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*.

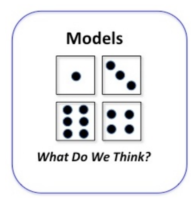
Video: The program follows the work of two physicists—an experimentalist and a theorist—studying systems with emergent properties by modeling their properties in different ways. Paul Chaikin, at New York University, experiments with close-packing using M&M's®. He determines the organizational principles 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

CLICKER/DISCUSSION QUESTION

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
- Plasma
- Liquid crystal: Isotropic
- Magnetic materials[6]
- Liquid
- Glass
- Liquid crystal: Nematic
- Superfluid/Bose-Einstein condensate
- Gas
- Insulator/conductor
- Liquid crystal: Smectic[5]
- 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).