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.

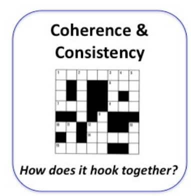
Video: The program delves into the cutting edge of our ability to manipulate light to our own ends. Quantum computing uses the probabilistic nature of quantum mechanics to create new computing architectures that enable different types of computing and cryptography. Paul Kwiat and his team at the University 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?

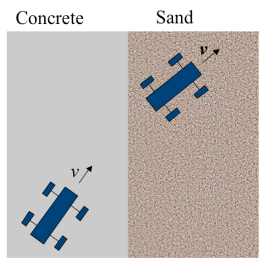
<u>Time</u>: 15 Minutes.

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.

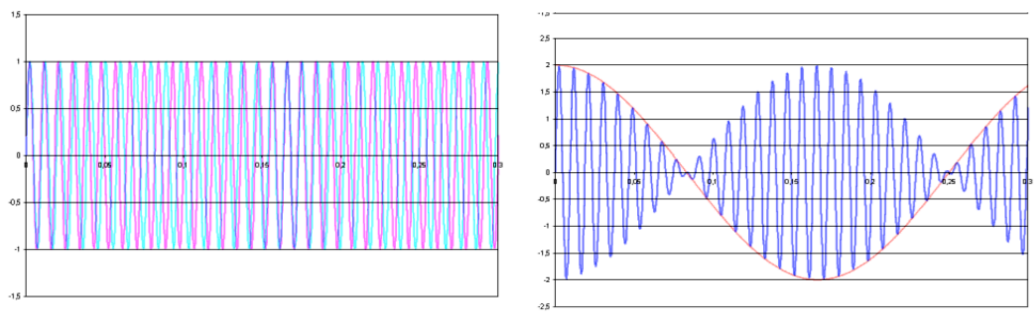
One should consider light as a particle when considering processes like absorption, when atoms in the materials have transitions near that photon wavelength, as for ultraviolet light absorbed by the atoms/molecules in the glass. A wave model for light works when the material is transparent, and so light 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.

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

<u>Time</u>: 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?

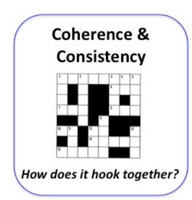
Classically, this experiment isn't surprising at all. Classically, each sock was pink or blue the whole time. But if these were entangled "quantum socks", then both socks together would be in a superposition state of pink and blue. Considering the experiments of Paul Kwiat and his team, the pink sock 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?