Force	Bosons
Fermions	Forces	Electricity & Magnetism	Gravity	General Relativity	String Theory
Quantum Mechanics	Wave-Particle Duality	Bose-Einstein Condensates	Laser Cooling	Quantum Entanglement	Superposition
Quantum Computing	Group Velocity	Special Relativity	Emergence	Super-conductivity	Granular Materials
Condensed-Matter Physics	Biophysics	Dark Matter	Dark Energy	The Universe	Matter

Optional terms to include:

AdS/CFT Correspondence	antimatter	Atom trap	Baryonic Matter	BCS Theory	Black Hole
Conservation of energy	Cosmic Microwave Background	Cosmological Constant	de Broglie Wavelength	Dimensions (0-D, 1-D, etc.)	Doppler shift
DNA	Entropy	$E=mc^2$	Equilibrium	Equivalence principle	Feynman diagram
Force carrier	Galaxy cluster	Graviton	Gravitational Lensing	Gravitational waves	Heisenberg uncertainty principle
Higgs boson	Hubble's Law	Inflation	Large Hadron Collider	Luminosity	MACHO / WIMP
Neutrino	Newton's law of universal gravitation	Orbits	Particle accelerator	Pauli exclusion principle	Phases of matter
Phase transitions	Phonons	Photons	Plum pudding model	Polymer	Potential energy
Probability density	Protein folding	Quantum electro-dynamics	Quantum chromo-dynamics	Quantum collapse	Redshift
Shell model (Bohr model)	Spacetime	Standard Model	Superpartner	Universality of free fall	Unstable equilibrium

Activity 2: Planning for the Classroom

Time: 1 Hour.

Purpose: To generate ideas and develop activities for teaching the topics of *Physics for the 21st Century* in participants' classrooms.

Materials:
- Butcher paper
- Digital camera

Make three columns on the board:
- Topics we plan to use in the classroom
- Topics we don't think we can use in the classroom
- Barriers in implementation of a topic

Initial Sharing (25 minutes)
Ask each participant to share their initial ideas (from *Between Sessions*) regarding classroom use of topics from *Physics for the 21st Century*. What topics did they choose, and why? What did they consider might fit within their curriculum, and what teaching approaches did they consider? What are the barriers to implementation of that topic? Are there one or two topics that they didn't choose? Fill their responses into the appropriate columns on the board. (*Note*: In groups of larger than 8 participants, we recommend this activity as a Think-Pair-Share). Discuss the barriers (e.g., student buy-in, resources, administrative support) and brainstorm.

Work in Small Groups (20 minutes)
Based on the results of this discussion, ask participants to self-organize into groups of no more than four to brainstorm and develop ideas for teaching those topics in their classroom. What activities might they use, and how might they relate to topics that they already teach? How might they assess student learning of these ideas? Which clicker questions might they use from the units? Record the ideas on butcher paper.

Share Out (15 minutes)
Ask each small group to present their ideas to the larger group. Take digital images of each group's butcher paper. Discuss.

Activity 3: Continuing the Conversation (optional)

Explore ways that the group could continue to coordinate to share teaching activities and ideas, such as an online forum or email list.

Thanks for participating in *Physics for the 21st Century!*

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