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."

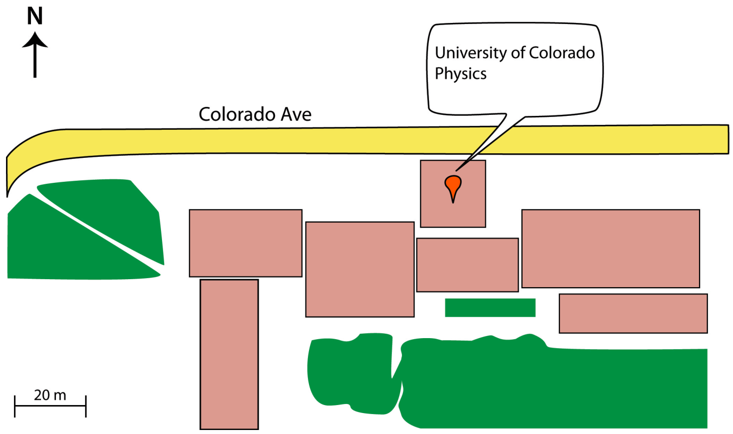
What's Going On?

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.

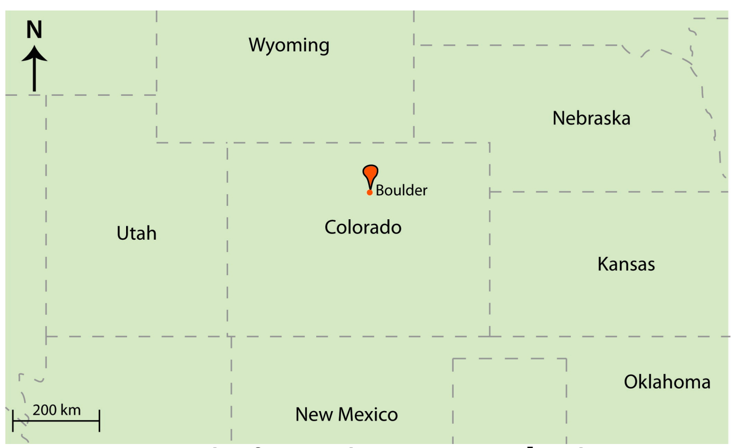
This gives a sense of just how much empty space is in the atom relative to the size of the nucleus, or the building, which is quite small. But there is a lot going on in that small space. In today's session, we'll be discussing the stuff inside the building—which isn't even part of this map at all.

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

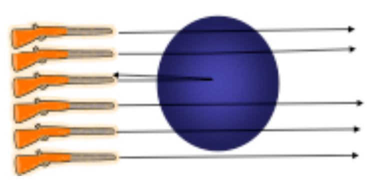
To Do and To Notice

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

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.

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.

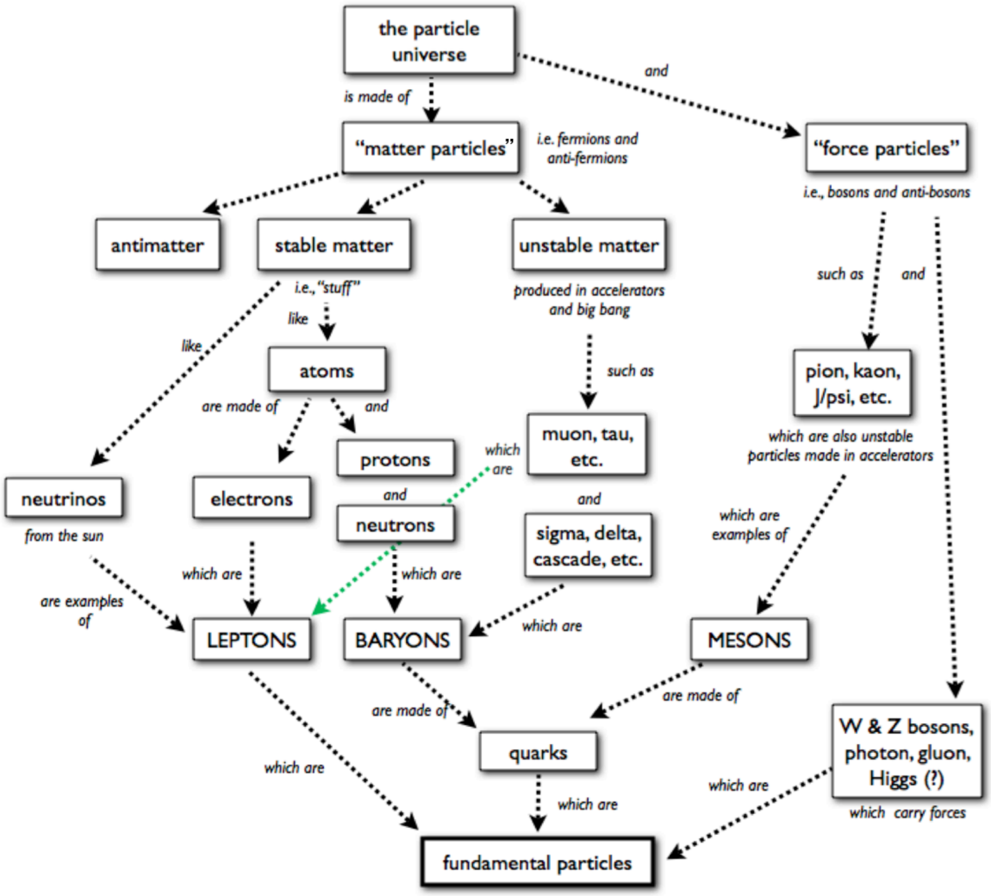
At the end of the activity, have participants make a clean copy of their group's concept map (or their own concept map, based on class discussions). This personal copy of their concept map will be used several times in later sessions.

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

Time: 20 Minutes.

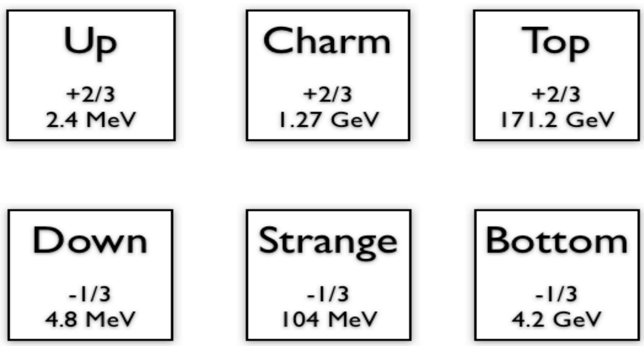
Purpose: To see how quarks combine to make the particles shown on the concept map, as well as how the Standard Model organizes quarks by their properties similarly to how the periodic table organizes the elements.

Materials:

- 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).