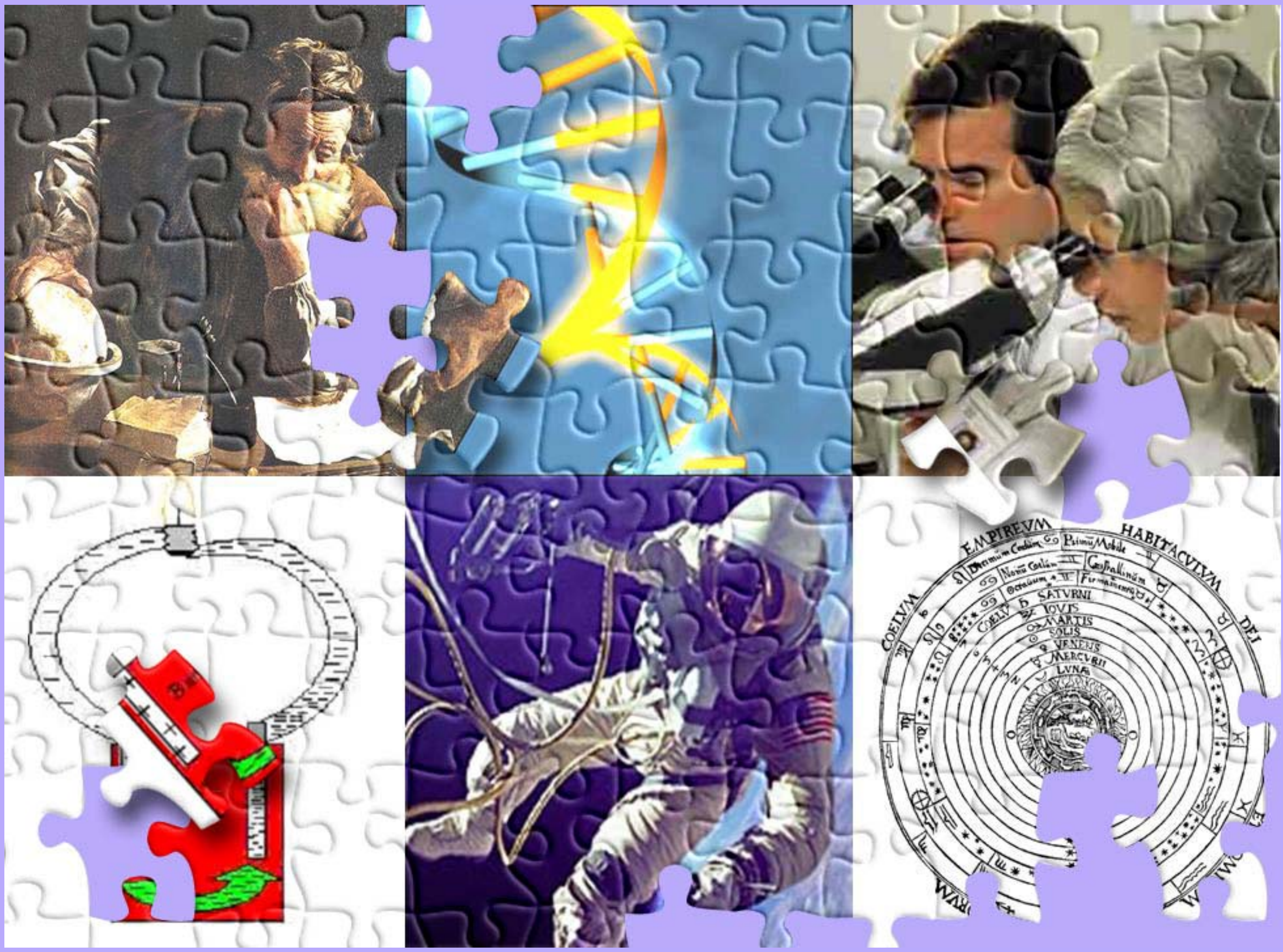
The Nature of Scientific Thinking

Lessons Designed to Develop Understanding of the Nature of Science and Modeling



The Understandings of Consequence Project
Project Zero, Harvard Graduate School of Education

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Lesson 1: In What Ways Do Scientists Come to Their Understandings?

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Understanding Goals

- While we often hear that scientists use "the scientific method," scientists draw upon a much broader range of methods in their work.
- Scientists do not always follow the same prescribed method to further their understanding.
- We can recognize different trends that scientists of the past and present have used in the discovery process

Background Information

Scientific Thinking is More Than "the Scientific Method"

Students in many science classrooms are presented with the scientific method as the fundamental plan scientists use to gain their understandings. Scientists throughout history have come to their conclusions in a variety of ways, not always following such a specific method. Interestingly, even when scientists do use the scientific method, they rarely use it in the stereotyped, step-by-step way that schools tend to teach it.

The following lesson introduces historical case studies of scientists. The case studies reveal that scientists over time have demonstrated a range of methodologies with some common characteristics. Studying these trends can help us in our own thinking in science classrooms. The lesson invites students to analyze the modes of inquiry that scientists engage in and then reflect on what this means for their own scientific thinking. The lesson encourages a constructivist approach to learning; instead of telling students what some of the patterns are in scientists' thinking, it encourages students to identify the patterns on their own. After reviewing the case studies, students should try to come up with the common patterns demonstrated by the scientists for themselves before you discuss and present additional information to the class.

While the scientists discussed in this lesson are largely from the past, several contemporary scientists are also included. It is important for students to realize that ways of thinking and knowing in science shift over time. It is also important to realize that if we only look back at famous scientists, it presents a distorted picture of how science in everyday life precedes. We are likely to look back and, with the benefits of 20/20 hindsight, only see those patterns that were important in the instances studied. Lessons three and four focus on 21^{st} century science and scientists for those teachers who would like to devote the time to exploring how science shifts and changes over time and some patterns specific to current day cutting edge science.

You might consider using these lessons at the beginning of the school year before the first science unit is taught (when the scientific method is usually presented). The lessons also might be infused during the school year, making connections when new topics are presented.

Patterns in Scientists' Ways of Finding Out

What patterns might students find? Some overall trends that the majority of the scientists seem to follow include: *creative and critical thinking; extensive documentation; strong powers of observation; synthesis of information and strong collaboration with others; taking advantage of serendipity; and use of technology and resources (often in a climate of discovery). These patterns are explained below.*

1. Creative and Critical Thinking: This involves coming up with new ideas, thinking outside the box, connecting imagination with logic, and then communicating these ideas to others.[1] Many times these ideas go against the prevailing belief system. Here are some examples:

> <u>Bonnie Bassler</u> **–** (b. 1962; Discovered that bacteria communicate with chemical language[2]). While working at a lab near the Pacific Ocean, Bassler noticed organisms that lit up in the water. Upon further study with another geneticist, Mike Silverman, Bassler determined that different species of bacteria have two-way communications with a type of chemical language called *quorum sensing.* She continued with this research even though other biologists thought it was not worth investigating. In 1994, she was given an appointment at Princeton University, but through the late 1990's

[1] Conner, M. (Spring 2001). Great minds: A thoughtful interview with Michael Gelb. *LiNE Zine*. Retrieved 28 December, 2006, from http: //linezine.com/4.1/interviews/mgmc.htm
[2] Bonnie L. Bassler, Ph.D. (n.d.). Retrieved March 28, 2007 from Howard Hughes Medical Institute: http://www.hhmi.org/research/investigators/bassler_bio.html

Bassler had difficulties getting money to continue with this research. She continued her hard work with determination. Her theories have now been accepted and today many other scientists believe Bassler's research could help find new ways to fight deadly strains of disease and world health problems.[3]

Sir Isaac Newton – (b. 1643; d. 1727; Physics principles including the Laws of Motion and Universal Gravitation). To build on the earlier ideas of Galileo and Copernicus on the Nature of the Universe, Newton was faced with the challenge of proving his laws of gravitation. He needed more developed math concepts and they did not exist, so he invented Calculus to work on such issues.[4] His ideas were published in his most famous book *Principia.*

Albert Einstein – (b. 1879, d. 1955; Theory of Relativity) Einstein believed strongly in the child-like power of imagination. His quotes include; "When I examine myself and my methods of thought, I come to the conclusion that the gift of fantasy has meant more to me than my talent for absorbing positive knowledge." (Atlantic Monthly 1945) "The process of scientific discovery is, in effect, a continual flight from wonder." "I am enough of an artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world." (The Saturday Evening Post Oct.26, 1929)[5]

2. Extensive documentation – Many scientists keep detailed notebooks, drawings and correspondence of comments, suggestions, and revisions of their ideas, lectures and experiments. Documentation is a means of helping them to download thinking onto paper (reducing the memory load) and of helping them to see patterns that otherwise might go unnoticed. Here are some examples:

Leonardo da Vinci – (b. 1452, d. 1519; Many paintings and inventions including plans for a flying machine, helicopter, parachute, bicycle, hydraulic jack, snorkel, world's first revolving stage, armored tank, mortar, submarine, comparative anatomy, geotropism, fossilization, and a multitude of breakthroughs in optics and mechanics)[6] He compiled 6000 pages of manuscript in mirror handwriting (starting at the right side of the page and moving left) and with intricate drawings.[7] He believed drawing was the key to understanding creation and creativity. He was constantly adding to

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[3] Silberman, S. (2003, April). The bacteria whisperer. Wired, 11(4). Retrieved March 28, 2007, from http: //www.wired.com/wired/archive/11.04/quorum_pr.html.
[4] Conner, M. (Spring 2001). Great minds: A thoughtful interview with Michael Gelb. *LiNE Zine*. Retrieved 28 December, 2006, from http://linezine.com/4.1/interviews/mgmc.htm
[5] Albert Einstein. (n.d.). Retrieved February 2, 2007 from http://www.websophia.com/aphorisms/einstein.html
[6] Gelb, M. J. (1998). *How to think like Leonardo Da Vinci: Seven steps to genius everyday*. New York: Random House.
[7] Leonardo: Right to left. (n.d.). Retrieved 22 February 2007 from Museum of Science: http://www.mos.org/sln/Leonardo/LeonardoRighttoLeft.html

his notebooks and first employed the techniques of perspectives and cross section drawing.[8]

Sir Isaac Newton **–** (b. 1643, d. 1727; physical principles including Laws of Motion). Newton kept rigorously detailed notebooks, even as a young student. He didn't share his scientific thoughts with friends or colleagues. The notebooks were found in a metal box after 200 years. They included over three million words describing his interest in many areas including mathematics, alchemy (chemistry), and astronomy, specifically descriptions of comets.[9]

Albert Einstein – (b. 1879, d. 1955; physical principles including Theory of Relativity). He replied to many letters. According to Albert-Laszlo Barabasi of University of Notre Dame and Harvard University and Joao Gama Oliveira of Universidade de, Portugal and Notre Dame, Einstein sent more than 14,500 letters and received 16,200. These two scientists analyzed the correspondence and compared it to the way people reply to emails, calculating response times.[10]

Benjamin Banneker – (b. 1731, d. 1806; predictions of solar and lunar eclipses; inventor and astronomer, African American). Banneker kept his extensive observations and calculations of astronomical phenomena in notebooks and journals. His work was eventually published in a six-year series of almanacs.[11]

Charles Darwin – (b. 1809, d. 1882; Theory of evolution – Natural Selection). Darwin relied on his voluminous notebooks that included private ideas, questions, fragments of thoughts, notes from his five year voyage on the ship the *Beagle*, and systematic documentation of specimens collected from the trip. He wrote more than sixteen books.[12]

3. Strong Powers of Observation - Many scientists' attention to detail and examination of research encompasses many years of investigation to reach their understandings.

Barbara McClintock **–** (b.1902, d. 1992; Genes shift on chromosomes). As the first woman president of the Genetics Society of America, Barbara McClintock's intense observation and exceptional ability to read patterns of genes in the chromosomes of kernels of corn led to a Nobel Prize for medicine for the discovery of *transposition*. Her conclusions went against the thinking of the time. She also faced obstacles to

[8] Gelb, M. J. (1998). *How to think like Leonardo da Vinci: Seven steps to genius everyday*. New York: Random House.
[9] Dyson, F. (2006). *The scientist as rebel*. New York: New York Review of Books.
[10] Dume, B. (26 October 2005). What do Einstein, Darwin, and e-mails have in common? Retrieved 28 December 2006 from http://physicsweb.org/articles/news/9/10/15/1
[11] http://en.wikipedia.org/wiki/Benjamin_Banneker; Accessed 7.23.09
[12] Museum of Science, Boston. (2005). Darwin: Online Educator's Guide. http://www.mos.org/darwinguide/synopsis.html Retrieved February, 2007.
In-person visit to Museum of Science, Boston, Darwin Exhibit. March 9, 2007.

gaining acceptance because she was a woman.[13] According to Joan Dash, McClintock "used only the ordinary microscope, cross-breeding, and observation. But it was the observation of a scientist to whom each ear of corn was an individual, a member of her family, and the brilliantly colored kernels were as carefully observed as traits of a growing child."[14]

Mary Leakey – (b. 1913; d. 1996; Archeologist and paleoanthropologist discovered early man nicknamed "Nutcracker Man") Along with her husband Louis, Mary Leakey changed the view we have of early human prehistory. Mary was in charge of the digging sites and was known for her "systematic and careful attention to detail."[15] She was an artist and illustrated most of what her husband wrote. The Leakey's most important find happened in 1959 while she was walking her dogs in Tanzania, Africa. She found the remains of ancient man with a ridge on the top of the head. The amazing discovery gave scientists major information about this history of early humans.[16]

Jocelyn Bell Burnell (b. 1943) and Antony Hewish (b.1924) – (Discovered pulsars—dense stars from which light seems to "pulse"). In 1967, observing with a radio telescope, graduate student Jocelyn Bell and her advisor Antony Hewish noticed a "strange twinkling" from a particular direction in the sky. Thinking it was interference in the receiver, they continued collecting data. They discovered three radio sources – three objects – that seemed to be pulsing, so they were called pulsars.[17] It is now known that pulsars are very dense stars that, due to several reasons, emit light in a particular direction; the light from the star sweeps around as the star rotates, similar to the light in a lighthouse. This is the first time pulsars were detected.[18]

Arno Penzias (b.1933) and Robert Wilson (b. 1936) – (Microwave background radiation exists throughout the universe).Working at Bell Labs in New Jersey in 1964, Penzias and Wilson were looking for signals with a radio antenna. They had background noise in the signals that would not go away. Through careful investigation – even finding pigeons in the equipment—they still had the noise and

[13] Spangenburg, R & Moser, D. K. (1994). *On the shoulders of giants: The history of science from 1946 – 1990's.* New York: Facts on File, Inc.
[14] Dash, J. (1991). *The triumph of discovery: Women scientists who won the Nobel Prize.* Englewood Cliffs, New Jersey: Julian Messner. Quotation from p. 91.
[15] Spangenburg, R & Moser, D. K. (1994). *On the shoulders of giants: The history of science from 1946 – 1990's.* New York: Facts on File, Inc. Quotation from p. 132.
[16] Spangenburg, R & Moser, D. K. (1994). *On the shoulders of giants: The history of science from 1946 – 1990's.* New York: Facts on File, Inc.
[17] Spangenburg, R & Moser, D. K. (1994). *On the shoulders of giants: The history of science from 1946 – 1990's.* New York: Facts on File, Inc. Quotation from p. 51.
[18] Pulsars. (n.d.). Retrieved 6 April 2007 from NASA: http://www.Imagine.gsfc.nasa.gov/doc/science/know_l1/pulsars.html

decided it was coming from space. The type of echo was microwave radiation. Scientists now have more information as to the composition of our universe.[19]

4. Synthesis of Information and Strong Collaboration with Others - Scientists often support ideas by looking across work in the field and synthesizing it. They work in collaboration, are open to ideas of others, and communicate extensively with colleagues.

Jones Salk – (b. 1914, d. 1995; Polio vaccine). Salk brought together a series of findings of other scientists while working with Thomas Francis Jr., developing an influenza vaccination. Along with other scientists, he focused on three strains of the polio virus. Soon after Salk, Albert Sabin developed an oral live vaccine for polio that he felt was more effective and easier to distribute but had difficulty gaining attention. Eventually this was widely adopted.[20]

Giglielmo Marconi – (b. 1874, d. 1937; 2,000 mile radio transmission of Morse Code across the Atlantic Ocean). Marconi was a brilliant collaborator and manipulator of other scientists' findings – he used Heinrich Hertz's discovery of radio waves in 1888. Hertz died shortly after making this discovery and it was Marconi who realized the importance and uses for these waves. He had the backing of his wealthy family to make the equipment and start the Marconi Wireless Company, the first to send and receive radio transmissions.[21]

Sir Isaac Newton – (b. 1643, d. 1727; Laws of Motion). Newton built on earlier observations made by Galileo. He corresponded about Universal Gravitation with Robert Hooke and elliptical orbits with Edmund Halley.[22]

Charles Darwin – (b. 1809, d. 1882; Theory of evolution – Natural Selection). Darwin had many scientific mentors and role models. Darwin sent his collections to experts for identification and made use of other advisors who included gardeners and zookeepers. He corresponded with fellow naturalists around the world.[23] As meticulous as Darwin was, he was made some errors while studying finches on his voyage to the Galapagos Islands. He failed to note which islands some of the birds came from. The ship's captain had recorded the correct information, not Darwin.[24]

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[19] Spangenburg, R & Moser, D. K. (1994). *On the shoulders of giants: The history of science from 1946 – 1990's.* New York: Facts on File, Inc.
[20] Balchin, J. (2003). *Science: 100 scientists who changed the world*. New York: Enchanted Lion Books.
[21] Gelb, M. J. (1998). *How to think like Leonardo Da Vinci: Seven steps to genius everyday.* New York: Random House.
[22] Kilgour, F.G. (1982). William Harvey. *Scientific genius and creativity: Readings from* Scientific American. New York: W.H. Freeman and Company
[23] Same as footnote #15 (from Museum of Science exhibit only)
[24] Metz, K. (1997). On complex relation between cognitive developmental research and children's science curriculum. *Review of Education Research, 67(1),* 154-156.

5. Taking Advantage of Serendipity – Many discoveries happened while scientists were looking for something else, sometimes they were by accident, and sometimes after specific experiments provided surprising findings.[25] Not all science is explored solely by controlled experiments.

Louis Pasteur – (b. 1822, d. 1895; Pasteurization process). Pasteur started out looking for what causes wine to sour and an accident with chicken cholera bacteria lead Pasteur to the development of vaccines and to make significant contributions to our understanding of microbial biology.[26]

Antoine Henri Becquerel – (b. 1852; d. 1908; Radioactivity). Investigating x-rays, Becquerel noted the use of radioactive materials for medicine after he was accidentally burned by some radium left in his pocket.[27]

Alexander Fleming – (b. 1881; d. 1955; Penicillin). Fleming discovered mold in his lab that was left there over a vacation and used the connection in the production of penicillin. It took ten more years for the production of large amounts.[28]

Frederick Kekule – (b. 1829; d. 1896; Structure of benzene ring). A configuration of the structure of benzene came to Kekule in a dream as he was napping on a bus. He dreamt of a snake circling with a tail in its mouth and it inspired thoughts as to the structure of benzene.[29]

George de Mestral **–** (b. 1907, d. 1990; Velcro – a type of hook and loop fastener). While walking his dog in the woods in Switzerland, de Mestral found burrs stuck to his pants and realized that the concept could apply to fasteners.[30]

Charles Goodyear **–** (b. 1800, d. 1860; Vulcanized Rubber). In 1839, after working on a stronger rubber material that was not affected by changes in temperature, Goodyear accidentally dropped a mixture of rubber with sulfur on a hot stove and it boiled over. When sulfur and other additives are combined, and heat and pressure are applied, a vulcanized or hardened rubber can be used for vehicle tires.[31]

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[25] Dunbar, K. (1995). How scientists really reason: Scientific reasoning in real-world laboratories. In R.J. Sternberg, & J. Davidson (Eds.), *Mechanisms of insight*, 365-395. Cambridge, M.A.: MIT Press.

[26] Balchin, J. (2003). *Science: 100 scientists who changed the world*. New York: Enchanted Lion Books. BBC History. Louis Pasteur. http://www.bbc.co.uk/history/historic_figures/pasteur_louis.shtml. Retrieved June 28, 2007.

[27] Balchin, J. (2003).

[28] Balchin, J. (2003).

[29] Roberts, R. M. (1989). *Serendipity: Accidental discoveries in science.* New York: John Wiley and Sons, Inc.

[30] Roberts, R. M. (1989).

[31] Goodyear. The Charles Goodyear Story. http://www.goodyear.com/corporate/history/history_story.html Retrieved June 28, 2007. Reprinted from Reader's Digest (1958), The Strange Story of Rubber.

Archimedes – (b. 287 B.C., d, 212 B.C.; Volume of irregular solids – Archimedes Principle). While thinking about a problem for King Hiero about the authenticity of a gold crown, Archimedes was taking a bath and noticed when he got in the tub some water spilled out. He made the connection to his volume and water displacement and then transferred this idea to the volume of the gold crown.[32]

Sir Isaac Newton – (b. 1643, d. 1727; Laws of Motion and Universal Gravitation) Newton saw an apple fall from a tree (it may be a myth that the apple actually hit him in the head) and reasoned that a force must have pulled the apple to the ground. He saw a connection between this force and the orbit of the moon around the earth.[33]

6. Use of Technology and Resources (Often in a Climate of Discovery) – These scientists used the techniques available at the time and had a vision of what was to come. Many experienced an environment that fostered experimentation and research. Often they had patrons with access to money and facilities of a laboratory and/or university setting.

Leonardo da Vinci – (b. 1452, d. 1519; Many inventions as outlined above). da Vinci lived at a very enlightened time in Florence and had several wealthy patrons. Leonardo was fascinated with the latest inventions of his time and if the technology was not available he imagined what could be used.[34] Many of his manuscripts included sketches of these creations.

Sir Isaac Newton – (b. 1643, d. 1727; Laws of Motion and Universal Gravitation). Math at the time was limited, so Newton invented Calculus as a tool to resolve his questions.[35]

Thomas Edison – (b., 1847; d. 1931; Incandescent light bulb). Edison practiced continuous questioning and registered for 1,093 patents. He founded a research and development center in Menlo Park, New Jersey. Of note is that his virtual deafness contributed to less distraction according to his colleagues. Edison engaged in a strong pursuit of learning.[36]

Charles Darwin **–** (b. 1809, d. 1882; Theory of evolution – Natural Selection). Darwin collected microscopes, magnifying glasses and chemicals to pursue his investigations. His wealthy family included his paternal grandfather who was an inventor and bold thinker, and the famous Wedgwood China family on his mother's side. He grew up during the beginning of the Industrial Revolution when the worldview was starting to

[32] Balchin, J. (2003).
[33] Balchin, J. (2003).
[34] Baumgaertel, F. (1997). Leonardo Da Vinci – A Genius and His Time. Leonardo Homage to Leonardo da Vinci by IWC and Mercedes Benz, Zurich: Haumesser Publishing, 1997, pp. 6 – 8.
[35] Conner, M. (Spring 2001). Great minds: A thoughtful interview with Michael Gelb. *LiNE Zine*. Retrieved 28 December, 2006, from http://linezine.com/4.1/interviews/mgmc.htm
[36] Balchin, J. (2003).

expand. He attended the University of Cambridge and Edinburgh University and made many scientific contacts. Towards the end of his life the younger scientists were questioning the religious views of the times and defended Darwin's theory of evolution.[37]

Joycelyn S. Harrison (b. 1963) is a scientist who specializes in chemical engineering at NASA Langley Research Center.[38] She researches polymers and uses this information and advanced technology to invent new materials.[39] These new materials will be used to improve satellites and may be used in the future to form synthetic muscles in robots.[40]

Your class might notice other patterns in addition to or instead of those described here. The exact set of patterns that each class comes up with is less important than having students think deeply about scientific thinking and how nuanced it can be in comparison to what we are often led to believe.

[37] Same as footnote #15 (Museum of Science exhibit)
[38] July, 2009, from http://oeop.larc.nasa.gov/fwp/won/won-profile.html
[39] July 2009, from http://www.cnn.com/fyi/interactive/specials/bhm/story/black.innovators.html
[40] http://inventors.about.com/od/hstartinventors/a/Harrison.htm

Lesson Plan

Materials

- Student notebooks or journals
- Case studies
- White board or chart paper

Prep Step

- Review lesson plan, background information and understanding goals
- Make copies of detailed and short case studies for the class

Analyze Thinking

Step 1: Reveal Current Thinking

Start with a group discussion. Ask students to share the ways they think scientists go about making scientific discoveries. Write their ideas on the board or on large white paper. Responses may include *doing experiments*, *researching information on the web, talking to other scientists, etc.*

Then, instruct students to make their own list in their science notebooks or journals. Once they have done this, have them share their list and add it to the class list. Ask students to share any other ideas they have at this time.
Follow up with these ideas and ask them to explain their thoughts.

Step 2: Thinking About How Scientists Come to Discoveries

Ask the class if they can think of particular scientists and what they are famous for discovering. Have them think back to other grades and topics they studied. Record as a group what scientists and discoveries the class comes up with. If you do not get too many responses ask the class if they know what Thomas Edison and Albert Einstein were famous for (*The light bulb and the Theory of Relativity*). *You can include any scientists you think they may have studied.*

Pose the question "Do you think that these scientists came to their discoveries in the same way?" Listen to the responses. They may include – *they are different topics so the way they came to their understandings would be different, they had different technology and did different experiments.* Tell them that they did have various methods for the units of study, but there are several patterns or trends we notice that they have in common. We are going to study some scientists from our past and present and see what the class thinks the patterns are. We will discuss the trends and our goal will be to apply the scientists' methods to our own thinking in science class.

Step 3: Analyzing Scientist Case Studies

Hand out the scientist detailed case studies from the Resources Section. Read the first case study as a class and have students write in their notebooks the name of the scientist, what his discovery was, and all the ways the scientist made their discovery.

Possible Answers for Case Study #1: Charles Darwin

Darwin developed the theory of Natural Selection (living things came from a common ancestor and adapted over time to their environment). Some ways that he came to his understandings include:

- Extensive documentation — notebooks, sketches, letters, manuscripts and organizing collected specimens
- Collaboration with others — wrote letters and consulted with scientists and experts, help from professors and teachers
- Use of resources available — did research at universities; money from his family helped his studies, used microscopes, magnifying glasses, and chemicals
- Take advantage of serendipity — right place to get job on ship, the *Beagle*, looking for a particular specimen and found many varieties
- Creative and critical thinking — went against the known theories of the times
- Strong powers of observation — involved in over twenty years of study before publishing his findings.

Discuss their ideas in depth. Explore different points of view. Are their methods obvious, do students differ with each other, can we always be sure, is historical information always accurate?

Instruct the class to read the second case study. They should do the same thing with this second entry and then compare the second scientist's methods with the first scientist. What is the same and what is different in terms of their pattern of investigation?

Possible Answers for Case Study #2: Leonardo da Vinci

da Vinci was a painter, sculptor, architect, inventor, scientist, city planner, cartographer (mapmaker), and military engineer. Some ways that he came to his understandings include:

- Extensive documentation — notebooks with close to 6,000 pages of notes (in shorthand and mirror writing), sketches, drawings, and maps
- Collaboration with others — apprentice to a master painter, worked with assistants and had pupils of his own, shared ideas with fellow guild members
- Use of resources available — was given work through the ruling Medici family and Andrea de Verrocchio, was constantly creating and trying out his inventions
- Creative and critical thinking — the list of massive accomplishments shows an amazing ability to think outside the box
- Strong powers of observation — extremely detailed drawings and sketches

Possible Answers in Comparing Darwin and da Vinci

Both Darwin and da Vinci documented their ideas, worked with others, spent many years developing their ideas, took advantage of resources available to them, and had many accomplishments. They lived and worked on different discoveries in different times.

Tell students that as they read more case studies, several more themes should emerge. Also have the class think about what they do as science students and how they explore science concepts. This will be addressed in Lesson 2. Depending upon how much class time you have you could assign further case studies or assign several for homework.

Both of the detailed case studies (Charles Darwin and Leonardo da Vinci) and the short case studies included in the ***Background Information — Patterns of Scientists' Ways of Finding Out*** are available at the end of the lesson as handouts.

Review, Extend, Apply

Step 4: Discussing the Case Studies

If you assigned several case studies in class or for homework, take the next part of a class period to go over what the students investigated. Write down as a class what patterns they noticed with the scientists they read about. Can they make any connections in terms of the types of discoveries, the times they lived, and their overall circumstances?

Step 5: Researching a Scientist who is not on the List

Explain to the class that you want them to research a scientist *not* on our case study list. Have the students find a scientist, check with you (you may choose to have each student in the class study a different scientist or assign several groups in the room to work on the same scientist), and have them include in a short report:

1. Name of scientist, birth date, date of death (if applicable), and some facts about their early life.
2. What were they famous for and a brief description of their discovery?
3. What ways did the scientists go about making their discoveries? How did they come to their ideas?
4. A bibliography of their sources.
5. Any other information they feel is important to include.

This report can be presented as an oral presentation. The class can then keep track of what methods the various scientists used and look for trends. This activity could take several class periods or assigned as a short-term project. You may also consider doing this at other times during the school year.

Step 6: Making Connections to One's Own Thinking

Pose the following question "Do you notice how you learn science? Think about how you thought about the world around you as a young child, and about studying science in your science classes over the years.   Is there anything the same about your science investigations and those of the scientists you have studied so far?" This topic will be revisited in an upcoming lesson.

Lesson 2: How Might Patterns of Scientific Thinking Impact Our Own Learning?

Photo Credit: FreeClipArtNow.com, c. 2008

Understanding Goals

- The thinking patterns that scientists use can help us in our own learning.
- Thinking like scientists includes identifying and pursuing questions about the everyday world.
- Curiosity and a sense of wonder are characteristics that many scientists recall from their childhood and still hold today.

Background Information

Building on the previous lesson about how scientists of the past and the present came to their discoveries, this lesson invites students to reflect upon their own scientific thinking. Six trends or patterns of scientific thinking were presented in Lesson 1 and they include *(1) creative and critical thinking (2) extensive documentation (3) strong powers of observation (4) synthesis of information and collaboration with others (5) taking advantage of serendipity and (6) use of technology and resources*. Students may engage in these forms of thinking without realizing that they are thinking as a scientist would.

Thinking like a scientist includes a sense of wonder—searching for questions to explore in the everyday world, and reasoning about possible answers to those questions. In this lesson, help your students to connect back to their "inner scientist." Curiosity and a sense of wonder are part of the childhood experience. Going back and tapping into this time offers students a sense of what it means to be a scientist. It enables them to test what they are capable of understanding and to make connections to what they are interested in. Recalling activities and situations also validates their personal experiences. Hopefully this excitement about learning something new continues throughout their lives.

Many scientists recall moments and activities that guided them to follow a path in science. As we learned from the two detailed case studies in Lesson 1, as very young children both Charles Darwin and Leonardo da Vinci were extremely curious, da Vinci with nature drawings and Darwin with nature collection. As little boys, both scientists also wrote in codes they created. In the book *Curious Minds: How a Child Becomes a Scientist*[41], John Brockman has compiled twenty seven essays written by present day scientists and asked them to explain what occurred when they were children that encouraged them to follow a life in science. Some interesting examples of childhood recollections include:

1. Murray Gell-Mann – (b. 1929) (physics, Nobel Prize in 1969) Gell-Mann remembers going with his older brother to museums, spending time bird watching, and having a father who had a great interest in science and fostered that in his children. (pp. 35–36).

2. Mary Catherine Bateson – (b. 1939) (cultural anthropologist) Both of Bateson's parents were anthropologists, Gregory Bateson (background in biology) and Margaret Mead (background in psychology). Bateson remembers from her father "When I think of Gregory, I think of studying tide pools, collecting beetles, constructing an aquarium, and taking and developing photographs together but also of logical puzzles and problem solving" (p. 93). Her mother helped her recognize human behavior and placed an emphasis on "cultural differences: different races, different religious services, visitors from all over the world where she and her colleagues had done research" (p.95).

3. Paul C.W. Davies – (b. 1946). (theoretical physicist and cosmologist) Davies recalls his fascination as an eight year old looking at constellations and shooting stars with his father. He then became interested in light and electricity and at age twelve was given a gift of a photographic developing kit. Two years later he made his own telescope. (pp.55-57).

4. Ray Kurzweil – (b. 1948). (inventor including character recognition software and the music synthesizer). At age four, Kurzweil decided he was going to be an inventor. He built a rocket ship including pieces from an erector set, then moved on to go-carts, boats, and a mechanical baseball game. Both of his parents were artists and greatly influenced his creativity (pp. 164-165).

Lesson 2 encourages the class to think about their own childhood experiences, connect to these experiences, and consider how they fit with the six patterns of thinking that scientists use, and with their own science understanding.

[41] John Brockman. (2004). *Curious minds: How a child becomes a scientist.* New York: Vintage Books.

Lesson Plan

Materials

- Students notebooks or Journals
- White board or chart paper
- List of the six trends in scientist's thinking (on white board or chart paper)

Prep Step

- Review the lesson plan for Lesson 1 specifically the explanations of the six trends in scientist's thinking.
- Make copies of the five scientists' recollections of their childhood science experiences (Resources Section).

Analyze Thinking

Step 1: Reflecting on our science experiences

Introduce the following scenario to the class. Say,

"We are going to try something different today. I want each of you to take a step back and try to remember when you were much younger. Try to recapture a time when you first remember being curious about the world around you. Everyone has different recollections at various ages. Use the following questions and situations to help spark those memories and answer as many of them as you can."

Slowly read the list to the students, pausing and giving them time to think about each question:

"When you were young did you ever wonder what causes a firefly to light up?"
"Why do some things sink and others float when you put them in water?"
"What causes a rainbow?"
"Why is the sky blue?"
"Why did the dinosaurs become extinct?"
"Did you have a collection of bugs, rocks, shells, plastic dinosaurs, cars or trains? Did you know all their names and characteristics?"

"Do you remember visiting a zoo, museum, aquarium, farm, tide pool, or observatory?"
"Have you ever taken care of an animal or designed and installed a bird feeder?"
"Were you the kind of child who took things apart, put models together and always wanted to know how things worked?"
"Were you the kind of kid who knew more about the computer and other technology than the adults around you?"
"Did you read a lot of books about science topics?"
"Do you remember cooking and trying different recipes?"
"Answer as many of these questions as you can by thinking about your own experiences including home and school. Write down what you remember being curious about and how you explored this curiosity."

Note to Teacher: When students are thinking about their childhood experiences, have them go back as far as they can remember. Also tell them to include their science classes starting with pre-school and go to the present. While the students are working, think about your own recollections from childhood. Share them with the students in the next step. It will help them to feel comfortable sharing their own recollections.

Step 2: Invite the students to share their recollections

After the pupils have written down their childhood recollections, invite them to share. Some students may feel shy about sharing their ideas so be sure to encourage a thoughtful environment for the class discussion. Collect their memories on the board or chart paper.

Review, Extend, and Apply

Step 3: Making a deeper connection to the scientists

After the pupils have written down their childhood recollections, discuss what they wrote as a class. You can write down on the board or chart paper their shared memories. Move the discussion toward connecting these experiences to the six trends of the scientists. Say,

"The way you thought about and investigated these ideas is very similar to how scientists investigated their topics. As we learned from our last lesson, not all scientists come to their understandings in the same way and neither do we. The patterns of thinking that scientists use can help us in our own learning."

Have them refer to a posted list of the six patterns and see if they notice similarities. They should write their reflections in their journals or notebooks and try to be as specific as possible. You may want to have them do this with a partner and share with each other before sharing with the whole class. Then write on the board or chart paper what connections to the six trends they have made as a class.

Pass out the recollections of some present-day scientists from the Resources Section. Have the students read them individually or as a group. Ask the students to compare what they read to their own experiences while they are reading. Also review the two detailed case studies from Lesson One on Charles Darwin and Leonardo da Vinci for additional information focusing on their early years.

What might students say? Here are some possible answers to connect their recollections to the trends of scientists are as follows:

1. *Creative and critical thinking* – always asking questions such as "Why is the sky blue?" etc., designing a secret code, imaginative play, thinking outside the box, enjoying projects and open ended questions in school, making connections between different lessons and units, inventing things
2. *Extensive documentation* – keeping a diary, drawing, doodling, note-taking, outlining, and modeling
3. *Strong powers of observation* – collections, telescope watching, counting bird species at a bird feeder, recognizing all the different kinds of dinosaurs, experimenting and classroom discussions
4. *Synthesis of information and collaboration with others* – group play, building a clubhouse or fort, putting ideas together in a classroom lab group, working with others on a group science project or assignment, and study groups
5. *Taking advantage of serendipity* – trip or hike that had unexpected results, accidental discoveries in school lab or at home, classroom activities that turned out differently than planned
6. *Use of technology and resources* – taking apart or putting toys or machines together, effectively using the Internet for assignments, designing technology, library resources, specific experiment equipment, school guest speakers, and field trips.

Picture of Practice
Making Connections to How Scientists Think
A Middle School Science Class

Mrs. C: Would anyone like to share their memories as to what they were curious about as a child?

Sarah: I remember taking long walks in the woods near our house collecting all kinds of plants and animals. But I especially remember getting an ant farm for a birthday gift.

Mrs. C: What do you remember about that?

Sarah: I just remember watching the ants for hours – it was really cool.

Mrs. C: That's excellent Sarah. Does anyone else have a science experience they'd like to tell us about?

Mike: I remember building things with legos. I also was constantly taking things apart to see how they worked.

Mrs. C: What kind of things?

Mike: The computer mouse and video game controller. It drove my parents crazy.

Mrs. C: Do you still take things apart?

Mike: Yeah, I work on car engines with my older brother. I really like fixing our computer when my parents have trouble with it.

Mrs. C: I wonder how many other people in the class do similar things?

Step 4: Thoughts About Our Learning

After the students have shared their "inner scientist" childhood memories and made connections to real life scientists pose the following questions to them.

"Do you think you still connect to your 'inner scientist'?"
"Are you as curious about the world around you as you were as a little child?"

Then encourage them to connect to that curiosity now. Say,
"Let's try now to find our present "inner scientist" and connect to that curiosity. What comes to mind and what do you wonder about?"

You might get some possible responses such as:
"Could we ever travel to other planets?"
"I wonder what causes thunderstorms."

"How do baseball pitchers throw gyro balls?"

Ask: "Why is this connection important for real learning, learning that is for you, not just for a grade?" "What, if any, are the obstacles for this personal exploration?"

Listen and discuss their ideas. Tell students that as we learn different science concepts, they should try to keep in mind that the activities we do, the discussions we have, and how each of them come to their own science thinking, connects to how scientists of the past and present think about science, too.

Lesson 3: What are Some Characteristics of 21st Century Scientific Thinking?

Photo Credit: En.Wikipedia.org, copyright 2006 Mysid

Understanding Goals

- The classic examples of scientists in the past and how they think and approach their work are not the only ways of reaching understanding.
- The rapid advancement of technology and the accumulation of information are changing the patterns of scientific thinking and research in the 21st century.
- While scientists in the 21st century share many similar characteristics with scientists of the past, there are also distinguishing differences in the way modern scientists go about their work.
- Identifying characteristics of successful scientist and their thinking patterns, helps us become better science students by applying these skills to our own learning.

Background Information

The 21st Century Scientist

This lesson specifically focuses on modern scientists of the 21st century. In the first lesson, students learned about famous scientists such as Charles Darwin (natural selection), Louis Pasteur (germ theory of disease), and Nicolaus Copernicus (heliocentric universe). While these tales are very important in conveying a sense of thinking in science over time, cutting edge science of today stresses a different set of ways of knowing or ways of finding out. While there is overlap between the thinking approaches addressed in lesson one and in this lesson, there are also differences. As science has changed through the centuries (e.g. shifted from reductionist to integrative/systems approach, shifted from hypothesis-driven to information-driven, shifted from biological to artificial), so have the scientists and their ways of thinking and knowing. Such changes in the patterns of scientific thinking and research came with the rapid advancement of technology and accumulation of information due to the digital age of the 21st century.

This lesson will help students discover that, while there are fundamental ways of thinking and knowing that are shared among scientists across time, there are also distinguishing differences in the way modern and past scientists go about their work. Studying trends in scientists' way of thinking and knowing can help students in their own thinking in science class. Students can analyze the modes of inquiry that scientists engage in and reflect on what this means for their own thinking in science.

Scientists are categorized as 21^{st} century scientists based on their active involvement in the scientific community in the 21^{st} century. While their inventions and discoveries may not have occurred exactly within the 21^{st} century timescale, this is the period where their initial inventions and discoveries are being refined for novel applications.

Lesson Plan

Materials

- *Characteristics of a successful scientist* handout
- Detailed 21^{st} century scientist case studies (Jay Keasling, Robert Langer, Angela Belcher)
- Student notebooks or journals

Prep Step

- Review lesson plan, background information and understanding goals
- Make copies of *Characteristics of a successful scientist* handout (Resources Section)
- Make copies of detailed 21^{st} century scientist case studies (Resources Section)

Analyze Thinking

Step 1: Review: What are Characteristics of a Successful Scientist?

Remind the students of the list that they developed in Lesson One. Ask students, "What are some characteristics that successful scientists might have? Think about characteristics such as the way scientists think or skills that they might have, and not so much physical characteristics." Collect students' recollections from Lesson One.

Encourage the students to think about their thinking. Ask students, "Did you have a scientist in mind when you thought about these characteristics? How did you come up with these characteristics?" Ask whether they had a historical figure in mind or a current day scientist. This may explain why the class-generated list might be more aligned with one list versus the other— a list of characteristics for the past scientist or 21^{st} century scientist.

Explore Outcomes

Step 2: Identifying Characteristics of a Successful Scientist

Hand out *Characteristics of a Successful Scientist* for the class to look over. What are some initial reactions? Point out to students how there are two different lists of characteristics (one for scientists of the past and one for scientists of the 21^{st} century). How are the two lists similar and different?

After reviewing the list with students, ask them, “Do you think all scientists come to their discoveries in the same way,” “Do scientists display all these characteristics at all times?” Their responses may include: *scientist study different topics so the way they came to their understandings would be different* or *they had different technology and did different experiments*. It is important to point out to students that scientists have various methods of going about their experimentation and work, and depending on the type of work they are doing, scientists don’t always share the same methods. The list of characteristics given to them is just several patterns or trends we noticed that scientists have in common.

Step 3: How Did Your Lists of Characteristics Compare?

Identify any similarities and differences between this list and the class-generated list. Did the class-generated list align more with characteristics of scientists of the past or of the 21st century? Ask students why they think their list doesn’t include some of the characteristics on the distributed list. Students might recognize that they might not know enough examples of scientists and their work, especially more modern scientists. This would be a good segue into the exploration of case studies, where you will study several modern scientists and identify some of their characteristic ways of thinking and working.

Step 4: Analyze Case Study of a Successful 21st Century Scientist

Hand out the detailed case study on Jay Keasling. Work together as a class to identify any patterns of thinking or methods that the scientist displays. Make sure to ask students to specifically identify what part of the case study justifies their claims. Have students write the class findings in their journals/notebooks.

Some questions to have students consider: “Do we agree with each other’s analyses? Or are there conflicting analyses?” “Can we always be sure that the scientist is really displaying these characteristics? Is historical information always accurate?” These questions help develop students’ sense of the nature of knowing in science and history—what we know is provisional, and can change depending on what we know at the time.

Possible Findings from Case Analysis: Jay Keasling

Keasling is a pioneer of synthetic biology—a field that designs and constructs new organisms for useful purposes. He is known for creating a microbe that produces a drug to treat malaria (making drugs from bugs). Some of his characteristics as a scientist include:

- *Creative and imaginative:* wanted to invent new tools that could turn cells into chemical plants which take in something very simple and spit out something complicated and valuable; developing other applications of synthetic biology (using microbes to break down pesticides, making biodegradable plastics, creating fuels from plants)
- *Critical thinking:* thought about how to design and create microbes to produce artemisinin much quicker and cheaper, how to integrate genes from different species into a microbe to fabricate the drug
- *Seek and integrate information:* integrated methods and concepts from engineering and biology, leading to synthetic biology
- *Supported with significant resources:* did research at universities and received grant money
- *Practical-minded:* microbes will churn out anti-malarial drug for a fraction of its current cost, making it accessible to much more of the world and potentially saving millions of lives
- *Strong disciplinary understanding:* studied biology and chemical engineering extensively, leading to his PhD and professor position at UC Berkeley
- *Good business skills:* manage a team of people working under him (comprised of graduate students, post-docs, and research assistants), got funding from Bill and Melinda Gates Foundation, marketing research findings via interviews

Step 5: Case Analyses in Groups

Divide students up into groups of 3-4 students. Each group will work on a case study on Robert Langer or Angela Belcher (ideally, only two groups will work on the same scientist). Remind students to think through the case study as was done for the first case study. Again, have students write their findings in their journals/notebooks.

Possible Findings from Case Analysis: Robert Langer

Langer developed a new way of drug delivery using polymers (a type of plastic), and is a pioneer of organ regeneration using polymer scaffolds. Some of his characteristics as a scientist include:

- *Creative and imaginative*: used window screen analogy to develop a way to gradually release drugs at target sites, designed polymers with special properties to protect the drug from being broken down too early or released too quickly
- *Engaged in critical thinking*: thought of different applications for polymers (polymer for drug deliver, and polymer for organ regeneration)

- *Used advanced technology*: invented his own advanced technology (polymer scaffolds)
- *Supported with significant resources*: did research at universities, money from grants
- *Collaborate with large teams of people*: collaborated with scientists in different fields (e.g. neurosurgeons) and worked with more than 100 researchers in his own lab
- *Practical-minded:* worked on various different projects at the same time to generate a constant flow of grant money
- *Have good business skills:* ran the largest research laboratory lab in the world, started numerous companies

Possible Findings from Case Analysis: Angela Belcher

Belcher used viruses to grow small wires (nanowires) and batteries. Some of her characteristics as a scientist include:

- *Creative and imaginative*: grew batteries and other small objects using viruses
- *Engaged in critical thinking*: thought about how abalone can naturally assemble hard objects like their shell, and realized that maybe we can have viruses self-assemble objects we want
- *Used advanced technology*: used advanced microscopes
- *Supported with significant resources*: did research at universities, money from grants
- *Practical-minded:* worked on several projects all at once with energy applications, made batteries that were environmentally-friendly and compact
- *Have good business skills:* got funding from fellowships, started own company

Note: Students can watch an online cartoon video of Belcher's biography (Resource Section).

After students' group analyses, take some time to go over what the students investigated as a class. By having more than one group work on the same scientist, students will be more efficient at identifying all relevant characteristics; and including just three scientists makes it easier for students to make comparisons between the scientists. Have students write down the patterns that their classmates noticed with the other scientists they read about.

Note to Teachers: It may be difficult for students to hold all of the scientists (including Jay Keasling) in their heads all at once. You may want to help make connections between the common characteristics of the different scientists for the students.

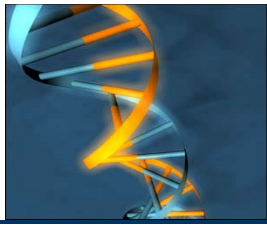
Review, Extend, and Apply

Step 5: How Do You Think Like a Scientist?

Ask students to reflect on how they think and explore science concepts in science class. Looking at the characteristics we've discussed in today's class, how it is different or similar to how scientists work? Ask students, "Think about how you study and learn in your science classes over the years. Is there anything that is the same about your science investigations and those of the scientists you have studied today?" Discuss with students how they can apply scientists' patterns of thinking and working to our own thinking in science class.

Step 6: Analyze Additional Case Studies [Optional]

More case studies can be assigned as homework. Through additional case studies, students would be able to identify more characteristics of scientists as listed in the handout. Students would also be better able to make connections and notice patterns between different scientists and different types of discoveries.



Lesson 4: What is Synthetic Thinking?: An In-depth Example of 21st Century Science

Photo Credit: Examiner.com, copyright 2009 Clarity Digital Group LLC d/b/a Examiner.com

Understanding Goals

- The 21st century scientist is not limited to working with organisms that naturally exist in the world. Scientists often think synthetically by re-designing and constructing new organisms for useful purposes.
- Designing and creating novel organisms by combining various biological components from different cells is one way scientists think synthetically in the 21st century.

Background Information

What is Synthetic Biology?

In addition to common characteristics that successful 21st century scientists share, there are also certain thinking dispositions unique to the 21st century scientist. One such disposition is to think more synthetically or artificially. With the rapidly emerging field of synthetic biology, blurring the lines of biology and engineering, scientists are no longer limited to working with organisms that naturally exist in the world. Scientists often think synthetically by re-designing and constructing new organisms for practical and novel applications.

Synthetic biology is an extension of genetic engineering. Some even describe it as a more sophisticated version of genetic engineering, taking into account a broader rational design perspective[42]. The engineering influence seeks out the simplicity in biological systems, and brings standardization and modular design principles to biology[43].

Synthetic biologists can use interchangeable parts from natural biology to assemble systems that function in new ways, never existing before in living systems[44]. Modular

[42] Salisbury, M.W. (2006). Get Ready for Synthetic Biology. *Genome Technology Magazine*. Retrieved from http://www.genome-technology.com.
[43] Drubin, D.A.,Way, J.C., & Silver, P.A. (2007). Designing biological systems. *Genes & Development 21*, 242-254.
[44] Benner, S.A. & Sismour, A.M. (2005). Synthetic biology. *Nature Reviews Genetics 6*, 533-543.

circuit components (e.g. metabolic enzymes or fluorescent output genes) that are well characterized and can act independently of other cellular processes are used to build synthetic biological circuits. Much like the ease of using Legos—standardized bricks that can attach to any other part—synthetic biology starts from the use of standardized biological building blocks.

The goal of synthetic biology is to both better understand how organisms function at the DNA, protein, and cell level by creating artificial biological systems, and to solve important real-world problems, the latter having caught the attention of scientists, politicians, and entrepreneurs. Promising fields of application include energy, environmental monitoring and remediation, biotech and pharmaceuticals, and materials fabrication.

As pointed out in the detailed case study of Jay Keasling (one of the pioneers of synthetic biology), another key difference between synthetic biology and genetic engineering is the complexity of products or task the engineered organism can produce and accomplish. Genetic engineering is typically limited to having microbes produce small proteins (e.g. insulin, growth hormones) by simply inserting a single gene, from a different organism, into a microbe. However, with synthetic biology a complex interaction of several genes can be produced in a specified sequence, much like what goes on in a chemical plant: petroleum goes in, and after a whole chain of reactions, plastic comes out.

Helping Students Understand Synthetic Biology

This lesson is a two-day exploration to help students understand how modern scientists think synthetically. The activities in day one (*Making a Better Cow*) and day two (*Designing a New Microbe*) build on each other, asking students to think synthetically like scientists. The first activity presents students with a problem (cows that only graze at night) and asks them to think creatively about how they can modify the cow to help them graze better at night. This activity is meant to have little to no constraints on students' imagination. The goal is to encourage students to think "outside of the box" and to imagine the impossible, which is what many synthetic biologists are doing.

The second activity also presents students with a problem (need for hydrogen gas as alternative fuel) and asks students to design a microbe that can use starch and water to make hydrogen gas. Students are given a set of organism cards to work with. Each card symbolizes a different type of organism (bacteria, rabbit, yeast, archaea, spinach, and mouse). Proteins (molecules that can convert one molecule into another) that are unique to each organism are listed on the card. Students' engineered microbe will essentially have different proteins from different organisms, placed in a certain sequence, to end up with a final product of hydrogen gas. Students are given the *Designing a New Microbe* worksheet to help them visualize the problem better and reduce the cognitive load (i.e. amount of information they need to carry in their heads) of solving the problem.

This second activity places more constraints on students' imagination than the first activity, as it requires students to draw upon components that already exist in nature to design a new microbe. It is still a creative process because these components can be from a variety or organisms. This activity, created from an actual experiment conducted in 2007[45], is more authentic to what synthetic biologists actually do, compared to the first activity.

Taken together, the two activities allow students to discover that synthetic biology is a "mind-blowing" field, accomplishing things that most people never realized was possible. This includes the students themselves! While students may have initially thought the first activity was outrageous, by the end of the two-day lesson, they will have realized how seemingly impossible feats can be possible especially when scientists are thinking creatively and synthetically. By thinking and working synthetically, scientists have more freedom then before in creating organisms for real-world applications.

This lesson can be used immediately following Lesson 3, or it may be infused during the school year as students learn more about genetic engineering or creative thinking.

[45] Zhang Y.H., Evans B.R., Mielenz J.R., Hopkins R.C., Adams M.W. (2007). High-yield hydrogen production from starch and water by a synthetic enzymatic pathway. *PLoS ONE 5*: e456.

Lesson Plan: Day 1

Materials

- *Making a Better Cow* worksheet
- Student notebooks or journals

Prep Step

- Review lesson plan, background information and understanding goals
- Photocopy *The Cow that Grazes at Night* worksheet (Resource Section)

Analyze Thinking

Step 1: Making a Better Cow

Hand out *Making a Better Cow* worksheet. Following the directions of the handout, ask students to come up with special properties or powers that the cows or other organisms in the environment can have to help cows better graze at night. This activity is meant to have students think creatively to solve a problem. Encourage students to think outside of the box, and let them know that there are no "right" answers. Guide students along by asking, "what are some properties that the cows can have to help their situation, and can you think of existing organisms that have those properties we can borrow from?" or to frame it in another way, "what are some properties that existing organisms might have that you can give to the cows or other organisms in the surrounding environment?"

Possible ideas students might come up with:

- Cows that glow in the dark or light up so they can see each other and farmers can keep track of their cows—some jelly fish are glow in the dark, fireflies light up at night
- Grass that glow in the dark or light up so cows can find patches of grass better
- Cow can produce trail pheromones common in social insects like ants, to mark their paths so they can better locate food source or return home
- Cows can produce alarm pheromones when attacked by a predator, triggering flight (in termite) or aggression (in bees) in other cows.
- Cows with owl eyes to see better at night

- Cow's fur produces a waxing coating like plant leaves so that they don't get wet when they fall into the water

Note to Teachers: Students do not need to be able to map their ideas to properties of existing organism; this step is meant to scaffold students' thinking and help them come up with ideas. This activity is meant to have little to no constraints on imagination. But feel free to map students' ideas to organisms for them!

Write students' ideas on the board—if students are having a hard time, give them a few examples to help them get started. Promote collaborative thinking as students are contributing ideas by asking the class whether we can take the idea further, or help identify existing organisms that may have these properties. It is good to point out to students that one of the main reasons why scientists collaborate is because different people can draw on different background knowledge to help each other advance their thinking.

Once students have the idea, you may want to work on a second example to help students see that we are not just talking about cows here. For instance, if you don't water your house plants, they wilt and die. What are some properties, that if plants or the surrounding environment had them, it would solve or help with the problem? *(For instance, what if plants could turn bright red when they needed water? Or if they all developed waxed leaves when the weather became dry?)*

Step 2: Is This Possible?

After the activity, take some time to reflect and ask students, "Do you think scientists think like the way we did in this activity?" "If this scenario was true, do you think our ideas can be carried out?" "Is this realistic?" Give students some time to write their reflections in their notebook/journals. Then as a class, collect a representative sample of students' thoughts and write it on the board. Leave students' rationale up on the board for tomorrow's part of the lesson.

Lesson Plan: Day 2

Materials

- *Designing a New Microbe* worksheet
- Organism cards
- Student notebooks or journals

Prep Step

- Review lesson plan, background information and understanding goals
- Photocopy *Designing a New Microbe* worksheet (Resource Section)
- Cut out organism cards (each group of 3-4 students will have a set of cards) (Resource Section)

Explore Outcomes

Step 1: Designing a New Microbe

Spend some time reviewing what the students did in the previous lesson (*Making a Better Cow*). Introduce today's activity by saying, "the activity we will be doing today is actually modeled after a real experiment done by scientists in 2007."

Divide students into groups of 3 or 4. Each group receives a set of organism cards. Each student receives a *Designing a New Microbe* worksheet. Remind students that proteins (or enzymes) are molecules inside cells that convert one molecule into another (e.g. "Protein T" in bacteria converts "How" into a different molecule called "Home"). An analogy would be to see the protein as a blender; blenders function to convert/change one thing (a solid whole apple) into a different thing (liquid apple juice). And because they are different, we call them by different names; "whole apple" becomes "juice," much like how the molecule "How" becomes "Home."

Following the directions in the handout, have students create a kind of assembly line that integrates proteins from different organisms into a microbe that uses water and starch (inputs) to ultimately produce hydrogen (output). While the *Making a Better Cow* activity captures the general essence of synthetic biology, this activity brings students even closer to emulating the synthetic biologist by working under the constraints of known organisms.

Possible Answers to *Designing a New Microbe*

There are two possible pathways that can lead to hydrogen production:

1. Starch & water → Protein G → Protein P → Protein D → Protein R → Protein T → Protein F → Protein H →Hydrogen

2. Starch & water → Protein G → Protein P → Protein D → Protein H → Hydrogen

Guide students along by encouraging students who have already figured out how to attempt the problem to reveal and share with the class how they are thinking through the problem. Stop students periodically to ask, “How are you thinking through this problem? What is your goal, and how is your thinking helping you reach that goal?” Students may find either working sequentially forward or backward to fill in the worksheet to be easier.

Note to Teachers: The hydrogen production pathway from starch and water is a shortened version of the actual 2007 experiment for learning purposes. The organism types and molecule names are true to the experiment. Protein names are made up for simplicity.

Step 2: Discuss Students’ Findings

Have students tell you what they found as you record their findings on the board. Students may have discovered by now that there are two paths that lead to hydrogen production. Ask students, “does this activity remind you of any scientist we studied in our last class?” Students might recall that Jay Keasling may have done something similar by making an antimalarial drug from sugar using synthetic biology.

Students may have also discovered that no proteins from the mouse organism were used for the design of their new microbe. Ask students, “what do you think is the purpose of having a mouse organism when we didn’t need it?” Help students understand how in reality scientists have hundreds of organisms to choose from, some of which are irrelevant to their work. Therefore, a common characteristic that all scientists share, is being about to *seek and integrate information* (studied in Lesson 3), which is being able to identify and pull together important and relevant information.

Review, Extend, and Apply

Step 3: Making Connections

Start by asking, “what did we do in our first (*making a better cow*) and second (*designing a microbe*) activity? What are some similarities and differences between the two activities?” Students should be able to point out that we were designing and creating new organisms with a practical purpose in mind.

Referring back to the rationale that was written on the board from the last class, ask students again, “does the cow activity seem more realistic after today’s activity?” Students might comment on how the first activity seemed more outrageous at first glance, but essentially the two activities are very similar.

Step 4: How Do Scientists Think Synthetically?

Explain: "What we did today is very characteristic of the thinking processes of 21st century scientists, who often think synthetically by re-designing and constructing new organisms for useful purposes. The 21st century scientist is not limited to working with organisms that naturally exist in the world, but can work with novel organisms that they created. However, it is important to note that we can only create organisms from components that actually exist in nature. There are still some constraints to our creativity, as was experienced in the second activity (designing microbe)."

"There are scientists who specialize in designing and constructing new organisms, so we call them synthetic biologists, or scientists who do synthetic biology. As you have experienced in our cow and microbe activity, synthetic biology is a very mind-blowing field, accomplishing things that a lot of people never thought was possible, including us!"

Resources For Section 1

Detailed Case Study #1:
Charles Darwin

(b.1809, d.1881) *Theory of Evolution by Natural Selection*

Charles Darwin was born in rural England in 1809 to a wealthy family. His father was a physician and his grandfather was an inventor. As a child, Charles collected various beetles, bird's eggs, seashells, and moths. He liked to write in code and would climb a tree; then he'd ask his sister to pass messages to him by ropes and pulleys. He was not the best student and was bored by lessons—especially Greek and Latin. He spent many hours watching birds and reading about nature. His mother died when he was eight years old and he was sent to boarding school. As a teenager, he was excited about chemistry, geology, botany, and biology. He did many experiments with his brother.

Charles' father wanted him to be a physician and sent him to the University of Cambridge. His teachers recognized his potential as a bright student. But Charles did not enjoy studying medicine and spent a great deal of time collecting and sketching beetles as he had done as a young boy. His father pulled him out of that school and sent him to Edinburgh University to study religion. This was also not what he wanted to do, so he focused on studying science, specifically plants and animals.

Charles heard about a job on a ship, *The Beagle*, as a naturalist. He would collect and study plant and animal specimens. His father objected, but with some convincing, Charles took the position. It was the best five-year experience of his life! The trip went to many places including several countries in South America, the coasts of Africa and Australia, and the Galapagos Islands. He often had seasickness, but could not wait to collect all kinds of sample specimens. Parts of his extensive collections were sent back to England on passing ships. His brother and other scientists catalogued the samples as they received them.

After the five year journey, he returned to England, got married, and settled in the countryside. He began studying his *Beagle* research in a very systematic way. He collected microscopes, magnifying glasses and chemicals. In addition to researching his data alone, he relied on experts of the day for information. Charles sent some specimens to London to see what the authorities had to say and their information greatly influenced his theories. He also corresponded with many scientists around the world and sought the advice of gardeners and zookeepers.

Origin of Species. One idea is that he wasn't finished thinking and felt he needed more evidence to convince others of his new ideas. A second idea is that he feared that important scientists would criticize his theories. His ideas were different from the religious beliefs of the day. Many of his friends, including young scientists, encouraged him to publish. It wasn't until he received a letter from a scientist who had a similar theory of natural selection, (the idea that living things came from a common ancestor and adapted over time to their environment) that Charles published *The Origin of Species*, which sold out on the first day. There was some criticism, but the book was a hit with the young science community. Over his lifetime Charles Darwin published over sixteen books, wrote many papers and manuscripts with detailed descriptions and sketches. He is considered one of the most famous British scientists.[46]

[46] Museum of Science, Boston. (2005). Darwin: Online Educator's Guide. http://www.mos.org/darwinguide/synopsis.html Retrieved February, 2007.
In-person visit to Museum of Science, Boston, Darwin Exhibit. March 9, 2007.

Detailed Case Study #2:
Leonardo da Vinci

(b. 1452, d. 1519) *Master painter, sculptor, architect, inventor, scientist, city planner, cartographer, and military engineer*

Leonardo da Vinci was born in Vinci, Italy, the son of an accountant and a peasant woman. When he was five years old, Leonardo was taken to live in his grandfather's home. As a young child he was fascinated with nature, drawing, and mathematics. Leonardo was exceptionally curious and was constantly questioning and investigating the world around him. This love of learning continued throughout his life.

At age fifteen, he became an apprentice to the master painter and sculptor, Andrea de Verrocchio. In addition to painting and sculpting, at Verrocchio's studio, he learned many technical skills. Verrocchio, his teacher, recognized that he was a gifted artist and gave his apprentice many assignments. Both Leonardo and his teacher received money for many artistic projects from the ruling family of Florence, The Medicis. When Leonardo was twenty years old, he was accepted into the guild organization of San Luca.[47] [48] Many important artists, chemists, and physicians were also members and it was a place to share ideas, especially focusing on the botany and anatomy studies (seen in Leonardo's early paintings). Through the Medici family, Leonardo was introduced to a variety of great artists, mathematicians, and thinkers in the city. Florence, Italy, at this time called the Renaissance, was a major center of culture and business.

In 1482, when Leonardo was thirty he moved to the city of Milan where he created the masterpiece *The Last Supper*. At this time he also was involved with studying more anatomy and botany as well as astronomy, geology, geography, flight, military technology, and many scientific inventions.

By 1500, Leonardo had moved back to Florence. Two years later he became chief engineer to the commander of the Pope's army which involved traveling around Italy. This allowed him to make extremely detailed maps. Around this same time, he painted his most famous work, a portrait of a nobleman's wife called the *Mona Lisa.*

Leonardo was at the height of his fame and influence. He had many students and assistants. He also focused on his scientific ideas and always carried a notebook with him to write down questions, observations, drawings and sketches. It is estimated that his notebooks included close to six thousand pages.[49] While reviewing his notebooks scholars noticed a unique type of shorthand writing and a mirror writing technique. Leonardo was left-handed and started at the right side of his pages and then moved to the left. When he wrote letters to other people, he wrote in the normal direction. There are many ideas as to why he wrote this

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[47] Gelb, M. J. (1998). How to think like Leonardo da Vinci: Seven steps to genius everyday. New York: Random House. Actual location of footnote not noted.
[48] Same as footnote #37 except just p. 6 (Baumgaertel article on Leonardo)
[49] Gelb, M. J. (1998).

ideas, disguising his thoughts from the Church who considered his ideas to be against their thinking, and writing as a left-handed person was messy and the ink would smudge as his left hand moved left to right.[5]

Leonardo's accomplishments are so numerous that they are difficult to list. Here are a few examples. As an *artist*, he was one of the first to use oil paints and perspective. He was a talented architect who designed many buildings and he was a sculptor. As a *scientist,* he studied many branches of science. He studied anatomy and was one of the first to draw cross sections especially of humans and horses and to make casts of the brain and heart. He studied botany, specifically, geotropism (attraction of earth on plants) and heliotropism (attraction of plants to the sun). He also studied geology focusing on soil erosion and fossilization. He studied physics including the theory of gravity (before Newton), ideas about optics, hydrostatics, and mechanics. He also focused on astronomy and the theory of the sun not moving (before Copernicus). Leonardo was an *inventor*. He drew many sketches and ideas about mechanical clocks, flying machines, parachutes, helicopters, mechanical wings, self-propelled transmissions, three speed gears, bicycles, extendible ladders, snorkels, moving theater stage, hydraulic jack, automated looms for weaving, and map making and city planning designs.[6]

Leonardo da Vinci's extensive accomplishments are a tribute to his amazing powers of observation, his curiosity, ability to test and learn from mistakes, imagination and incredible use and development of technology. Many historical scholars consider Leonardo da Vinci to be one of the greatest geniuses of all time.

[5] Leonardo: Right to left. (n.d.). Retrieved 22 February 2007 from Museum of Science: http://www.mos.org/sln/Leonardo/LeonardoRighttoLeft.html
[6] Gelb, M. J. (1998).

Short Case Studies:
Patterns in Scientists' Ways of Finding Out

The following is a collection of types of thinking and examples of scientists whose work exemplifies each type. As you read each case, consider what makes it an example of that type of thinking.

1. Creative and Critical Thinking – This includes coming up with new ideas, thinking outside the box, connecting imagination with logic and then communicating these ideas to others. Many times these ideas go against the prevailing belief system.

Examples:

Bonnie Bassler – (b. 1962; Discovered that bacteria communicate with chemical language). While working at a lab near the Pacific Ocean, Bassler noticed organisms that lit up in the water. With her colleague, Mike Silverman, Bassler found that different species of bacteria have a means of "talking to each other" with a type of chemical language called *quorum sensing.* She continued her research even though other biologists thought it was not worth investigating. Up to the late 1990's, she had difficulty getting money to continue with her research, however, she persisted with hard work and determination. Today many other scientists believe Bassler's research could help find new ways to fight deadly strains of disease and world health problems. See a video of Bonnie Bassler talking about her work at: http://www.ted.com/index.php/talks/bonnie_bassler_on_how_bacteria_communicate.html (18 min.14 sec.)

Albert Einstein – (b. 1879, d. 1955; Theory of Relativity). Einstein believed strongly in the child-like power of imagination. His quotes include: "When I examine myself and my methods of thought, I come to the conclusion that the gift of fantasy has meant more to me than my talent for absorbing positive knowledge;"[52] "The process of scientific discovery is, in effect, a continual flight from wonder;" "I am enough of an artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world."[53]

2. Extensive documentation and strong powers of observation– Many scientists keep detailed notebooks, drawings and correspondence of comments, suggestions, and revisions of their ideas, lectures and experiments. Documentation is a means of helping

[52] Atlantic Monthly, 1945
[53] The Saturday Evening Post Oct.26, 1929

them to download thinking onto paper (reducing the memory load) and of helping them to see patterns that otherwise might go unnoticed.

Leonardo da Vinci – (b. 1452; d. 1519; A multitude of breakthroughs in optics and mechanics; paintings and inventions including plans for a flying machine, helicopter, and parachute). He compiled 6,000 pages of manuscript in mirror handwriting (starting at the right side of the page and moving left) and with intricate drawings. He believed drawing was the key to understanding, creation, and creativity. He was constantly adding to his notebooks and first employed the techniques of perspectives and cross-section drawing.

Sir Isaac Newton – (b. 1643; d.1727; Physical principles including Laws of Motion). Even as a young student, Newton kept rigorously detailed notebooks. He didn't tell his scientific thoughts to others. The notebooks were found in a metal box after 200 years. They included over three million words describing his interest in many areas including mathematics, alchemy (chemistry), and astronomy, specifically descriptions of comets.

Benjamin Banneker – (b. 1731, d. 1806; predictions of solar and lunar eclipses; inventor and astronomer, African American). Banneker kept his extensive observations and calculations of astronomical phenomena in notebooks and journals. His work was eventually published in a six-year series of almanacs.[54]

Albert Einstein – (b. 1879, d. 1955; Physical principles including Theory of Relativity). He replied to many letters. According to scientists Albert-Laszlo Barabasi and Joao Gama Oliveira, Einstein sent more than 14,500 letters and received 16,200. These two scientists analyzed the correspondence and compared it to the way people reply to emails, calculating response times.

Charles Darwin – (b. 1809, d. 1882; Theory of evolution; Natural Selection). Darwin relied on his voluminous notebooks that included private ideas, questions, fragments of thoughts, notes from his five year voyage on the ship the Beagle, and systematic documentation of specimens collected from the trip. He wrote more than sixteen books.

[54] http://en.wikipedia.org/wiki/Benjamin_Banneker; Accessed 7.23.09

3. Strong Powers of Observation – Attention to detail, careful observation, and in-depth examination of research over many years of investigation can lead to break through understandings.

Barbara McClintock – (b. 1902, d.1992; Genes shift on chromosomes). Barbara McClintock's intense observation and exceptional ability to read patterns of genes in the chromosomes of kernels of corn led to a Nobel Prize for medicine for the discovery of *transposition*. Her conclusions went against the thinking of the time. She also faced obstacles to gaining acceptance because she was a woman.[55] According to Joan Dash, "McClintock used only the ordinary microscope, cross-breeding, and observation. But it was the observation of a scientist to whom each ear of corn was an individual, a member of her family, and the brilliantly colored kernels were as carefully observed as traits of a growing child."[56]

Mary Leakey – (b. 1913, d. 1996; Discovered early man nicknamed "Nutcracker Man"). Along with her husband Louis, Mary Leakey changed the view we have of early human prehistory. Mary was in charge of the digging sites and was known for her "systematic and careful attention to detail."[57] She was an artist and illustrated most of what her husband wrote. The Leakey's most important find happened in 1959 while Mary was walking her dogs in Tanzania, Africa. She found the remains of ancient man with a ridge on the top of the head. The amazing discovery gave scientists major information about this history of early humans.[58]

Arno Penzias (b. 1933) and **Robert Wilson** (b. 1936); (Microwave background radiation exists throughout the universe). Working at Bell Labs in New Jersey in 1964, Penzias and Wilson were looking for signals with a radio antenna. They had background noise in the signals that would not go away. Through careful investigation – even finding pigeons in the equipment – they still had the noise and decided it was coming from space. The type of echo was microwave radiation. Scientists now have more information as to the composition of our universe.[59]

4. Synthesis of Information and Strong Collaboration with Others – Scientists often support ideas by looking across work in the field and synthesizing it. They work in collaboration, are open to ideas of others, and communicate extensively with colleagues.

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[55] Spangenburg, R & Moser, D. K. (1994). *On the shoulders of giants: The history of science from 1946 – 1990's.* New York: Facts on File, Inc.
[56] Dash, J. (1991). *The triumph of discovery: Women scientists who won the Nobel Prize.* Englewood Cliffs, New Jersey: Julian Messner. Quotation from p. 91.
[57] Spangenburg, R & Moser, D. K. (1994). Quotation from p. 132.
[58] Spangenburg, R & Moser, D. K. (1994). .
[59] Spangenburg, R & Moser, D. K. (1994).

Jones Salk – (b. 1914, d. 1995; Polio vaccine). Salk brought together a series of findings of other scientists while working with Thomas Francis Jr., developing an influenza vaccination. Along with other scientists he focused on three strains of the polio virus. Soon after Salk, Albert Sabin developed an oral live vaccine for polio that he felt was more effective and easier to distribute but had difficulty gaining attention. Eventually this was widely adopted.[60]

Giglielmo Marconi – (b. 1874, d. 1937; 2,000 mile radio transmission of Morse Code across the Atlantic Ocean). Marconi was a brilliant collaborator and manipulator of other scientists' findings – he used Heinrich Hertz's discovery of radio waves in 1888. Hertz died shortly after making this discovery and it was Marconi who realized the importance and uses for these waves. He had the backing of his wealthy family to make the equipment and start the Marconi Wireless Company, the first to send and receive radio transmissions.[61]

Sir Isaac Newton – (b. 1643, d.1727; Laws of Motion). Newton built on earlier observations made by Galileo. He corresponded about Universal Gravitation with Robert Hooke and elliptical orbits with Edmund Halley.[62]

5. Taking Advantage of Serendipity – Many discoveries happened while scientists were looking for something else, sometimes they were by accident, and sometimes after specific experiments provided surprising findings.[63] Not all science is explored solely by controlled experiments.

Louis Pasteur – (b. 1822, d. 1895; Pasteurization process). Pasteur started out looking for what causes wine to sour and an accident with chicken cholera bacteria lead Pasteur to the development of vaccines and to make significant contributions to our understanding of microbial biology.[64]

Alexander Fleming – (b. 1881, d. 1955; Penicillin). Fleming discovered mold in his lab that was left there over a vacation and used the connection in the production of penicillin. It took ten more years for the production of large amounts.[65]

[60] Balchin, J. (2003). *Science: 100 scientists who changed the world.* New York: Enchanted Lion Books.
[61] Gelb, M. J. (1998).
[62] Kilgour, F.G. (1982). William Harvey. *Scientific genius and creativity: Readings from* Scientific American. New York: W.H. Freeman and Company
[63] Dunbar, K. (1995). How scientists really reason: Scientific reasoning in real-world laboratories. In R.J. Sternberg, & J. Davidson (Eds.), *Mechanisms of insight,* 365-395. Cambridge, M.A.: MIT Press.
[64] Balchin, J. (2003). ; BBC History. Louis Pasteur. http://www.bbc.co.uk/history/historic_figures/pasteur_louis.shtml. Retrieved June 28, 2007.
[65] Balchin, J. (2003).

George de Mestral – (b. 1907, d. 1990; Velcro – a type of hook and loop fastener). While walking his dog in the woods in Switzerland, de Mestral found burrs stuck to his pants and realized that the concept could apply to fasteners.[66]

Charles Goodyear – (b. 1800, d. 1860; Vulcanized rubber). In 1839, after working on a stronger rubber material that was not affected by changes in temperature, Goodyear accidentally dropped a mixture of rubber with sulfur on a hot stove and it boiled over. When sulfur and other additives are combined, and heat and pressure are applied, a vulcanized or hardened rubber can be used for vehicle tires.[67]

Archimedes – (b. 287 B.C., d. 212 B.C.; Volume of irregular solids – Archimedes Principle). While thinking about a problem for King Hiero about the authenticity of a gold crown, Archimedes was taking a bath and noticed when he got in the tub that some water spilled out. He made the connection to his volume and water displacement and then transferred this idea to the volume of the gold crown.[68]

<u>5. Use of Technology and Resources (Often in a Climate of Discovery)</u> **–** These scientists used the techniques available at the time and had a vision of what was to come. Many experienced an environment that fostered experimentation and research. Often they had patrons with access to money and facilities of a laboratory and/or university setting.

Leonardo da Vinci – (b. 1452, d. 1519; Many inventions as outlined above). da Vinci lived at a very enlightened time in Florence and had several wealthy patrons. Leonardo was fascinated with the latest inventions of his time and if the technology was not available he imagined what could be used.[69] Many of his manuscripts included sketches of these creations.

Charles Darwin – (b. 1809, d. 1882; Theory of evolution, Natural Selection). Darwin collected microscopes, magnifying glasses and chemicals to pursue his investigations. He had family wealth. His paternal grandfather was an inventor and bold thinker. Darwin grew up during the beginning of the Industrial Revolution when the worldview was expanding. He attended the University of Cambridge and Edinburgh University and made many scientific contacts. Towards the end of his life the younger scientists were questioning the religious views of the times and defended Darwin's theory of evolution.[70]

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[66] Roberts, R. M. (1989).
[67] Goodyear. The Charles Goodyear Story. http://www.goodyear.com/corporate/history/history_story.html Retrieved June 28, 2007. Reprinted from Reader's Digest (1958), The Strange Story of Rubber.
[68] Balchin, J. (2003).
[69] Baumgaertel, F. (1997). Leonardo Da Vinci – A Genius and His Time. <u>Leonardo Homage to Leonardo Da Vinci by IWC and Mercedes Benz,</u> Zurich: Haumesser Publishing, 1997, pp. 6 – 8.
[70] Same as footnote #15 (Museum of Science exhibit)

Joycelyn S. Harrison (b. 1963; specializes in chemical engineering). Harrison is a research scientist at NASA Langley Research Center.[71] She researches polymers and uses this information and advanced technology to invent new materials.[72] These new materials will be used to improve satellites and may be used in the future to form synthetic muscles in robots.[73]

[71] From http://oeop.larc.nasa.gov/fwp/won/won-profile.html
[72] From http://www.cnn.com/fyi/interactive/specials/bhm/story/black.innovators.html
[73] http://inventors.about.com/od/hstartinventors/a/Harrison.htm

Scientists' Childhood Recollections

Murray Gell-Mann (b. 1929; physics, Nobel Prize in 1969). Gell-Mann remembers going with his older brother to museums, spending time bird watching, and having a father who had a great interest in science and fostered that with his children. (pp. 35–36).

Mary Catherine Bateson (b. 1939; cultural anthropologist). Both of Bateson's parents were anthropologists, Gregory Bateson (background in biology) and Margaret Mead (background in psychology). Bateson remembers from her father "When I think of Gregory, I think of studying tide pools, collecting beetles, constructing an aquarium, and taking and developing photographs together but also of logical puzzles and problem solving" (p. 93). Her mother helped her recognize human behavior and placed an emphasis on "cultural differences: different races, different religious services, visitors from all over the world where she and her colleagues had done research" (p. 95).

Ray Kurzweil (b. 1948; inventor including character recognition software and the music synthesizer). At age four, Kurzweil decided he was going to be an inventor. He built a rocket ship including pieces from an erector set then moved on to go-carts, boats and a mechanical baseball game. Both of his parents were artists and greatly influenced his creativity (pp. 164-165).

Characteristics of a Successful Scientist

Scientists of the past	21st century scientists
1. Were creative and imaginative 2. Engaged in critical thinking 3. Observed mindfully 4. Sought and integrated information 5. Took advantage of unexpected results 6. Used advanced technology 7. Supported by significant resources 8. Documented extensively 9. Collaborated with others	1. Are creative and imaginative 2. Engage in critical thinking 3. Observe mindfully 4. Seek and integrate information 5. Take advantage of unexpected results 6. Use advanced technology 7. Are supported by significant resources 8. Document selectively 9. Collaborate with large teams of people 10. Are practical-minded 11. Have strong disciplinary understanding 12. Understand advanced mathematics 13. Have good business skills*

Successful scientists of the past tended to:

1. **Be creative and imaginative**

   Scientists commonly tap into their creativity and imagination to help them generate new ideas to explore, or think of different ways to solve a question or problem. To generate ideas and ways to solve a problem requires scientists to see and imagine various possibilities, to think outside the box and not always follow the majority or prevailing belief system. Scientists usually work in environments that tolerate and foster creativity and imagination (e.g. research universities).

2. **Engage in critical thinking**

   Scientists think analytically and logically about their work, paying attention to how practical and feasible their work is.

3. **Observe mindfully**

   Scientists pay close attention to details, and actively use their mind to guide them in their observations, as certain cues tip them off to what to look at next, and how else the phenomenon can be observed (e.g. under the microscope, after it is frozen, after it is sliced apart, etc.).

4. **Seek and integrate information**

   Scientists are able to look at a variety of information from different fields and sources and be able to pull together what is important and relevant. They know what questions to ask, and how to incorporate other people's work into their own ideas and creations.

5. **Take advantage of unexpected results**
   Many discoveries happen while scientists are looking for something else, but end up discovering something surprising and unexpected. This happens sometimes because not every aspect of an experiment can be controlled, especially when the scientist is unaware of the non-obvious variable.

6. **Use advanced technology**
   Scientists regularly use technology, and the technology is usually advanced for the time. Scientists use technology with a vision of what is possible for their work and the technology in the future.

7. **Be supported with significant resources**
   Scientists commonly have patrons or sponsors (often with their own interests/agenda) with access to money and facilities (e.g. laboratories) to support their research.

8. **Document extensively**
   Scientists keep detailed notebooks, drawings, and letter correspondence of comments and revisions of their ideas and experiments. Documentation is a means of helping them to "download" thinking onto paper (reducing memory load) and see patterns that otherwise might go unnoticed.

9. **Collaborate with others**
   Scientists often work in collaboration with other scientists within and across fields. They are generally open to other people's ideas and communicate extensively with colleagues.

Successful scientists of the 21st century tend to:

1. **Be creative and imaginative**
2. **Engage in critical thinking**
3. **Observe mindfully**
4. **Seek and integrate information**
5. **Take advantage of unexpected results**
6. **Use advanced technology**
7. **Be supported with significant resources**

8. **Document selectively**

    The 21st century scientist spends less time on the act of documentation itself, but more time organizing and assembling a tremendous amount of data, video, and graphics that is usually generated automatically by advanced information technology. Scientists decide what is important and selectively document things that are original and novel (such as a new invention or procedure).

9. **Collaborate with large teams of people**

    Collaborations are often with a large group of people and between multiple institutions and laboratory groups. The problems and questions that are being tackled are more complex and greater in scale requiring collaboration with groups of people with differing expertise and resources/facilities

10. **Be practical-minded**

    The 21st century scientist tends to work on research problems that yield immediate returns (e.g. that will receive recognition or funding from the government or private institutions). It is common for scientists to work on multiple projects at the same time, some smaller than others, with at least one project generating the funds to support the other projects of interest.

11. **Have strong disciplinary understanding**

    The 21st century scientist has a deep understanding of the knowledge, methods, and ways of thinking in science. Present day scientists stand on the shoulders of more giants than scientist before them, thus there is more background knowledge and more skills to acquire to be conversant in the field.

12. **Understand advanced mathematics**

    Scientists frequently demonstrate their findings in mathematical equations, or use mathematics to justify and explain their work. For example, when scientists talk about a molecule moving along a DNA strand or diffusing through a cell, a mathematical representation is often included, and even required by some scientific journals.

13. **Have good business skills (*Not a science skill, but facilitates the science)**

    Established scientists (often the lead scientist, or Principal Investigator) are quite similar to CEOs of a corporate company. Lead scientists often have many other scientists working for them (e.g. undergraduate and graduate students, post-docs, research assistances, etc.) thus they have to know how to manage people, get funding, budget finances, and communicate effectively in presentations and interviews to market their products or promote interest in their discoveries or inventions.

Detailed Case Study
Jay Keasling
(b. 1964)

Photo: Permission by Jay Keasling

Best known for: *pioneering the new field of synthetic biology, which designs and constructs new organisms for useful purposes. He is also most known for creating a microbe that produces a drug to treat malaria (making drugs from bugs).*

Jay Keasling was raised on a farm, and spent his childhood exploring the practical side of biology, chemistry, and engineering. This background eventually led him to work in the rapidly growing field that uses living organisms like bacteria for various practical purposes, such as food processing, agriculture, and medicine.

In the early 1980s, genetic engineering became popular because microbes can be "convinced" to produce insulin, growth hormones, and other valuable proteins by simply inserting a single gene, from a different organism, into bacteria. However, Keasling believed that genetic engineering wasn't harnessing the full power of these cells. The production of molecules isn't always so simple; it requires a complex interaction of several genes (not just one) being produced in a certain sequence. So Keasling wanted to invent the tools that would allow him to create these kinds of genetic assembly lines. Thus, what goes on in a cell is a lot like what goes on in a chemical plant: petroleum goes in, and after a whole chain of reactions, plastic comes out.

Keasling went to college studying biology and chemical engineering extensively, and got his Ph.D. in 1991. He is now a professor at the University of California at Berkeley. He spent his first 10 years at UC Berkeley building the new tools he would need to turn cells into chemical plants. He also invented powerful chemical switches (like a light switch) that allowed him to control when he wanted to "turn on" and "turn off" protein production in cells. This way of borrowing techniques from engineering and figuring out how to manipulate microbes came to be called synthetic biology.

After years of perfecting his biological tool kit, Keasling wanted to find a real-world use for it. In 2002 he learned of the dire need for artemisinin, a compound derived from the sweet wormwood plant, which is 90 percent effective against the parasite that causes malaria and has few side effects (malaria kills some 3 million people a year). However, extracting the drug from sweet wormwood is a slow and expensive process. Keasling figured he could design and create microbes to produce artemisinin much quicker and cheaper. Rather than wait months for sweet wormwood to grow on farms, Keasling wanted to create it simply by pouring sugar into a tank full of microbes that could use the sugar to make the drug via a chemical pathway he had designed—he wanted to integrate genes from different species into a microbe to fabricate the drug.

In 2006, Keasling's team (comprised of graduate students, post-docs, and research assistants) published their success of the production of artemisinin. It is expected to lower the cost of artemisinin production from a dollar per gram to just 10 cents. He was awarded a $43 million grant from the Bill and Melinda Gates Foundation, and awarded DISCOVER magazine's first ever Scientist of the Year Award.

Fighting malaria is just one part of Keasling's larger agenda to explore the potential of synthetic biology. Students in his lab are engineering microbes to break down pesticides, make biodegradable plastics, and create ethanol and other fuels from plants.

Biography adapted from: Zimmer, C. (2006). Scientist of the Year: Jay Keasling. *Discovermagazine.com*. Retrieved from http://discovermagazine.com/2006/dec/cover.

Detailed Case Study
Robert Langer
(b. 1948)


Photo Credit: Web.MIT.edu, © 2009 MIT, with permission by Robert Langer

Best known for: *pioneering a new way of 1) delivering drugs into the body using "polymers" that releases the drug slowly and at a constant level and 2) growing human tissues and organs (also known as organ regeneration)*

Langer was born in Albany, New York. His interest in science was sparked by a chemistry set he received as a gift when he was 11 years old. He received his Ph.D. in chemical engineering at the Massachusetts Institute of Technology (MIT) in 1974. Because of the oil crisis at the time, most of his peers went to work for big oil companies. "But I thought I could make a bigger impact elsewhere," Langer said; so he went to work at the Children's Hospital in Boston, which started his career in biomedicine (using biology to make medicine).

Imagine writing a letter of life-and-death importance and trying to mail it only to discover that you have the wrong address and the wrong envelope. Langer spent 25 years wrestling with a problem very much like that. In his case the letters were life-saving drugs, and the goal was to deliver them to the right place at the right dose and at the right time.

Langer came up with the novel idea to wrap something like a window screen, with tiny holes, around the drug that would allow the drug to slowly work its way out. Thus drugs were coated in polymers (a type of plastic that can be broken down by the body) that penetrate cells in your stomach more easily and enter the bloodstream more quickly. Polymers can be designed to swell-up in response to exposure to stomach acid, thus protecting the drug inside from being broken down too early, or designed to have a slow-release mechanism that allows medication to be released gradually.

This was a breakthrough in drug delivery, where drugs can be targeted to a specific area and released into the body at a desired constant level. "This will help all patients take their medications when they need them and in the amounts they need," Langer concluded. Langer collaborated with neurosurgeons to apply this new technology to help treat brain, spinal, and various other cancers.

Langer became a professor at MIT and ran the largest academic bioengineering lab in the world, with more than 100 researchers. He has written more than 1,050 scientific papers and started more than a dozen companies with over 40 products that are currently being sold or in clinical trials. Langer has received more than 170 prestigious scientific awards, and brings in about $10 million to his lab in yearly grants.

He is able to accomplish all of this by doing various different projects at the same time. For example, he is also the pioneer of organ regeneration—growing human tissues and organs. Langer collaborated with a researcher at Harvard University to design polymer scaffolds on which human tissue can grow. A polymer scaffold is designed in the shape of an organ, say, a liver. Cells are harvested from a person's body, and placed on the scaffold. There, in a tightly controlled environment, the cells can grow into a functioning liver and the scaffold dissolves away. This new technology will make it easier for more patients to receive organs. The government has already approved skin and rib cages grown using Langer's technology.

Biography adapted from:

Bjerklie, D. (2001). Drug Deliveryman. *CNN.com*. Retrieved from http://www.cnn.com/SPECIALS/2001/americasbest/science.medicine/pro.rlanger.html.

Burke, M. (2002). Innovators: Plastic Man. *Forbes.com.* Retrieved from http://www.forbes.com/free_forbes/2002/1223/296.html.

Langer Lab. (2007). Professor Robert Langer. Massachusetts Institute of Technology, Department of Chemical Engineering. Retrieved from http://web.mit.edu/langerlab/langer.html

Photo Credit: Spectrum.MIT.edu,
© 2005 MIT with permission from Angela Belcher

Detailed Case Study
Angela Belcher
(b. 1958)

Best known for: *using viruses to grow small wires (nanowires) and batteries.*

Angela Belcher grew up in Houston, Texas. She had a learning disability when she was a child, called dyslexia, which made it hard for her to read and write. But with hard work and her love of learning, she was still able to do well in school. As a child, Angela Belcher wanted to be an inventor. Her lab was the family garage. "I'd go in there and say to myself, 'I'm not leaving until I invent something'," Belcher comments. "And it was really hot, over 100 degrees. But there I would be… I never really invented anything," she says. But that was then.

Now, Belcher is a professor at the Massachusetts Institute of Technology (MIT), and has become a real inventor and innovator. Her best-known invention is a new technique for creating useful objects such as nanowires and batteries from viruses!

While in college, Belcher met one of the world's experts on abalone, a marine snail. Belcher was intrigued by the abalone's shell. "They're 98 percent chalk," she says. "But they're 3000 times stronger than chalk." She became interested in how nature, and its natural organisms, could construct this special material out of a common mineral. Also, "in nature, organisms build hard structures in a nontoxic way," says Belcher. "They generate little waste… Suddenly, I wondered, what if we could assemble materials like the abalone does? What if we could…grow new materials?"

Belcher applied her idea to viruses. By 1999, Belcher and several collaborators were able to design viruses that could bind and coat themselves with specific metals. These viruses can then be manipulated to line up, creating nanowires and various components of a battery that is far more compact and powerful than anything available. Virus assembled batteries are also environmentally friendly because it doesn't produce any waste and is biodegradable, unlike conventional batteries that generate a lot of waste during manufacturing and are hard to dispose of.

Belcher's team is interested in very practical applications for their viruses. They can use their viruses to build various small structures because viruses are really tiny themselves—a billion of the viruses Belcher uses "could fit into a single drop of water," she notes. The viruses and the objects they create are so small that they can only be seen under advanced microscopes.

Today Belcher is involved in several projects with energy applications. She also started a company called Cambrios in California that applies biology and electronics to make commercial products. Belcher's work has already brought her many honors, including a MacArthur Foundation Prize Fellowship, or "genius grant" of $500,000 in 2004. She was named Researcher of the Year by Scientific American magazine in 2006, and a "Hero" of climate change by Time Magazine in 2007.

Online cartoon video biography:
The Story of Angela Belcher. http://www.lawrencehallofscience.org/nanozone/TN/thennow_belcher.htm.

Biography adapted from:
Anthony, R. (2005). Building on Nature. *MIT Spectrvm*. http://spectrum.mit.edu/issue/2005-fall/building-on-nature/.

Name___________________________ Date ____________

Making a Better Cow

Photo Credit: PublicDomainPictures.net, © 2008 Petr Kratochvil. http://www.publicdomainpictures.net/view-image.php?picture=black-cow&image=627

Scientists recently discovered a special type of cow that only grazes at night; it will only eat when it is dark outside. As you can imagine, this is very problematic for farmers for many reasons. For example, farmers have a hard time keeping track of their cows in the dark; the cows can't see where they are going so they sometimes wander too far into the woods or too close to a predator (e.g. wolves), and often walk into each other. Because the cows can't see well, they waste a lot of time trying to find a nice patch of grass to eat, and often eat dirt and random flowers instead. They sometimes even fall into the lake before they can catch themselves!

If you could modify the cows and give them special properties to help them navigate better what would you suggest? Be as creative as you can; nothing is impossible! You might want to also think about modifying other organisms in the environment to help farmers track their cows better.

Name______________________________ Date _____________

Designing a New Microbe

Task: Gas prices have reached an all time high! As a result, scientists are trying to think of ways to produce alternative fuels, such as hydrogen gas, in a much cheaper and quicker way. You are a scientist and you are familiar with six different organisms. Based on what you know, can you come up with a way to generate hydrogen from starch and water by designing a microbe that borrows different mechanisms/proteins from different cells? Fill in the blanks with protein names and the organism that the protein was taken from.

Materials: Each team has a set of cards, each card symbolizing a different organism. On the card, you will see the name of the organism, a picture of the organism, and proteins that is unique to them. Proteins (or enzymes) convert one molecule into another.

Your Microbe

Starch & Water → Protein borrowed:______ → Protein borrowed:______ →
Input | Organism: | Organism:

↓

Protein borrowed:______ ← Protein borrowed:______ ← Protein borrowed:______.
Organism: | Organism: | Organism:

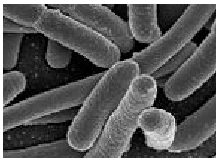
↓

Protein borrowed:______ → Protein borrowed:______ → Protein borrowed:______ →
Hydrogen
Organism: | Organism: | Organism:
Output

Experiment adapted from: Zhang Y.H., Evans B.R., Mielenz J.R., Hopkins R.C., Adams M.W. (2007). High-yield hydrogen production from starch and water by a synthetic enzymatic pathway. *PLoS ONE 5*: e456.

Organism Cards (one set)

Teachers: Please make as many copies as the number of groups of students. Cut the cards out and shuffle before handing to students.



Bacteria

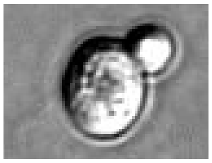
- Protein T uses *[X5P]* to make *[S7P]*
- Protein F uses *[S7P]* to make *[NADPH]*

Photo Credit: En.Wikipedia.org, © n.d. Rocky Mountain Laboratories, NIAID, NIH

Rabbit

- Protein G uses starch and water to make *[G-1-P]*
- Protein P uses *[G-1-P]* to make *[G-6-P]*

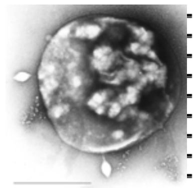
Photo Credit: Commons.Wikimedia.org, © 2005 Paul Henjum



Yeast

- Protein D uses *[G-6-P]* to make *[NADPH]* and *[R5P]*

Photo Credit: En. Wikipedia.org, © n.d. Masur/ Source Code: http://en.wikipedia.org/wiki/File:S_cerevisiae_under_DIC_microscopy.jpg



Archea

- Protein H uses *[NADPH]* to make *Hydrogen*

Photo Credit: En. Wikipedia.org, © n.d. Xiangyux

Spinach

- Protein R uses *[R5P]* to make *[X5P]*

Photo Credit: FreeClipArtNow.com, © 2008

Mouse

- Protein X uses *[T8P]* to make *Hydrogen*

Photo Credit: Genome.gov, © National Human Genome Research Institute

Experiment adapted from: Zhang Y.H., Evans B.R., Mielenz J.R., Hopkins R.C., Adams M.W. (2007). High-yield hydrogen production from starch and water by a synthetic enzymatic pathway. *PLoS ONE 5*: e456.

Section 2:
Modeling in Science

Lesson 5: What is a Model?

Photo Credit: NASA.gov

Understanding Goals

- A model is a representation of something. It is a way to describe something.
- A model can represent anything, whether in nature or made by humans.
- A model is *similar* to what it is representing; it is not the *same*.
- A model usually represents *part* of something; a model rarely represents *all* of something.
- More than one model can be used to represent and describe something.
- To evaluate a model, ask Key Questions:
    - What is the purpose of this model? What is the model trying to represent?
    - What are some ways that this model works well or fits well?
    - What are some ways that this model does not work well or fit well?

Background Information

What Are Models?

In science and in everyday life, there are times when we want to discuss some object or process without having full access to that object or process. At those times, a model can help. A model is a theoretical representation; it is a way to describe the thing or process. Models usually represent only part of some thing or process, not the object in its entirety. Therefore, models are not copies: they are *similar* to what they represent, but they are not the *same* as what they represent.

For example, a medical student learning about the human heart may not have access to a real human body with a real functioning heart. Instead, the student may look at drawings of a human heart in a textbook. These drawings serve as models of the heart. The drawings represent the heart and act as a visual description of the heart. The drawings represent only part of the heart: the drawings only show certain features and cannot, for instance, represent the changes the heart undergoes over time. And of course, the ink and paper drawings are not copies of the real heart.

Different Models for the Same Thing

Because models only represent part of some thing or process, more than one model can be used in its description. In the example of the medical student, other models of the human heart are necessary for the student to develop a deep understanding of how the organ works. For example, a three-dimensional, seamless, hard plastic model might be helpful in showing what the surface of the heart is like. Or, computer graphics could be used to show how the heart functions over time, such as how the heart beats and pumps blood. (You can search the Internet to find "heart beating animations" to share examples of animated models with your class.) Even a table-top biology or chemistry lab could demonstrate how the cells within heart tissue function. These varied models represent very different aspects of the human heart, and they each contribute towards the student's deep understanding of the heart.

Evaluating Models

Because models are similar to, but not the same as the thing or process that they simulate, it is often important to evaluate models, both individually and in comparison to each other, for what they do and do not model well. What are some ways that a particular model works well? What are some ways that the particular model does not work well?

To answer these questions, it is important to think about the purpose of the model[74]. Take the three-dimensional, seamless, hard plastic heart for example. If the purpose of the model is to represent the structure of the heart, perhaps the plastic model does well at showing the external structure – the shape, the color, the texture of the muscle, and so on, It does not do well at showing the internal structure – the model cannot be disassembled to show the ventricles and atria. Yet if the purpose of the model is to represent how the heart functions over time, then the hard plastic model will not work as well as, say, a computer graphics program that shows how the heart beats and pumps blood.

Concepts and Constructivism

Sometimes, concepts are discerned by prototypes. In other words, sometimes concepts cannot be constructed completely "from scratch," but instead must start with "seed examples" or cases. This lesson introduces typical, recognizable examples of models– model cars and model solar systems. It invites students to think about different kinds of models that they may be familiar with. From there, as students evaluate the typical examples, they will construct their understanding of what a model is, as well as what makes models work well (and not so well). This approach often works because we

[74] Gilbert, J.K., Boulter, C.J., & Elmer, R. (2000). Positioning Models in Science Education and in Design and Technology Education. In J.K. Gilbert and C.J. Boulter (Eds.), Developing Models in Science Education (pp. 3-17). Kluwer Academic Publishers. Printed in the Netherlands.

already have an implicit understanding of the concept that can be unpacked from the prototypes.

Language in Science and Everyday Life

One tricky thing in learning about models in science is the widespread use of the word "model" in everyday language. Science education researcher, Janice Gobert, found that students often think of a fashion model when asked what a model is. Is a "fashion model" the same type of science model described here? Not really—the fashion model isn't really representing or describing something. It could perhaps be said that the fashion model "represents" clothing, but more in the sense of being a form on which clothing can be displayed. A science model represents something in the sense that the science model is a description of something. Is a "floor model" of a vacuum cleaner the same type of science model described here? Again, not really: though the vacuum cleaner floor model isn't *exactly the same* as the vacuum in the box that the consumer actually buys, the floor model is *a copy* of the purchased vacuum.

Such examples as fashion models and floor models, as interesting as they may be for discussion, could end up confusing the issue of just what a scientific model is for many students. If students are confused by the language of models (i.e. a fashion model isn't the same as a science model, even though the same word is used), it might provide a nice opportunity to discuss the differences between words and language used in science and words and language used in everyday life, and that sometimes the words in science and in everyday life mean different things.

Sometimes a distinction is made between conceptual or mental models—the models that we hold in our heads—and models in the real world. Some scientists talk about models only as a set of ideas in our minds of how something works or came to be, but not as representations of those ideas, like sculpture or drawings. In this unit, we talk about models both as the ideas in our minds and as the representations of those ideas and focus on the conversation between the two.

Note to Teacher: Lesson 5 explores how models change over time. Your students' ideas and models will change over time, too! As an interesting learning tool, you may wish to keep an accumulating list of concepts students have about models as students go through these lessons. One way to do this is to write students' responses on large sheets of chart paper that can posted and seen in the classroom. New ideas can be continually added.

Lesson Plan

Materials

- Simple wooden or plastic toy car
- More detailed (than the wooden toy) toy car, such as a Hot Wheels car
- Two different solar system models (pictures, class projects, etc., depending on what is available and easy to obtain)
- White boards or laminated white cardstock
- Dry erase markers, at least one per student
- Large chart paper and marker (both optional)

Prep Step

- Review the lesson plan, background information, and understanding goals
- Gather materials

Analyze Thinking

Step 1: Exploring and Evaluating Typical Models – Cars and the Solar System

Model Cars

Start by having students think about and discuss model cars. Show students the simple toy car and the more detailed toy car. Have students share what they think about these toy models. Ask: "What are these toys representing?" Students may stop with the obvious answer ("cars"). Try to guide students beyond the obvious by asking about different features of cars. *Examples: What is it about cars that these toys are representing? Are these toys representing the shape of cars? Are these toys representing how an engine works? Are these toys representing how the doors on a car open?*

Continue to have students share what they think about the model cars. Ask: "What are some ways that these toys work well as representations?" If students are having difficulty, prompt with questions similar to those above. *Examples: Do these toys represent the shape of cars pretty well? Does one of these toys represent how the doors on a real car open?*

Next, have students think about what doesn't work well. Ask: "What are some ways that these toys do not work well as representations? Allow students to discuss.

Wrap up with the model cars by having students think about and answer the following. Ask: "Are the toy cars similar to real cars?" *[Yes.]* "Are the toy cars the same as real cars?" *[No.]*
"Do the toy cars represent an entire car, or only part of a car?" *[Part. The simple car, for example, may not have a windshield; the more detailed car, for example, may not have a hood that will open to reveal an engine, etc.]*

"Even if we have a preference for one or the other, can both toys be used to represent real cars?" *[Yes.]*

Model Solar Systems
Next, have students think about and discuss model solar systems. Show students two different representations of our solar system; these could be drawings, mobiles, class projects, etc. Have students share what they think about these representations. Ask: "What are these representations representing?" Students may stop with the obvious answer ("the solar system"). Try to guide students beyond the obvious by asking about different features of the solar system. *Examples: What is it about the solar system that these models are representing? Are these models representing the sizes of the planets? Are these models representing the distances between planets? Are these models representing what the planets are made of?*

Continue to have students share what they think about the model solar systems. Ask: "What are some ways that these models work well as representations?" If students are having difficulty, prompt with questions similar to those above. *Examples: Do these models represent the sizes of the planets compared to one another pretty well? Do these models represent the distances between the planets very well?*

Next, have students think about what doesn't work well. Ask: "What are some ways that these toys do not work well as representations? Allow students to discuss.

Wrap up with the model solar systems by having students think about and answer the following. Ask: "Are the model solar systems similar to the real solar system?" *[Yes.]* "Are the model solar systems the same as the real solar system?" *[No.]* "Do the model solar systems represent all aspects of the solar system, or only parts of the solar system?" *[Parts. For example, model solar systems often represent the scaled-down sizes of all the planets compared to one another, but they rarely represent the scaled-down distances between the planets. Also, they cannot represent what the planets are made of, or how the planets change over time, such as how the clouds on Earth are always moving and changing.]*
"Even if we have a preference for one or the other, can both model solar systems be used to represent the real solar system?" *[Yes.]*

Step 2: Constructing and Evaluating Models – Drawings of the Classroom

Next, have students construct their own models – drawings – of their classroom. Start by having them think about different ways to model their classroom. Ask: “Think about this classroom for a moment. Now imagine one of your friends in a different class or in a different school has never been to this classroom. If there was no way to actually show your friend this classroom, what would you do so that your friend would know what this classroom is like?” Write students’ responses on the board; keep the ideas on the board for later. Responses may include *making a drawing, making a technical diagram, making a sculpture, writing about it, making a graph, writing a play, and so on.*

Explain why they are going to make drawings instead of some of the other ideas they had. Say: “These are all interesting ways to make models. But given how much time it would take to do some of them, and given what materials we have available here in the classroom, we are going to just do one of those ideas: we are going to draw our models.”

Have students make models – drawings – of their classroom on the dry erase boards or laminated cardstock. The intent should be to “model” their classroom so that their friend will know what the classroom is like.

If students have difficulty, try guiding them with questions such as these: What do you want your model to show? What is important for your friend to know? What would help your friend understand what the classroom is like? What might confuse your friend if you put it in your drawing?

When students have finished (or, after 5-10 minutes of drawing/modeling), bring your class back together. Remind students of the questions they answered when evaluating the model cars and model solar system. Ask students if they think these questions are important questions to ask about any model. Write the Key Questions to Evaluate Models on the Board so all students can see them.

Key Questions to Evaluate Models

- What is the purpose of this model? What is the model representing?
- What are some ways that this model works well, or fits well?
- What are some ways that this model does not work well, or does not fit well?

Invite students to share their models of the classroom. Encourage the entire class – the student sharing the model included – to answer the Key Questions for each shared model.

Wrap up with the classroom models discussion by having students think about and answer the following:
"Are the classroom models similar to the real classroom?" *[Yes.]*
"Are the classroom models the same as the real classroom?" *[No.]*
"Do the classroom models represent the entire classroom, or only part of the classroom?" *[Part. Even the most detailed drawing of the classroom's location will have left* something *out: a pencil sharpener, the exact number of tiles on the floor, etc.]*
"Even if we have a preference for one, can all of the classroom models used to represent the real classroom?" *[Yes.]*

Step 3: What is a Model?

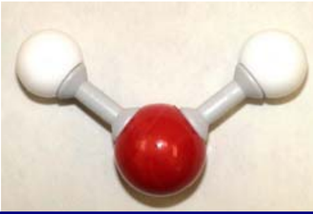
Have students think about what they think "model" means. Ask: "What do you think the word 'model' means? When you hear the word 'model' what do you think about?" Gather students' responses. If students do not mention the aspects of models described in the Understanding Goals, remind students of the model examples they discussed – cars, solar system, and classroom. Ask:
"Were the models similar to the real thing?" *[Yes.]*
"Were the models the same as the real thing?" *[No.]*
"Did the models represent the entire thing or only part of the thing?" *[Part.]*
"Even though the models were different, was it possible to use more than one model to represent the real thing?" *[Yes.]*

> **Note to Teacher:** If students mention "fashion model" or "floor model," take the opportunity to discuss the differences between language used in science and language used in everyday life, and that sometimes the languages mean different things. If students do not mention these examples, there is no need to mention them: these possibly confusing examples are probably best left for later discussions.

Review, Extend, Apply

Step 4: Making Connections: Thinking about Models in Everyday Life

Between this lesson and the next one, ask students to think about when and what models they use in their everyday lives. Ask them to keep track of some of the models they think about, and any questions that might come up. Encourage students to think about all types of models in addition to drawings, such as some of the ideas they may have mentioned when thinking about ways to model their classrooms (sculptures, technical diagrams, etc.)



Lesson 6:
How Do Models Help Us Think?

Photo Credit: Rebecca Lincoln, Causal Patterns in Density

Understanding Goals

- Models help us solve problems. For example:
  - If something is too complex, a model can simplify something by representing only the important features.
  - If something is too big or too small, a model can represent something by "zooming out" or "zooming in" on something.
  - If something happens too fast or too slowly, a model can represent something by slowing down or speeding up what happens.
  - If something is hidden and we cannot see how it works, a model can represent something by showing what is hidden.
- Models help us develop an idea in our minds of how something works or came to be.
- Models help us think about the idea by letting us
  - unpack our thinking and share our thinking with others;
  - download cognitive load;
  - think about dynamic aspects of a problem;
  - test assumptions against the models and make predictions from the model;
  - deal with size and scale issues.
- We use models in our everyday lives as well as in science.
- Models are not perfect, and can sometimes confuse us instead of helping our thinking.

Background Information

What Problems Do Models Help Us Solve?

Models often represent something we cannot see. For example, something may be *too complex* to understand all at once, such as the inner workings of a car engine. A model can simplify something and focus on the important features, like a model of a car engine that focuses only on the pistons and not on the key in the ignition. This could be very helpful for a car mechanic trying to fix a particular piston or spark plug. Something may be *too big* to see all of it at once, such as the layout of a city. So, a model can show a "zoomed out" view, like a map of the city that shows the major streets of the city; this could be very helpful for someone in one part of the city plotting their course to another part of the city. Or, something may be *too small* to see it at all, such as atoms and their components. A model can "zoom in" and show the small pieces, like the components of atoms. This could be very helpful for a person wanting to understand electricity and induction. Also, something might happen *too fast* to really see what happens, such as a sound wave traveling in air. A model can show a slowed down version of the event, like a slow-motion animation of a sound wave traveling through air; this could be very helpful for someone trying to understand how sound works. Or, something might happen *too slowly* to see what happens, such as the life cycle of a plant. A model can show a sped up version of the event or even "snapshots" of the event, like time lapse animation of a plant's life cycle or pictures of different stages during the plant's life; this could be very helpful when the events being studied take a very, very long time to happen. Finally, something may be *hidden from our view*, such as the processes which occur in the interior of Earth. A model can show what is hidden, like computer models or drawings that show the processes driving plate tectonics. This could be very helpful for scientists trying to deeply understand earthquakes so that they can better predict when earthquakes or even tsunamis might occur.

Models are used to try and visualize what might be happening in an event or process. Models help us develop an idea in our minds of how something works and/or came to be.

How Do Models Help Us Think?

In addition to solving these problems, models also help us to overcome limits in how we think. For instance, our minds can only hold a certain amount of information at once. Also, we might find it difficult to think about how information changes over time. There are a number of ways models help us think.

Download cognitive load. Sometimes, there is just too much information about an event or process to hold it all in our mind! Models provide a way to "download" some of our thoughts about an event or process, a way to get them out of our minds into a holding area. In this way, we can focus on one piece of what we are trying to understand at a time, and come back to other pieces later.

Think about dynamic aspects of a problem. Events or processes that change over time can be challenging to understand. We often reduce these to static snapshots of events.[75] This can work in some instances but in others, it loses important information. Talking about this with students in terms of "snapshot reasoning" and "video-reasoning" can help them think about how their minds process information differently in each case.[76] Static

[75]Feltovich, Spiro, & Coulson, 1993
[76]Grotzer, T.A. (2009, April). *Addressing the challenges in understanding ecosystems: Classroom studies.* National Association of Research in Science Teaching (NARST) Conference, Orange Grove, CA, April 18, 2009.

models can help with snapshot reasoning. Sometimes, we need a dynamic model to help us when we need the dynamic picture to understand what is going on (such as how a heart beats).

Test assumptions against the models and make predictions from the model. Part of determining if we are on the right track in solving a problem or understanding an event or process is to test our ideas. Having a model to think with can allow us to reason through the patterns in a phenomenon.

This lesson invites students to think about different types of models through the lens of how each model helps us. It engages students in analyzing different models to see how they support us in our thinking in an effort to help students realize the value of models in science.

Lesson Plan

Materials

- Paper for students to track their ideas
- Three or four different models (for instance; a computer animation; a globe; a doll house, etc.)

Prep Step

- Review the lesson plan, background information, and understanding goals.
- Collect a set of models as examples. Try to come up with a contrasting set. For example, you might choose to use one of the many computer animations of molecular behavior from the internet; architectural models or a dollhouse if you have access to one; and a globe or map.

Explore Outcomes

Step 1: Models in Everyday Life

Remind students that at the end of the last lesson, you asked them to think about what models they use in their everyday lives, and that they were encouraged to think about all types of models including drawings, such as sculptures, technical diagrams, etc.

Invite students to share some of the everyday models they thought about. Gather students' responses, and make a list of their ideas on the board or on chart paper. If students are struggling to develop examples, try suggesting some of the following; *maps and globes, shopping mall directories, model airplanes, model trains, floor plans, dolls, doll houses, silk plants, plastic fruit, calendars (representing time), a heart shape (representing love), thought bubbles on cartoons (representing thoughts), and a smiley face (representing happiness).*

Analyze Thinking

Step 2: In What Ways Do Models Help Us Think?

Consider five or six different models: models of cars (from Lesson 5); models of the solar system (from Lesson 5); the examples that you have chosen; and two or three of the models from their everyday lives (this lesson). Have students analyze each model by discussing the questions below. It would be good to go over one or two examples as a whole class. Then you might have the students break up into small groups and analyze the others.

For each of these models, have students evaluate the model using two of the Key Questions:

- What is the purpose of this model? What is the model representing?
- What are some of the ways that this model works well, or fits well?

For each of these models, have students discuss why we need the model, or what problem the model helps us solve. Ask guiding questions, for example:

- "Is there anything about what the model is representing that is really complex? Does the model help you simplify and think about what is happening?" *[There are many pieces and moving parts on a real automobile so more simple models show important pieces.]*
- "Does the model help you "zoom in" or "zoom out" to think about what is happening?" [*The solar system is huge, so we need much smaller models for use in the classroom; Computer animations can reveal what is happening at a molecular level.]*
- "Does the model help you slow down or speed up what is happening so you can think about what is happening?" *[Cars move very fast, so it helps to make a model car go slowly and see how the wheels turn; The planets take a long time to complete an orbit, so models help us speed up that process to see what is happening.]*
- "Does the model allow you to imagine what is hidden so you can think about what is happening? *[Models of the inside of the earth reveal it's layers; Can't see the inside of a piston firing in a car]*

For each of these models, have students discuss how models help us think. For example:

- *Unpack our thinking and share our thinking with others* – "Have you ever tried explaining something to a friend and you weren't quite sure what you were trying to say? Have you ever had to reflect on your own thinking before trying to explain something to a friend?"
- *Download cognitive load* – "Have you ever had an experience where a friend was telling you how something worked and you were following along and then suddenly, there was just too much information to think about at once?"
- *Think about dynamic aspects of a problem* – "Have you ever tried to understand something that happened so fast, you just wanted to slow it down to watch it? Or, has something ever happened so slowly, you just wanted to speed things up so you could watch it all?
- *Test assumptions against the models and make predictions from the model* – "With some models, you may have tested your ideas about what was going on using your model. What about the rest of these models? Have you ever had an

experience where you thought you understood something, so you played with a model to see if you were correct?"

Step 3: When Could Models Be Confusing?

Explain to students that models are not perfect. Sometimes, a model might actually confuse us instead of helping us think. What happens when a model does not work well, or fit well? What types of misconceptions could be developed?

Consider several of the models already discussed: model cars (from Lesson 5); models of the solar system (from Lesson 5); models of the classroom (from Lesson 5); and one of the everyday models shared by students (this lesson, Step 3). Have students analyze what might "go wrong" with these models using the questions below.

For each of the models, have students evaluate the model two of the Key Questions:

- What is the purpose of this model? What is the model representing?
- What are some ways that this model does not work well, or does not fit well?

For each of the models, have students discuss ways in which the models might mislead us or confuse us because of the ways the models do work well.

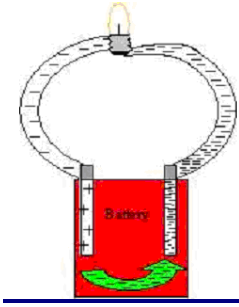
Example responses include:

- *Model Cars – Many model cars do not have wheels that turn so they can only go straight; if we are trying to think about how cars turn corners, this might be problematic.*
- *Solar System Models – The differences in sizes of solar system objects and the distances between them are so vast, solar system models in a classroom cannot correctly show the sizes and distances to scale; it is possible to develop misconceptions regarding the sizes of solar system objects and the distances between them.*
- *Classroom Models – A detailed model of the classroom and its contents will probably leave out information about where the classroom is in the school, where the school is in the neighborhood, etc. It is possible for someone to develop misconceptions about where the classroom is located. A model of the classroom showing where it is located in the city, in the neighborhood, in the school, may not be able to show details in the classroom, such as whether there are windows, sinks, the number of desks, etc.*
- *Everyday Models – Depends on the model chosen. How could the model lead our thinking astray?*

Review, Extend, Apply

Step 4: Making Connections: Using Models in Everyday Life

Between this lesson and the next one, ask students to think about how the models they use outside of the classroom help them think about different things or processes. Students can think about the same models they shared in class or they can think about new models. Ask them to keep track of the ways the models help them think, and any questions that might come up. Encourage students to think about all types of models.



Lesson 7: The Process of Modeling: How Can Drawing Models Help Us Build Understanding?

Understanding Goals

- ❖ Drawing models is a way to unpack our own thinking.
- ❖ Modeling can help us develop an idea in our minds of how something works.
- ❖ Modeling can help us think about concepts by letting us
    - unpack our thinking and share our thinking with others;
    - download cognitive load;
    - think about dynamic aspects of a problem;
    - test assumptions against the models and make predictions from the model; and
    - deal with size and scale issues.

Background Information

How Can Modeling Help Students Build Understanding?

Up to this point, the lessons in this section focused on using models to help us think about science concepts. In this lesson, we take a subtle shift from *using* models to *drawing* or *developing* models. The process of developing and revising models is an integral aspect of science and is an important means to developing an understanding of science. This lesson aims to help students see how modeling in science is helpful and also how modeling in their own scientific thinking is helpful.

Modeling encourages students to actively process concepts, to unpack and reveal their thinking, and to consider how the available evidence fits or not with their ideas. Increasingly, science lessons start with modeling as a means of helping students unpack their current beliefs. Giving students an open-ended question that embeds the concept of focus and letting them draw a model allows them to grapple with the ideas and build an investment in those ideas. It also gives all students think time and the opportunity to share ideas that they have had a chance to consider. When you start with modeling, don't be surprised when more students engage in the conversation—not just your fastest thinkers!

Modeling offers students an opportunity to think through ideas as they are developing their drawings. It gives each student a chance to think and to reason about what makes sense to them. It also helps with the kinds of thinking challenges that using models helps with. For instance,

Downloading cognitive load. Modeling enables us to think through complex phenomena without trying to hold everything in our heads at once. We can focus on aspects of what we are trying to understand at a time, moving back and forth between the ideas.

Thinking about dynamic aspects of a problem. We can draw our models to help us think through the dynamics of how something works. We can produce "snapshots in time" and consider the processes that link each one.

Testing assumptions against the models and making predictions from the model. Part of determining if we are on the right track in solving a problem or understanding an event or process is to test our ideas. Drawing a model invites us to reason through the patterns in a phenomenon's behavior.

How Does Modeling Encourage a Strong Community of Learners?

Models can be used as a point of discussion. Asking students to comment on what they see as working well about a model and what they would modify or change based upon specific evidence invites them to actively process science ideas. Models enable us to unpack our thinking and share it with others. They become important artifacts in a community of scientists and in the scientific community within the classroom as we unpack, share, and process ideas. They enable a concrete focus for discussion. As often as possible, have all students share their models with the class. It removes the social burden of deciding to share.

You can invite the co-construction of models as often as possible. Work towards models that "make sense" to the class. Invite students to tell you whether they find a concept to be sensible (they can grasp it), plausible (they see it as a possible explanation) and/or believable (they believe it to be so.) This separates understanding from acceptance of a concept.

In science class, don't hold back on the "scientifically accepted" model, but don't present it as "the right answer" either. It is best when a student presents some version or part of it and you can work towards it together as a class. Critique it as you would any other model. Encourage students to view their learning as trading up for better and better models, not as "getting the right answer." Science works this way and learning does, too. View learning as an evolution of understanding through different models.

In this lesson, students need to figure out how something called a "mystery tube" works. It is designed such that it is easy to generate simple and wrong answers if they do not take the time to think through carefully what they see and what that could mean for what they do not see. Students will see that their ideas necessarily shift as they gain more information and trade up for better explanations.

Lesson Plan

Materials

- Whiteboards or laminated white cardstock
- Dry erase markers, at least one per student
- For the Mystery Tubes
    - 5-6 Cardboard tubes (i.e. toilet paper rolls, paper towel tubes, or mailing tubes)
    - 5-6 metal rings, such as simple key chain rings
    - Scissors
    - 6 feet of string (approx.)
    - Marker or sharpie
    - Paper (to cover the ends of the cardboard tubes)
    - Tape (to cover the ends of the cardboard tubes)

Prep Step

- Review the lesson plan, background information, and Understanding Goals
- Make the Mystery Tubes (allow 15-45 minutes for each tube)
- Gather other materials

> **Note to Teacher:** Plan on taking 15-45 minutes to make each Mystery Tube. As you gain experience making the first tube or two, making the rest of the tubes should become easier and faster. The time needed will vary depending on several things, including the size of your tube, how big you make the holes in the tube, how big you must tie the knots in the string so that the string doesn't slip through the holes in the tube, and experimenting with the placement of the string as you construct the tube to make sure the strings move the way you want them to move.
>
> Look for *Mystery Tube – Construction Hints* at the end of this Lesson, on page 86.

Explore Outcomes

Step 1: A Modeling Activity – The Mystery Tube

Demonstrate the Mystery Tube to the whole class. Explain to students that they should think about the way the object works. Go through several sequences of string pulling to let students see what is happening. Allow students to direct you for several string pulls so they can test their ideas. Ask students if they have some ideas what is happening inside the Tube. Gather their responses.

Next, divide students into 5-6 groups, depending on how many Mystery Tubes are available. Pass out whiteboards (or laminated cardstock) and dry erase markers to each student, and pass out the Mystery Tubes, one to each group. Have students try to figure out what is happening inside the tubes (without peeking inside!) by drawing models on their whiteboards.

Have each group pick a "Metacognitive Monitor," or a "Thinking Monitor." This Metacognitive Monitor should observe the process of problem-solving and thinking within his or her group. At the end of the activity, the Monitor should be able to share his or her observations with the rest of the group and the rest of the class. What kinds of things might the Monitor share? For instance, he or she might notice that the group had just one idea and had a hard time getting away from it or that one person did most of the thinking, etc. The monitor should also try to note how the group's ideas changed over time.

Metacognitive Monitor

- Observe the problem-solving and thinking process.
- What was the process of their thinking like?
- How did their ideas change over time?

Allow 5-10 minutes for students to discuss and draw their models.

Analyze Thinking

Step 2: In What Ways Did Modeling Help Us Think About the Mystery Tube?

Ask students to share their thoughts and their models to explain what they think might be happening inside the tube.

Have students discuss the process of thinking about the Mystery Tubes, making their models, and how the models helped them think about the Mystery Tubes. Ask: "Why did we need models to help us think about the Mystery Tubes? What did models help us do? Or, what problems did models help us solve?" Ask guiding questions, for example:

- "Was there anything about the tube that was too complex? Did the process of modeling help you simplify and think about what was happening?"
- "Was there anything about the tube that happened to fast, or too slow? Did the models help you slow down, or speed up what was happening so you could think about what was happening?"
- "Was there anything about the tube that was hidden? Did modeling allow you to imagine what was hidden so you could think about what was happening?"

If students leave out ways that models help us think, ask questions to guide them towards the understanding goals as highlighted for this lesson. For example:

- *Unpack our thinking and share our thinking with others* – "Is it easier to think and talk about what is going on inside the tube with or without drawing models?"
- *Download cognitive load* – "As you were thinking about the tube, did you feel like you were starting to have a good idea of what was happening, but then suddenly you were thinking about too many things at once?"
- *Think about dynamic aspects of a problem* – "When you were watching how the tube works, were there moments when you thought you understood what was happening, but as the situation changed you weren't as sure?"
- *Test assumptions against the models and make predictions from the model* – "Were there moments when you thought you understood what was happening, so you tested your ideas with your model to see if you were right?"

Have the Metacognitive Monitors share their observations. Ask: "What was the process of each group's thinking like? How did their ideas change over time? Did their explanations do a better job explaining what happened with the mystery tube as they got more involved in modeling it? Gather comments. Consider how modeling can lead to changing our initial ideas and trading up for more powerful explanations.

Review, Extend, Apply

Step 3: Making Connections: Modeling in Science and Everyday Life

Ask your students to think of examples of situations where they might use modeling—either in science class or in everyday life. Collect their ideas. Ask them to try to notice at least two opportunities to use modeling in the next week or two as they go about their everyday lives.

Resources for Section 2

Mystery Tube – Construction Hints

This activity is inspired by the National Academy of Sciences (NAS) publication *Teaching About Evolution and the Nature of Science* (1998). This publication is available for purchase, and can be previewed for free, on the NAS website: http://www.nasonline.org. The image is from their free online preview (http://books.nap.edu/openbook.php?chapselect=yo&page=23&record_id=5787).

The materials and construction hints are from this lesson's author's experience constructing her own Mystery Tube.

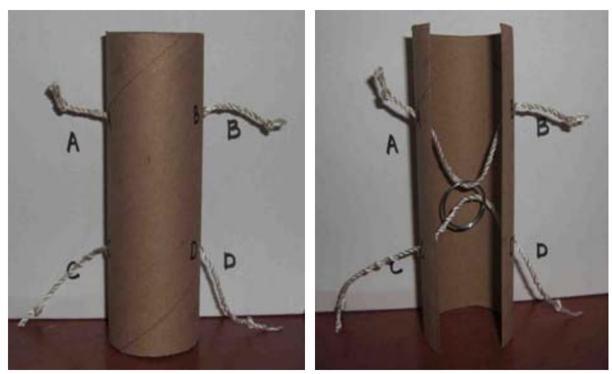
Materials

- 5-6 Cardboard tubes (i.e. toilet paper rolls, paper towel tubes, or mailing tubes)
- 5-6 metal rings, such as simple key chain rings
- Scissors
- 6 feet of string (approx.)
- Marker or sharpie
- Paper (to cover the ends of the cardboard tubes)
- Tape (to cover the ends of the cardboard tubes)

Hints

- Plan on taking 15-25 minutes to make each Mystery Tube; as you gain experience making the first tube or two, making the rest of the tubes should become easier and faster.

- Experiment as you build the tube, pulling each string to see how it affects the other strings, so you know where to tie the knots.



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- Other versions of the tube do without the metal ring and simply run the CD string over the AB string. We recommend keeping the metal ring for more smooth string-pulling action.

- Try to use a small metal ring compared to the size of your tube: this will minimize any clinking of ring against tube, and will keep your students guessing!

- Use the sharpie or marker to write the letters on the tube next to the string holes so you can keep track of the strings.

- Cover the ends of the tube so students cannot see inside the tube. You might tape paper to the ends of the tube, or just use duct tape or another non-see-through tape and tape over the ends.

Section 3:
Science as a Collaborative and Social Process

Lesson 8: Collaboration in Science

Lesson 9: Subjectivity and Objectivity in Science

Lesson 10: The Dynamic Nature of Science

Resources for Section 3

Resources for Lesson 8: Scientific Collaboration: A story from Pharmaceutical Research

Resources for Lesson 9: Zea[77] This DVD can be ordered from the National Film Board of Canada's online store. The following link will direct you to the homepage from which the online store can be accessed: http://www.nfb.ca/)

Background Information Cards

Question to Think About Worksheet

Resources for Lesson 10: Image of Geocentric Universe

Image of Retrograde Motion

Frame #1

Frame #2

Pieces of Evidence

New Pieces of Evidence

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[77] Forget, R. (Producer), & Leduc, A. & Leduc, J. (2006). *Zea* [Motion Picture]. Canada: National Film Board of Canada.

Lesson 8:
Collaboration in Science

Photo Credit: CDC.gov

Understanding Goals

- Science is a collaborative process. By sharing their work with others, scientists develop a deeper understanding of the problem they are working on, and they generate new ideas for future work.
- Solving a problem in science is collaborative puzzle solving. Each scientist brings a unique perspective, skill set, and background knowledge to this collaborative process.
- Collaboration can also involve time spent working alone, focusing on one part of the problem, before coming together to share results and work with others.
- Collaboration in science has unique characteristics compared to other types of collaboration, including:
    - You don't always know what the end result will be.
    - You don't necessarily follow a specific plan or method.
    - You can work across space and time without ever meeting the other scientists you are working with.
- Learning through collaboration in a science classroom is similar to "real world science" in several ways:
    - There are opportunities to revise our own thinking.
    - It allows each person to contribute his or her own ideas.
    - Provides different ways to collaborate, such as working in pairs, in small or large groups, and inter-group or intra-group.
    - Making metacognitive moves, or asking questions that help us check in with our thinking, can help us think collaboratively.

Background Information

The length of this lesson depends on how in-depth you want to explore the activities. Steps 1 through 5 should take more than one class period. Step 6 is optional.

Collaboration

One of the trends that scientists of the past and present have used in the discovery process is *Synthesis of Information and Strong Collaboration with Others*. This way of thinking can help us in our own learning and it starts at an early age as evidenced by group play, such as building a clubhouse and working together at school in projects and lab groups.

The purpose of this lesson is to experience the way scientists work together and see how this can help our learning in the science classroom. Scientists combine forces in different ways to solve different problems. Many people in their jobs work together with others and scientists are no exception.

Some examples of different collaborative experiences in general include:

- *Playing on a sports team* – in addition to the players, include a manager, coach, team sponsors, and parent volunteers
- *Putting on a play* – there are actors, producers, directors, stage managers, lighting, sound, and music technicians, costumers, make up artists, set designers, and ticket sales persons
- Other examples include constructing a house or being a member of a car racing pit crew.

Some examples of different collaborative experiences in science include:

- *Studying and preventing West Nile Virus* – entomologists (who study insects and mosquitoes); epidemiologists (who study what causes diseases and how diseases spread); biologists and biochemists who study the West Nile virus and how the virus affects humans (and other animals); doctors who collect the virus from infected patients
- *Studying tsunamis* – earth scientists and geologists who study how earthquakes happen and how to predict them; physicists that study motion in fluids; sailors and ocean-going scientists who place buoys out in the water to detect earthquakes.

Science is More Than the Scientific Method: Collaborative Puzzle-Solving

The work of scientists is often described as following a scientific method, a sort of pre-defined checklist that guides scientific research. While the scientific method is a fine way to introduce students to the ways science is done, it is certainly not the only way that scientists conduct science research. Some of the other ways are hinted at in the first lesson in this module: *The Patterns of Scientific Thinking*. For example, some work in science progresses through the recognition of serendipitous events, such as Becquerel's discovery of radioactivity, Pasteur's development of vaccines, and Newton's recognition of a gravitational force. Also, some science progresses more through powerful observation than intentional, methodical experimentation, such as McClintock's recognition of gene shifts on chromosomes and Bell and Hewish's discovery of pulsars. Or, science can progress in a somewhat trial-and-error fashion, such as the phases of pharmaceutical research and development, in which certain chemical compounds are tested on biological systems to determine their effectiveness. Some science even progresses through the recognition and studying of discrepancies, such as Penzias and Wilson investigating the source of the strange background noise in their antenna signal.

One way to think about how the work in science proceeds is to compare it to collaborative puzzle-solving[78] where different people work together without any strict, pre-defined method or procedure. Sometimes, there is not even a known result. Instead, the collaborators figure out what to do next as they go along, seeing what pieces will fit where, and anticipating what pieces they need by looking at what is already assembled.

In this lesson, students have the opportunity to experience collaborative puzzle-solving by actually working with their classmates to assemble a puzzle. In this activity, the end result – the picture on the puzzle – is unknown to the students. Furthermore, students will work together without a strict, pre-defined method for solving the puzzle; instead, students will figure out what to do next as they go along.

Metacognition Moves: Checking In With Our Thinking

It is one thing to know how something works; it is another thing to be aware that you know how something works and, for example, that there are still things you do not know. Metacognition involves being aware of our own thinking.

It is easy to get stuck in a mental "rut." This can become troublesome not only when you want to learn something new, but also if you are working with others. Taking a step back, so to speak, and reflecting on your thinking can help you get out of the rut and move forward in your thinking and collaborating with others. Making metacognitive moves, or reflecting on your thinking, can involve questions such as:

- Am I pushing my own thinking to explore the concepts deeply?
- Am I thinking carefully about what others around me are saying?
- Am I working "minds-on" – actively thinking about the problem – instead of just letting others solve the problem?
- Am I using others' ideas to "piggyback" to new ideas?
- Am I pushing myself to come up with ideas that are different from the others?

[78] Bauer, H. (1992). *Scientific literacy and the myth of the scientific method*, Chapter 3. How Science Really Works, pp. 42-62 and Chapter 4: Other Fables About Science pp. 63-87. University of Illinois Press: Urbana.
Kuhn, T.S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press. Chapters 3-9 (pp. 23-92)

- Am I bringing my previous knowledge/experience to bear on the problem at hand?

To help your students periodically check in with their thinking, you can post these metacognitive "Checking In With Your Thinking" questions in your room where all students can see them.

Many teachers feel that reflecting on one's thinking is a sophisticated exercise that only the top students in class will be able to handle. Research shows that it often benefits the lowest achieving students the most.[79] The process of reflecting on one's thinking helps struggling students identify what they are struggling with, it also helps them engage in their own learning.[80]

Deeper Exploration of the Puzzle Activity

In Step 4, students are invited to reflect on and share their experiences and thoughts regarding the puzzle activity. Furthermore, they are asked to think about ways to do the puzzle that might lead to better accuracy as well as improve their efficiency and collaborative process. If time and interest permits, you can follow up on students' ideas by actually trying out some of the ideas. Students may come up with the following ideas; feel free to either try these ideas or just discuss them, how they might or might not work, etc.

- Have the lab groups combine with other groups to see if they get more clues. *Puzzle analogy:* the puzzle can be completed faster, like scientists making their discoveries faster.
- Have all the groups work from a central spot in the classroom and try to put the puzzle together all at once. *Puzzle analogy:* each person has input but this may be more chaotic and therefore take longer to complete, like with too many scientists it may be hard to coordinate the work.
- You put the entire puzzle together. Then, break the puzzle up into sections – as many sections as there will be lab groups – take a few pieces away from each section, then put the remainders of each section into zip lock bags, one zip lock back per lab group. *Puzzle analogy:* Students will almost be able to fit all their pieces together, just as it seems that scientists often come close to complete understanding. However, students will find that there are missing pieces, just as in science there are always "missing pieces" to the "puzzle" scientists are trying to solve.

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[79] Zohar, A. & Ben David Adi (2008). Explicit teaching of meta-strategic knowledge in authentic classroom situations. *Metacognition and Learning, 3,* 59-82.
Zohar, A. & Peled, B. (2008). The effects of explicit teaching of metastrategic knowledge on low- and high-achieving students. *Learning and Instruction*, 337-353.
[80] White, B. & Frederiksen, J. (1995). An overview of the ThinkerTools Inquiry Project Causal Models Report: 95-04. Technical Report: University of California, Berkeley.

- Have students experience working with others across space and time. Within each class or block period, designate lab groups A, B, C, etc. All lab groups A will work on one puzzle, all lab groups B will work on another puzzle, and so on. So, for example, students in Block 1 group A will collaborate on the same puzzle as students in Block 2 group A. Students can collaborate by posting notes in the classroom, sending emails to each other, etc. *Puzzle analogy:* you are working with others on the same puzzle without meeting your fellow puzzlers, like many scientists working in different locations.

Lesson Plan

Materials

- 500-piece or more box puzzle (You will need a different puzzle for each class you teach. Puzzles can be purchased from a toy store. The suggested piece quantity is to make sure you have lots of pieces for your class.)
- Zip lock plastic bags
- Pieces of cardboard or poster paper
- Crayons, markers, colored pencils
- Drawing paper
- White board or chart paper
- Student notebooks or journals

Prep Step

- Review the lesson plan for Lesson 1 specifically the description of Synthesis of Information and Strong Collaboration with Others and the scientists included in this section.
- Take each puzzle and divide the pieces in the box putting them into the zip lock bags (six groups work well depending on the number of students in your class.)
- Divide your classes into lab groups of 4-6 students per group depending upon the number of students in your class.
- Post metacognitive "Checking In With Your Thinking" questions in the front of the room.

> **Note to Teacher:** Try to purchase puzzles with a variety of themes (one for each of your science classes) and, if possible, the same number of pieces in each box. If this lesson must be split over class periods, the pieces of cardboard or poster paper listed in the materials section act as a tray for storing unfinished puzzles. To save even more space in the classroom, each class section's trays can be put in a box and stored until needed again.

Analyze Thinking

Step 1: How Do Scientists Work Cooperatively in "Real World Science?"

Have a discussion with students about professions that require individuals to work together. Have students brainstorm examples of these jobs and the way employees must coordinate and with coworkers.   Ask the students what they think scientific collaboration means? They may remember from Lesson 1 *the scientists often support ideas by looking across work in the field and synthesizing it. They work with others and are open to their ideas and communicate extensively with colleagues.* Collaboration is an important skill in scientific fields. Ask students to look back to the hand out with the four scientists in this category (Jonas Salk, Guglielmo Marconi, Sir Isaac Newton, and Charles Darwin) and see if they recall how they collaborated. You may wish to have the class reread the handout and tell you how each of the scientists worked with others.

Pose to the class "What topics do you think are studied in this way today?" Possible responses may include cures for diseases and global warming where investigations are approached from different disciplines and different locations. For instance, studying a disease involves studying the source and the spread of the disease, investigating how it spreads from different locations, working with public health officials, and so forth. Studying global warming involves atmospheric research, oceanographic research, investigating effects in diverse locations on diverse populations, understanding weather patterns and so forth.

Have the students think about examples of collaboration that they have engaged in. Some general examples of collaboration that may be somewhat familiar to students include the following:

- *Playing on a sports team* – in addition to the players, include a manager, coach, team sponsors, and parent volunteers
- *Putting on a play* – you have actors, producers, directors, stage managers, lighting, sound, and music technicians, costumers, make up artists, sets, curtains, and ticket salespersons

Explore Outcomes

Step 2: Cooperative Puzzle Solving

Explain that in science classes, we often talk about scientists following a "scientific method" when they work. This method acts as a sort of checklist to guide research. This method is one way of thinking about science, and can be a very helpful thing to remember when a person gets stuck in his or her own research! However, many times science doesn't follow the checklist. Many times, it is more helpful to think of work that happens in science like collaborative puzzle-solving.

In collaborative puzzle-solving, different people work together without any pre-defined method or procedure. Sometimes, there is not even a known result. Instead, the collaborators just figure out what to do next as they go along, seeing what pieces will fit where, and anticipating what pieces they need by looking at what is already assembled.

Explain that we are going to consider how scientists collaborate as puzzle-solvers by working with our classmates on a puzzle.

Our goal in lab groups will be to decide what the picture of this 500-piece (or more) puzzle is without seeing the picture on the box cover. You will be in lab groups with a zip lock bag of puzzle pieces put in at random. Each group has approximately the same number of pieces. You are only to work in your own group and will be given a certain amount of time to complete the tasks assigned. We will meet as an entire class to share our ideas when the task is completed. We will also think about what worked well and what didn't work well within our group.

Remind students to think about their thinking as they work in their groups.

Note to Teacher: Depending upon the number of students in your class divide the class into groups of at least 4 to 6 students per group.

Once the students are assigned a group, allow them to take on the following roles::

(1) group recorder
(2) group illustrator
(3) group spokesperson
(4) group puzzle handler

Their task is to work with the puzzle pieces in their zip lock bag. They can try to put some of the puzzle pieces together, but remind the class they have approximately 75 pieces of a 500 piece puzzle, therefore they can't put all the pieces together.

While working with their puzzle pieces, the recorder should record observations on two lists. The headings for the two lists are *Things We Know* and *Things We Guess*. Encourage the groups to include at least 5 to 10 ideas on each list. Tell them they must collaborate and decide together what to put on their list. They are not to consult with any other lab groups at this time.

When they have finished with the two lists, students should predict what the picture is. Then the group illustrators – with input from the lab group – will draw a picture of what the group has decided the puzzle is picturing. Have crayons, colored pencils or markers and drawing paper available.

Allow adequate time for students to work on their puzzles, make their two lists, decide what their puzzle shows, and make their drawings.

Note to Teacher: Depending upon the length of the class period, you may want to have the groups work on a piece of cardboard or poster board. Discussion of their findings would follow and you don't want to rush the process. If class time finishes before students complete their puzzles, the unfinished puzzles on the cardboard or poster board can be stacked together and stored until the next class. If you have a long class period, you could limit the working time and start the sharing portion of the lesson.

Midway through the activity, ask students to pause and check in with their thinking. Refer to the metacognitive "Checking In With Your Thinking" questions posted at the front of the room. Have students ask themselves these questions.

Checking In With Your Thinking

- Am I pushing my own thinking to explore the concepts deeply?
- Am I thinking carefully about what my classmates are saying?
- Am I working "minds-on" – actively thinking about the patterns – instead of just letting my classmates solve the problem?
- Am I using others' ideas to "piggyback" to new ideas?
- Am I pushing myself to come up with ideas that are different from my classmates?
- Am I bringing my previous knowledge/experience to bear on the problem at hand?

Step 3: Sharing Puzzle Results

When all the groups have finished their lists and drawings the class is ready to share their findings. The group spokesperson for each lab group should report and the teacher should record on the white board or chart paper the results in two columns *Things We Know* and *Things We Guess*. Discuss what is similar and different for their lists and then have the group illustrators come up to the front of the room and show their illustrations at the same time. Compare what they included and then the groups can share what they think the entire puzzle is. How many groups agreed on the theme and how many different ideas for the puzzle do they have?

Review, Extend, Apply

Step 4: Our Experience with Group Collaboration

After the students have shared the results of the puzzle activity have them reflect on the experience of collaborating in their groups by asking the following questions:

- What did you experience as you worked together to complete the tasks?
- How did you decide what to put on your two lists, what to include on your illustration and what your puzzle was?
- What were any difficulties you noticed?
- What situations do groups face when they are to complete an activity?
- What can you do to improve how groups work together?
- What does it mean to think for yourself as well as collaborate with others?

Ask, "What do you think are the benefits of collaborating rather than thinking alone?" *[Possible answers include: I saw the problem in a new way or from a different angle; You get ideas other than your own; collaborating opens your mind to thoughts that you don't have and other people do.]*

Ask, "What are ways you can learn through collaboration such as what you experienced by working on these puzzles?" Gather responses. If students' comments do not mention the ideas given in the Understanding Goals, ask the questions below to guide them towards understanding how learning through collaboration in a science classroom is similar to "real world science."

- *There are opportunities to revise our own thinking* – "Did you change your original ideas? Did your thinking change as you worked with others? For example, if there was blue in your puzzle, did you first think it was sky, only to later realize it was a blue mailbox?"
- *It allows each person to contribute his or her own ideas* – "Did all members of your group have their ideas included on the list? Maybe not all their ideas, but at least one or two?"
- *Provides different ways to collaborate, such as working in pairs* – "Are there other ways you could have worked together? In pairs? In smaller or larger groups? With other groups in the classroom? How would working together in these other ways have changed things?"
- *Making metacognitive moves, or asking questions that help us check in with our thinking, can help us think collaboratively* – "When we paused during the activity to check in with our thinking, did it help you work more productively with your classmates? Did it help move your thinking along? Did it help you complete your lists and decide on the picture?"

Extend the discussion to ways they could do this activity to reveal other aspects of scientific problem solving. What suggestions do they have for solving the puzzle in a different way? If time and interest permits, you can follow up on these ideas by trying some of students ideas. Students may come up with the following ideas; feel free to either try these ideas or just discuss them, how they might or might not work, etc.

- Have the lab groups combine with other groups to see if they get more clues. *Puzzle analogy:* the puzzle can get completed faster, like scientists making their discoveries faster.
- Have all the groups work from a central spot in the classroom and try to put the puzzle together all at once. *Puzzle analogy:* each person has input but this may be more chaotic and therefore take longer to complete, like with too many scientists it may be hard to coordinate the work.
- You put the entire puzzle together. Then, break the puzzle up into sections – as many sections as there will be lab groups – take a few pieces away from each section, then put the remainders of each section into zip lock bags, one zip lock bag per lab group. *Puzzle analogy:* Students will almost be able to fit all their pieces together, just as it seems that scientists often come close to complete understanding. However, students will find that there are missing pieces, just as in science there are always “missing pieces” to the “puzzle” scientists are trying to solve.
- Have students experience working with others across space and time. Within each class or block period, designate lab groups A, B, C, etc. All lab groups A will work on one puzzle, all lab groups B will work on another puzzle, and so on. So, for example, students in Block 1 group A will collaborate on the same puzzle as students in Block 2 group A. Students can collaborate by posting notes in the classroom, sending emails to each other, etc. *Puzzle analogy:* you are working with others on the same puzzle without meeting your fellow puzzlers, like many scientists working in different locations.

Note to Teacher: This discussion for Step 4 could take the entire class period, and then the following two homework questions can be assigned. If you have the time in class the students can start the two homework questions during the class.

Step 5: Student Thoughts about Scientists’ Real Life Collaborating

Ask the students to consider the following two questions, either in their journals or as a class discussion:

(1) How does the puzzle activity connect to how scientists solve real life problems?

(2) What specific topics (other than those we covered in the beginning of this lesson) do you think scientists would study in this cooperative way? Include at least two examples.

Possible answers include:

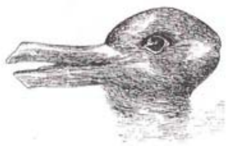
(1) Scientists have only some of the information and rely on ideas from other scientists. This is like having only part of the puzzle pieces to solve the entire puzzle. Scientists sometimes make guesses like we did on our two puzzle lists.

(2) Possible topics include gasoline shortage, cure for AIDS, effects of global warming on polar bear population

Say to the class “I am going to read you a story about scientists working with each other. I want you write down anything that you think is specific or special to the collaboration mentioned in the story. We are looking for any characteristics or trends that are unique to science collaboration as compared to collaboration in other situations.” See *Scientific Collaboration: A story from Pharmaceutical Research* in the Resources Section.

Gather students’ ideas. Include the following ideas in your class conversations about how collaboration in science has unique characteristics compared to other types of collaboration:

- You don’t always know what the end result will be.
- You don’t necessarily follow a specific plan or method.
- You can work across space and time without ever meeting the other scientists you are working with.



Lesson 9:
Subjectivity and Objectivity in Science

Photo Credit: Commons.Wikimedia.org

Understanding Goals

- Although scientists strive to be objective, they are inherently subjective like all humans
    - Different scientists can perceive and interpret the same information in different ways
    - Unintentional "confirmation bias" is one natural tendency that can hinder objectivity
- Through increased subjectivity (bringing many different passionate perspectives to bear on a problem), science can achieve greater objectivity over time
    - Scientists work together in order to increase objectivity in science

Background Information

Thus far in this unit, the students have learned about some of the ways in which scientists think, how models facilitate their thinking, and about the role of collaboration in science. In this lesson, students are encouraged to think about the natural subjectivity of people and how the scientific community works together to generate objective science.

Subjectivity in Perception and Interpretation

People often think of science as facts that are based on indisputable, objective observations. However, human perception is highly variable and subjective. For example, two people can look at the same painting and yet, notice different components and have different reactions. Although observing seems to be an objective task, this is far from the case. Visual experiences are not determined only by the object being observed, but are instead strongly influenced by past experiences, knowledge, and expectations of the viewer.[81] This is clear when comparing the visual experiences of experts to novices. For instance, when looking at an x-ray, an expert radiologist can quickly and easily identify the abnormality. A novice looking at the same x-ray, however, is unlikely to notice the problem. The differences extend beyond what novices and experts notice.

[81] Chalmers, A.F. (1999). *What is this thing called science?: 3rd Ed.* Indianapolis, IN: Hackett Publishing Co.: Chapters 1, 2, and 3 (pp. 1-40).

Depending upon what is familiar and meaningful to a particular person, research on perception and attention shows that they will notice certain patterns to the exclusion of others.[82]

Biases in Thinking and Reasoning: The Confirmation Bias

Subjectivity is further increased by certain shortcuts in thinking and reasoning that everyone uses. These shortcuts, or biases, are sometimes thinking traps that can lead to errors in reasoning. One example of a reasoning bias is that people often tend to confuse co-occurrence with causality. For example if a study showed that students with higher academic success also tended to participate more in sports, many people would tend to think that one causes the other although the two are only correlated.[83] Another reasoning bias is known as the availability heuristic.[84] Cognitive scientists have found that people tend to believe that something is more likely to be true or that an event is more likely to happen if they can readily recall a relevant example or incident. For example, a person who has recently caught the common cold is likely to take more precaution the next time than someone who has not caught a cold in years although both are equally susceptible.

Although science aims to produce objective information, scientists are no exception to such tendencies. A tendency that is particularly salient to scientific thinking is known as confirmation bias. Confirmation bias occurs when a person acknowledges only the information that is consistent with what they believe and simply misses, ignores, or even rejects contradictory information. This natural tendency can lead scientists to interpret the same thing in different ways.

Everyday examples of confirmation bias are superstitions. Consider the following situation: Billy believes that when he wears his lucky socks to his baseball game, his team wins. When Billy is asked why he believes this, he says, “Last week, when we played our rival team, I wore my socks and we won!” He may also add “And today, I didn’t wear my lucky socks and we lost.” In this scenario Billy exemplifies people’s natural tendency to focus on evidence that confirms their hypothesis or belief and not pay attention to disconfirming evidence. Billy’s team probably won games when Billy was not wearing his lucky socks and lost games when he was. However, Billy will likely not recall or acknowledge these cases that contradict his belief.

Although the example with Billy is a simple one, confirmation bias can also play a significant role in scientific thinking. There are several ways in which confirmation bias can play out in science. For instance, scientists may adhere to certain hypotheses or

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[82] Mack, A. & Rock, I., (1998). *Inattentional Blindness.* Cambridge, MA: MIT Press.
[83] Nickerson, R., Perkins, D., & Smith, E. (1985). *The teaching of thinking.* Hillsdale, NJ: LEA.
[84] Sunstein, C.R. (2002). *Risk and reason: Safety, law, and the environment.* Cambridge, UK: Cambridge University Press: Ch 2: Thinking About Risks, (28-52).

theories in the face of contradictory evidence. When sampling data for a study, a researcher may unknowingly give more weight or attention to data that supports an expected outcome. Some scientists may even choose to ignore data that disconfirms their hypotheses or fail to seek out contradictory data. However, it is important to keep in mind that confirmation bias is not always intentional. It is a mental shortcut or trap in thinking that often occurs unconsciously.

From Subjectivity to Objectivity in Science

All humans, including scientists, are innately subjective beings. As discussed, individuals perceive things in different ways and are also susceptible to certain biases in thinking and reasoning. How, then, do subjective beings produce more objective, scientific outcomes? Although it may seem counterintuitive, science can be viewed as a process where increasing the amount of subjectivity can lead eventually to more validated and objective knowledge. That is to say that the more subjective beings that are collaborating on a particular project and the more passionate they each are about their differing perspectives, the more objective the scientific knowledge they generate will be.

Henry Bauer further explained this aspect of science when he wrote, "Science progresses not because scientists as a whole are passionately open-minded but because different scientists are passionately closed-minded about different things (p. 76)."[85] All scientists are not openly accepting of new ideas—instead, each strongly supports a different view point, explanation, or theory. This passionate closed-mindedness can lead to subjectivity and biases in conducting science. Therefore, solitary people do not produce the best science. When a scientist proposes a new theory or idea, the scientific community is often initially skeptical about its validity. Therefore the new idea gets challenged and scientists must work hard to validate the idea before their colleagues will accept it. The process of scientists challenging each other's ideas and work, discussing different perspectives and debating various possible explanations is essential to eventual output of validated and more objective knowledge.

In this lesson students will learn how observation can be a subjective activity. They will experience how what a person sees is influenced by their background knowledge and their expectations for what they will see. Through discussion, they will also begin to develop an understanding of how people have a tendency toward confirmation bias without being aware of it. This lesson could easily take more than two class periods. Therefore, you may wish to divide the class between the discussion of the first activity and the beginning of the second activity (before Step 5).

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[85] Bauer, H. (1992) *Scientific literacy and the myth of the scientific method*, Urbana, IL: University of Illinois Press.

In the first activity (Steps 1-3) students will be asked to watch a short video. This video is filmed so that it is difficult to figure out exactly what is being shown. Students will be split up into 3 groups and each will be given different background information about the video. As confirmation bias unfolds, this may lead each group to come to different conclusions about what they are seeing in the video. Each group is given information that will increase their difficulty interpreting what is going on in the film, so each group is expected to struggle with some form of confirmation bias. The students will then be asked to discuss what they think the video was showing and why. Through the discussions students will begin to realize how background information and confirmation bias can influences observations and interpretations.

The second activity (Steps 4-6) will help students apply these new concepts to better understand the nature of subjectivity and objectivity in science. In this activity students will watch a short video on Dr. Judah Folkman, a well known scientist and surgeon. Folkman discovered angiogenesis, a process in which cancerous tumors signal the growth of blood vessels which can deliver nutrients and oxygen, allowing the tumor to grow. Although further research supported Folkman's hypothesis that cancerous tumor growth depended on angiogenesis, his ideas initially faced a great deal of resistance and skepticism from fellow scientists. This case study of Judah Folkman's experience in the scientific community will illustrate several ideas to the students. Students will realize that scientists looking at the same thing can see different aspects of it based on their background information. Also the scientific community's resistance to new ideas illustrates how confirmation bias can also play a role in science. In the end, however, students will realize that through collaboration scientists can work to increase objectivity over time.

In planning ahead for this class, it will be important to consider whether there are students in your class who have had cancer or have struggled with cancer in a friend or family member. If so, you may want to take them aside to talk with them prior to the class and to decide together whether or not they will be comfortable watching and discussing the Folkman case.

Lesson Plan

Materials

- *Zea*, A DVD that can be obtained from the Film Board of Canada[86]
- Background Information Cards (can be found in the Resources Section)
- *Questions to Think About* Worksheet
- Video on Judah Folkman found at: http://www.pbs.org/wgbh/nova/sciencenow/0306/04.html

Prep Step

- Review lesson plan, background information and understanding goals
- Watch the *Zea* video before class.
- Make copies of the background information cards (one card per group), cut them out on the dashed lines and fold them on the solid lines.
- Have link to Judah Folkman video on PBS website ready to play and watch the video prior to class.
- Make copies of the *Questions to Think About* worksheet for each student. You may also want to write these questions on the board.

Reveal Thinking

Step 1: Do We All See the Same Things?

Begin the lesson by asking the students, "When looking at the same thing, will three different people make the exact same observations?" Allow the students to discuss this for a few minutes. Invite students to weigh in on both sides of the debate. It is not important to guide the students toward one answer at this moment; this activity will help them form new ideas and conclusions in response to this question.

Explore Outcomes

Step 2: Exploring How We See Things

Explain that as they do the next activity, they will have different amounts and kinds of information just as people in real life do. Make sure that each student receives one of the background cards. There are three different kinds of cards so be sure that the cards are

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[86] Forget, R. (Producer), & Leduc, A. & Leduc, J. (2006). *Zea* [Motion Picture]. Canada: National Film Board of Canada.

fairly evenly distributed. Tell the students that this is some background information for the short video that they are about to watch and give a minute for everyone to read the card. Explain that they should not share what is on their cards with anyone else.

> **Note to Teacher:** Each student is given a different background card which will affect how they perceive the video and the conclusions they will arrive at. The goal of this activity is to show students that the same thing can be perceived differently due to background information and confirmation bias. However, the activity will not work well if students *know* that each group received competing information before watching the video. Therefore, ask the students to read the cards quietly and not talk to each other about it until after they have viewed the video and discussed their answers. None of the information is designed to help students perceive what is going on in the film. It is all designed to encourage confirmation bias.

Explain to the students that as they watch this video they should think about the following questions:

- What do you think this video is showing?
- What pieces of evidence from the video makes you think that?

Tell the students that they should be ready to discuss their answers to these questions after the video and that they can take notes on what they see if they would like to. Show the Zea video to the class, but stop the video at 3 minutes, 45 seconds so that they do not see the end (the end shows the students what the object is and will prevent a good discussion if the students see it).

Analyze Thinking

Step 3: Discussing Students' Observations

After you have shown the video, facilitate a whole-class discussion that will get students to think about how the same data can be perceived and interpreted in different ways. Another goal of the discussion is to get students to begin to see how confirmation bias can play a role in the way evidence is taken in and what pieces are given more attention. Throughout the discussion, make sure that students in each group respond to each question. Also, as you are writing comments on the board, cluster them into three sections (one for each group) so that the impact of the information on the card begins to become apparent.

Say to the students, "without revealing to the other students what your card said, talk about what you think you were watching in this video." *The poultry specialist group will likely say that it was an egg and they may also add either that it was a yolk turning into a baby chick or if they noticed the fire they may say that it was an egg about to be cooked.*

The microbiology group will likely say that they were looking at tiny microbes through a microscope. The astronomer group may say that that this video was a simulation of something in outer space like a landscape on a different planet.

Ask: "What parts of the video do you see as relevant to your hypothesis of what you saw? Or what did you see that makes you think that's what it is?" The poultry group may highlight things like the yellow was the exact same color as the yolk in an egg. They may also say that they saw an eye at one point that looked like a baby chick before it hatches. The microbiology group may highlight that many microbes live in water, so they noticed all the bubbles and they could see the microbes moving around. The geology group may mention the texture at the beginning looked like a rock or landscape.

Step 4: How Did Background Information and Confirmation Bias Influence Observations and Interpretations?

Ask the students, "Based on the background information you were given, what did you expect to see?" *The poultry specialist group will likely answer that they expected to see something that had to do with chickens. The microbiology group may respond that they expected to see tiny creatures through a microscope. The astronomy group may say that they expected to see something from outer space.*

"Did one group see things or pay more attention to certain parts that another group did not think was important? Why or why not?" *The students should be able to answer "yes" to this question and support their answer by pointing to things that were written in each group's column on the board that were not mentioned by the other groups.*

Now ask the students, "Once you thought you knew what it was, did you see anything that told you it was **not** an egg, microbes, or extraterrestrial land (to each group respectively)? Who did? Who didn't? What counter evidence do you have for your own hypothesis?" *Students will likely have a difficult time pointing out parts of the video that were disconfirming evidence for what they thought they were looking at. For instance, if they thought that the film was about an egg, they might be less likely to notice that as a crack forms, white appears through the crack and the object appears to lift up. Or if they thought it was an astronomical phenomenon, they might be less likely to report seeing a fish shape (as many people do) when the oil bubbles up from the side of the object.*

Ask the students, "Did what you expected to see influence what you actually saw? If so, how?" By answering these questions and engaging in this discussion, students should begin to understand that people tend to see things or label certain things as important based on prior knowledge or beliefs.

Explain that there is a natural human tendency to pay more attention to information that supports our ideas than to information that contradicts our ideas—this natural tendency is known as confirmation bias. As an example, point out how most of them could tell why they thought the video was showing a certain thing but could not recognize counter evidence (if that was the case, but if not, explain that it often is when groups engage in this activity.)

Explain that confirmation bias and expectations based on background information are two things that influenced the conclusions they came to about the video and the parts of the video they thought were important. Explain that people can show confirmation bias in several different ways and emphasize that it is often unintentional. Ask students if they can think of other examples when people show confirmation bias. Some examples include:

- For instance, you think that a friend of yours took your pen and you only notice things that fit with your belief (like the color of the ink on her papers) but not things that don't fit (like the fact that you haven't seen your pen since before she returned from being absent.)
- Or you judge someone based upon their style of dress and thus you stereotype them and don't notice characteristics that don't fit with that stereotype.

Discuss how research shows the following:

- People often unknowingly simply miss contradictory information.
- Sometimes people do not actively search out counter evidence.
- Still other times, people may refuse to acknowledge or consider contradictory information even if they recognize it as such.

Note to Teacher: It is optional to show the students the end of the video which will reveal to them that the entire video was about a kernel of corn turning into popcorn. If the students do view the end, they may feel tricked by the background cards and the activity. Explain to students that this activity was intended to simulate what sometimes happens in science research so everyone had information designed to lead them away from the actual outcome in the film. It is also possible that students in their generation will never have seen popcorn kernels cooked in oil in a pan. They may ask if this is what happens inside the bag in the microwave. Explain that this is how popcorn was often made prior to microwaves and hot-air poppers. Zea is the Latin word for "corn."

Encourage students to consider the following questions:

- Do scientists always know exactly what they are looking at?
- Is it possible for two scientists who are looking at the same thing to see it or interpret it differently?
- Do you think scientists might see different parts of it as important like the different groups of students did in this activity?

Review, Extend, Apply

Step 5: Is There Subjectivity in Science Research?

In this activity, students will learn how scientists can move toward objectivity in science through collaboration. Begin by asking the students to reflect on the previous activity with the Zea video.

Ask:
- Are observations always completely objective?
- What influences what different people see when they are looking at the same thing and how they interpret what they are seeing?

Based on the previous activity, students should be able to answer that people do not always see things in the same way. Background knowledge is one thing that can influence the way a person thinks and what a person considers important. People are also susceptible to confirmation bias in which case they may miss, ignore, or reject contradictory information and only value supportive evidence.

Have the students break up into new groups. Have them consider the following questions about how confirmation bias and different ways of interpreting information can play out in science:

- Do you think this happens in science?
- Why or why not?

Allow the students to debate these questions and take points from both sides. If students are reluctant to adopt one side of the argument or the other, you may have to play devil's advocate.

Lesson Plan Part II

Explore Outcomes

Step 6: The Role of Background Information and Confirmation Bias in Science: A Case Study of Judah Folkman.

Explain to the students that this next activity is going to look at some events that really happened in science. The video they are about to watch is about Judah Folkman who was a doctor, surgeon, and scientific researcher.

Note to Teacher: Due to the prevalence of cancer, there is a chance that one or several students in the class may have been affected by cancer in some way—perhaps personally, or through a family member or relative. It is important to be aware of this possibility and considerate of those students. You may want to talk with them prior to the class and consider how and whether they participate. This video will likely raise a lot of questions and especially for those students who are affected by cancer. Be prepared to either answer them or address them later.

After showing the students the video, first address any general questions the students may have about this very interesting story. Then divide the class into groups of four and ask them to think about and discuss the following questions:

1) Can scientists disagree? If so, what are the sources of disagreement? What about in this particular case with Judah Folkman?

2) What allowed Judah Folkman to see that the blood vessels were an important piece of evidence in learning more about cancer when many of the lab researchers did not?

3) How did confirmation bias play a role in this situation? Who, if anyone, exhibited confirmation bias?

Analyze Thinking

Address the above questions as a whole class. For the first question, the students should be able to point out from the video that scientists can and do disagree. The video shows how for a long time Judah Folkman's colleagues in the scientific community disagreed with him and rejected his ideas. Interestingly, before he died, Folkman also discussed his own persistence in pursuing the ideas that led to angiogenesis and questioned whether he had crossed the line to being too persistent or, as he put it, into being "pig-headed."

To help students answer the second question, remind them of the previous activity—all three groups were looking at the same thing but thought different parts were important. Why?

You can also guide the discussion by pointing out that Judah Folkman was primarily a surgeon and then asking, "How was he different from the other cancer researchers? Why did it matter?" Students should begin to see that Folkman's extensive experience as a surgeon was different from most cancer researcher's experience in laboratories and that this did make a difference. Remind the students that in the beginning of the video, the narrator talked about how when Folkman operated on patients, he noticed that the tumors were red and that the red indicated blood vessels. Through the discussion students should realize that due to his experience as a surgeon and his background knowledge, Folkman focused his attention on the blood vessels connected to the tumor instead of the tumor itself. Explain that in this way Folkman brought a different perspective to the same information about cancer.

Ask the students what they came up with in their groups in response to the third question.

Ask: "How did confirmation bias play a role in this situation?"

This may be a difficult question for the students to answer but help them to see how the cancer experts were exhibiting confirmation bias. These scientists were very focused on learning more about the actual cancer cells in the tumor and were certain that they held the key to a cure. Therefore, they were resistant to Folkman's new ideas which shifted the focus to blood vessels. Now, challenge the students to think about how Folkman himself may have been susceptible to confirmation bias. This question is a bit more difficult to answer from the video. Explain that when someone is so invested in a new idea, as Folkman was in this case, they may miss evidence that contradicts their hypothesis.

Review, Extend, Apply

Step 7: How Can Collaboration Help Science To Be More Objective?

Extend the students' thinking by asking, "Knowing that Folkman, like all humans, had a tendency for confirmation bias, why might it have been important for the scientific community to be initially skeptical of his new ideas?"

As the students respond to these questions, facilitate a discussion about the role of collaboration in moving toward more objectivity in science. The initial rejection from the scientific community forced Folkman to work hard to provide evidence in support of his ideas. Scientists in other laboratories also began to test his ideas. Ask: "How can collaboration—a lot of scientists working on the same hypothesis—help generate more objective scientific findings? Do you think one scientist can produce good, purely objective science on his or her own?"

After letting the students discuss the questions, explain that all scientists are innately subjective (i.e. susceptible to confirmation bias) to some extent. Therefore, having more people collaborating limits the effects of subjectivity and increases objectivity in the science produced.

Give the students the following clarifying example: "If you hear a rumor in school, would you believe one person's story to be completely true? Or do you think you could piece together a more accurate account of what really happened if you heard several versions from different people?"

Now ask, "Although there was disagreement about ideas of angiogenesis, how did the scientific community in the end come together as a field/discipline to generate more objective science?" As cancer researchers began to accumulate supportive evidence, more and more scientists began to accept these revolutionary ideas.

Lesson 10:
The Dynamic Nature of Science

Photo Credit: NASA.gov

Understanding Goals

- ❖ Advancing scientific knowledge involves trading up for better explanatory models.
  - ♦ Science is an ongoing process of learning more about the world.
  - ♦ Science develops explanations for how things work.
  - ♦ As new knowledge accumulates, existing explanatory models sometimes need to be modified or even replaced with better ones. Not just the details shift, the whole framing can also shift.
  - ♦ Scientific knowledge is seen as tentative. ('This is the best explanation given the evidence and all that we know right now.")
- ❖ Scientific discovery goes through different phases.
  - ♦ During what is called "normal science", scientists are working to support existing ideas and extend the knowledge base
  - ♦ During what is called "revolutionary science", scientists are making discoveries that lead to big changes in how a scientific concept is understood and framed.

Background Information

How Do Scientific Models Change Over Time?

Earlier lessons in this unit defined what a model is and addressed how models can help us think. This lesson explores how models change over time in the broadest sense. It moves beyond the idea that we, as individuals, trade up for better explanatory models to the idea that this is how science proceeds. This concept was introduced by the well-known philosopher of science, Thomas Kuhn, in the 1960s.[87]

An important aspect of the nature of science is that it is an *ongoing process* of trading up for better explanatory models.[88] Explanatory models are created by scientists to explain scientific phenomena. Once an explanatory model is proposed, scientists work to provide

[87] Kuhn, T.S. (1962). *The structure of scientific revolutions.* Chicago: University of Chicago Press.
[88] Kuhn, T.S. (1962). .

evidence to support it and prove its validity. This period of science, known as "normal science", is the phase in which most scientific work is done. Normal science can be seen in terms of "puzzle solving". The explanatory model can be seen as a completed frame to the puzzle and scientists doing normal science are working together to figure out how the remainder of the pieces fit together within that frame.

Although an existing explanatory model may function adequately for a period of time, science progresses through periods of "revolutionary science" during which new explanatory models challenge and replace existing ones.[89] Revolutionary science can be prompted in several ways. One way in which a new explanatory model can come about is by passionately invested scientists bringing a different perspective and way of interpreting the information. In terms of the puzzle analogy, these scientists would be able to take the pieces of evidence and create a different and more adequate frame. Science may also trade up for another explanatory model if it can explain anomalies that simply cannot be accounted for by the existing explanatory model or a modified version of it. Finally, revolutionary science can be incited by new observations and information that challenge existing models and impel the need to create new ones. A driving force in this is the advancement of technology which is constantly leading to new discoveries that could not have been made previously. The resulting accumulation of new evidence can lead to new interpretations and eventually better explanatory models.

An Example of Models Changing Over Time

In astronomy, for many years, the geocentric model was the widely accepted theory for how the universe worked. This model, strongly supported by Aristotle, placed the Earth in the center of the universe with the stars and planets moving around it in concentric spheres. The model was based primarily on two observations: 1) the Earth is solid, stable, and does not move, and 2) the Sun, Moon, planets, and stars rise and set each day—appearing as if they revolve around the Earth.[90] The model fits intuitively with the perceptual information available to us on Earth—it certainly appears from our perspective that the sun rises and sets each day.

Although this model appeared to be accurate at the time, there were two observations that the model could not account for. The geocentric model could not explain why the brightness of the planets changed and why planets appear to move backward at times (retrograde motion).[91] Ptolemy proposed some modifications to the original geocentric model that would accommodate these exceptions. He held onto the idea that the Earth is at the center, but added that the planets moved in circular "epicycles" as they rotated

[89] Kuhn, T.S. (1962).
[90] Geocentric Model. (2009, July 29). Wikipedia. Retrieved July 31, 2009, from http://en.wikipedia.org/wiki/Geocentric_model
[91] The Universe of Aristotle and Ptolemy (n.d.) Retrieved July 31, 2009, from http://csep10.phys.utk.edu/astr161/lect/retrograde/aristotle.html

around the Earth.[92] This new, more complex model accounted for both retrograde motion and varying planetary brightness.[93]

In 1543, Copernicus challenged Ptolemy's geocentric model by using mathematical computational systems to propose that the Earth and other planets revolved around the Sun.[94] In the early 1600s, Galileo, with the use of the telescope, observed that Venus displayed all phases much like the Moon. He noted that this observation could not be explained by the Ptolemaic universe, but was, however, consistent with the heliocentric system.[95] Following Galileo, the work of Kepler and Newton further supported the heliocentric model of the universe.

In early times people observed what they believed to be the daily rising and setting of the Sun, Moon, and stars and that the Earth did not move. The geocentric model with concentric circles fit these observations and therefore was the accepted model for many years. Ptolemy worked in the phase of normal science as he tried to fit pieces into the existing puzzle frame. That is, he modified and improved the existing geocentric model in order to explain certain observations (retrograde motion and varying planetary brightness) that were incongruent with the model. Centuries later, Copernicus brought a new perspective and initiated a phase of revolutionary science by proposing the new heliocentric model which he supported with mathematical analyses. Galileo further advanced the new explanatory model through new discoveries made possible by the telescope. For some time the heliocentric and geocentric models likely coexisted as rival models. Some people believed one to be true while others accepted the second as fact. As new knowledge accumulated and more scientists such as Kepler and Newton made important contributions, the new heliocentric model slowly gained more support. Eventually, this new explanatory model for the universe replaced the original geocentric view.

The ongoing process of modifying and/or trading up for better explanatory models is perpetually happening in science. Other clear examples from scientific history include the shifts from Lamarckian evolution to Darwinian evolution, from spontaneous generation theory to germ theory, and from the world being flat to the world being spherical.

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[92] Geocentric Model. (2009, July 29). Wikipedia. Retrieved July 31, 2009, from http://en.wikipedia.org/wiki/Geocentric_model

[93] Geocentric Model. (2009, July 29). Wikipedia. Retrieved July 31, 2009, from http://en.wikipedia.org/wiki/Geocentric_model

[94] Geocentric Model. (2009, July 29). Wikipedia. Retrieved July 31, 2009, from http://en.wikipedia.org/wiki/Geocentric_model

[95] Van Helden. (1995) The Galileo Project. Retrieved July 31, 2009, from http://galileo.rice.edu/chron/galileo.html

In this lesson, you will lead a discussion that gets students to think about different causes and reasons for trading up for better explanatory models in science. This discussion will be prompted by tracing the history of science in trading up for better explanatory models of the universe. Presenting images along with the historical accounts will help the students to better grasp the fairly simple science concepts and in turn to better understand the progression from one model to the next. Having Styrofoam spheres available for the students will be helpful because it will give them an opportunity to create and manipulate models of the solar system as they follow the history. Although basic astronomy concepts are included in the historical account, remember that the focus of this lesson is not on the scientific concepts but instead the process in which science develops and accepts new explanatory models.

In the second part of the lesson, students engage in an activity to help them learn about the process of trading up for a better explanatory model when the way in which the science is framed changes. Students are asked to fit paper cutouts into a given frame and then into a second frame as an analogy to the processes in how science builds new ideas. The metaphorical activity parallels the example that they discuss in the first part of the lesson—the shift from a geocentric model to a heliocentric model of the universe. Frame #1 represents the geocentric model, Frame #2 represents the heliocentric model, and the cutout pieces represent pieces of evidence used to support each model.

Lesson Plan

Materials

- Sets of 10 Styrofoam balls each (one set for each group of 4 to 5 students and one for the teacher)
- Large copies of the images in the Resources Section
- Copies of the following pages from the Resource Section: “Frame #1”, “Frame #2”, “Pieces of Evidence”, and “New Pieces of Evidence” (one of each per group of 3 students plus one extra).

Prep Step

- Review lesson plan, background information and the understanding goals.
- Make copies of the images.
- Set up stations around the room with a set of Styrofoam balls at each
- Make copies of Frame #1 and Frame #2.
- Make copies of “Pieces of Evidence” and “New Pieces of Evidence” in two different colors (this will help to separate them after each class). Also make these copies on paper where the front is distinguishable from the back. This will help students keep track of what side should be facing up.
- Cut out the pieces of evidence and put them in their respective envelopes labeled “Pieces of evidence” and “New pieces of evidence”. There should be one of each envelope for each group of students.

Reveal Thinking

Step 1: Reveal Current Thinking

Ask the students the following questions:

“Once we decide that something is true through science, does that discovery remain true forever?” “Who thinks that it does?”, “Who thinks that it does not”, “Why?”

Invite students to respond on both sides of the question and allow them to discuss their ideas either as a class or in small groups. Also, encourage students to support their position with real examples they may know from science.

After a few minutes of discussion, introduce the lesson by telling the students that today we are going to trace the history of what people thought the solar system looked like. Ask them to keep the question in mind as they go through the activity.

Explore Outcomes

Step 2: Analyzing a Model From Ancient Greece

Split the students into groups of four or five and have each group go to a station with a set of Styrofoam balls. Explain that they will receive directions about how to use the Styrofoam balls.

Explain to the students that the first model of the universe was proposed by the ancient Greeks and that they believed in a geocentric universe. In this model, the Earth stood still in the center of the universe while the Sun, Moon, planets, and stars moved in a series of perfect circles around the Earth. Pass out copies of Figure 1 to each group to help them picture the Greek geocentric model of the universe. It may also help to use the Styrofoam balls to represent the planets, Sun, and Moon.

Lead the students in a discussion using one or more of the following questions:

- What observations would lead to this initial model of the universe?
- In what ways does this model make sense?
- Given what people of the time could perceive and know, why might this geocentric model make sense to them?

To further prompt discussion you may ask, "For example, can we *feel* or *see* the Earth moving?" In this way, encourage the students to think about what observations can be made through our unaided senses alone that can be used as evidence for the geocentric model.

Some possible answers that students my give or be guided toward include: "*We can see the Sun, Moon, planets and stars rise and set every day and night. Therefore, it looks like they are moving in a circle around the Earth.*" "*When objects fall, they fall to the ground (toward the Earth), so the Earth must be at the center.*"

Some students may also mention the religious or theological reasons behind the geocentric model of the universe. In ancient Greece, people strongly believed that God created man and also the universe and, therefore, they were certain that God would place man at the center of the universe. Although religious reasons were influential in the creation of an Earth centered model, these reasons need not be explicitly discussed or prompted for the purposes of this lesson.

Step 3: Finding Gaps in the Model

Next ask:

“Based on the observations that could be made, what might be some scientific problems with this geocentric model of the universe with circular orbits?”

Since the answer to this question requires some knowledge of the science, the following answers may have to be explained to them.

Explain that there are two main scientific problems or gaps in the model. The first is that the model cannot explain retrograde motion. Retrograde motion refers to the phenomenon where, from the Earth, a planet can be observed to be moving forward, stop, change direction and move backwards, stop again, and continue again in a forward direction (Refer to Figure 2). Using the Styrofoam balls, demonstrate retrograde motion to the students. Ask: “Would we see retrograde motion if the Earth was motionless in the center of the universe?”

Ask the students to now work in their groups using the Styrofoam balls to model retrograde motion and to consider whether the geocentric model accounts for it best. Because this phenomenon can be difficult to understand, walk around and help clarify it for each group. Allow them to work and discuss in groups for a while and then repeat the question. The students should realize that in a model where the Earth is still, it is difficult to explain why the planets appear to be moving backward.

The second scientific problem is that the brightness of the planets changes throughout the year. Ask: “If the planets were all moving in perfect circles, would the distance between Venus (for example) and the Earth ever change?”

You can give the students a couple of minutes to use their Styrofoam model to answer this. The answer would be “no” because every point on a circle is equidistant from the center.
Ask: “If the distance does not change, does this model explain the varying brightness of Venus that we see throughout the year?” The students should again answer “no”.

Step 4: A Revised Model: The Ptolemaic Model

Explain to the students that a man named Ptolemy modified the original geocentric model of the universe. Ptolemy’s model kept a stationary Earth in the center of the universe. The planets, however, moved in small circles called “epicycles” as they orbited around the Earth.

Help the students to see Ptolemy’s model by either drawing it on the board or by showing an image or animation.

Have the students work in groups to recreate the Ptolemaic model with the Styrofoam balls and compare it to the geocentric model. Write the following questions on the board:

1. Why did Ptolemy develop a new model of the universe?
2. In what ways was it a better model than the first model of a geocentric universe?
3. Why did people trade up for this different model?

As they work, ask the students to answer the questions in their groups.

The goal of this discussion is to get students to begin thinking about why people might trade up for better explanatory models in science. In this particular case, there were faults or explanatory holes in the existing model and therefore, it could not account for certain observations. Ptolemy's model accounted for the observed motions of the planets in a way that the original model could not. It explained why the planets sometimes appear to move in a reverse direction and their varying brightness as observed from the Earth. People accepted Ptolemy's modified model of the universe because it was better at explaining all their observations than the original geocentric model.

Step 5: A New Model: Copernicus, Galileo, and the Heliocentric Model

Explain the following historical information about the start of Copernican ideas to the students. In the 1500s Copernicus, a mathematician and astronomer put forth a heliocentric model of the universe based on mathematical calculations and reasoning. The Copernican model showed the Sun fixed in the center of the solar system with the planets, including the Earth, revolving around the Sun. One year marked one revolution by the Earth around the Sun and one day marked each turn on its axis. Through his heliocentric model, Copernicus was able to accurately calculate and predict the motions of the heavenly bodies.

Say: "We just discussed how the Ptolemaic model was designed to explain observations that the older model could not. What do you think led to the development of this new model for the universe? How was it different from how or why Ptolemy created his new model?"

These questions aim to get the students thinking about the various reasons for or ways in which new models come about. The Ptolemaic model actually worked fairly well in predicting motions of planets—so why and how did Copernicus propose a new model? This particular case is an example of how changes can result because a scientist or group of scientists thinks about the same phenomenon in a new and different way. Copernicus developed what he thought was a better explanatory model based on the mathematical calculations—one that fit with the mathematical patterns he observed.

Explain: "Nearly a century after Copernicus proposed the heliocentric model (in the early 1600s), the geocentric model was still the most widely accepted model of the solar system. Around this time, however, Galileo, made a new telescope that could see further than any before it. With his new invention, Galileo was able to make new key observations that supported the heliocentric model and encouraged people to trade up for this new model."

Ask: "This time, what was one reason that people traded up for a new model?"
The students may answer that it was because there was a new discovery that supported the new model.

Ask: "How did scientists get this new information?"
Students may give the direct answer of "the invention of telescopes".

Help the students to recall from Lesson 1 that advancements in technology can lead scientists to develop and support better explanatory models. Can the students think of any other examples of when new technology led to new discoveries?

Explore Outcomes

Step 6: The Frame Shift Activity: Fitting the Pieces of Evidence into Frame 1

In the next activity, students are asked to fit paper cutouts into a given frame and then into a second frame which will serve as an analogy for what happens in science when we trade up for explanations that fit differently. The activity metaphorically parallels the shift from a geocentric model to a heliocentric model of the universe. Frame #1 represents the geocentric model, Frame #2 represents the heliocentric model, and the cutout pieces represent pieces of evidence used to support each model.

Divide the class into groups of three and give each group Frame #1 and an envelope with the cutouts from the page titled "Pieces of evidence" in it. Ask the students to work together in their groups to fit the pieces (like a puzzle) into Frame #1.

> **Note to Teacher:** This task may be more difficult for some groups than others. In order to move the activity along, you may need to offer assistance as students fit the pieces into the frame. It may be useful to carry a reminder of how the pieces fit together (by saving a copy of the "Pieces of Evidence Sheet" that is not cut out). Also remember that some students may organize the pieces differently than the Key shows, but still fit all the pieces into the frame.

Once all the groups have fit in all the pieces into the frame, tell the class to imagine that "Frame #1" represents the geocentric model of the universe. The cutouts represent pieces of evidence that they as "scientists" were just using to reinforce the idea or frame. Also explain to the students that what they are doing by fitting the pieces of evidence into an existing frame represents "normal science". Most of the work done in science is "normal science" where scientists are working to support and reinforce existing ideas and models.

Ask: "What evidence is there that the Earth is at the center? If you believe the Earth is at the center, what can you tell with your senses that support this idea? In other words, what could those pieces of evidence represent?"

Students should be able to answer this question as it is review from the last activity. Some possible answers include: *The Earth feels like it is standing still because we cannot feel it moving. The Sun, Moon, and planets rise and set everyday so it looks like they're moving in circles around the Earth.*

Step 7: The Frame Shift Activity: Fitting the Pieces of Evidence into Frame 2

Now hand each group of students Frame #2 and ask the students to fit the same pieces they have into the new frame. Explain that this shift in frames or models represents "revolutionary science" which happens when a new frame or model is proposed and begins to be supported.

Students will likely ask, "Are they all going to fit?" Do not answer this question yet and simply encourage them to keep working on it. In fact, students will not be able to fit in all pieces into Frame #2. Some of the pieces will fit in and some empty space will remain in Frame #2. Allow the groups a few minutes to struggle with this part of the activity. You can ask the students, "Do you think you have everything you need to complete Frame #2?" Students will likely begin to realize that they will not be able to fit all the pieces they have and that they may need more pieces to complete Frame #2.

Once you reach this point in the activity, give each group another envelope with cutouts of the "New pieces of evidence." Allow time for the students to add these new pieces into Frame #2. However, they will still have some empty spaces remaining in the frame.

Note to Teacher: Not all the groups are going to get to the same point in this activity. Ask them to stop when all the groups have fit some of the original pieces *and* some or all of the new pieces into Frame 2. At this point begin the discussion about the process they used during this activity.

Analyze Thinking

Step 8: Why Is It Hard to Shift Frames?

Begin a discussion with the whole class. Ask: "What was hard about moving from the old frame to the new frame? What did you have to do to go from Frame #1 to Frame #2?"

Students will likely answer that they did not have all the pieces and that they needed new pieces. They had to rearrange the pieces as well. Also, as they worked on Frame #2, they learned that they had to get rid of some of the pieces that fit into the old frame but not into the new frame.

Remind the students that Frame #1 represents the geocentric model of the universe and explain that Frame #2 represents the heliocentric model proposed by Copernicus. Ask: "Thinking about it in this way, how is this activity like science? What does it tell us about why it may be difficult in science to shift from one model (or frame) to another?"

Students should be able to see by now that in science, like this activity, trading up for another model requires rearranging of how the evidence is pieced together, throwing out some pieces of evidence that are now realized as irrelevant or incorrect, and adding in some new pieces of evidence to support the new model. Write the following three points of discussion on the board:

1) Threw out some pieces of evidence
2) Used some pieces in both frames
3) Needed new pieces of evidence.

Step 9: Discarding Pieces of Evidence

Explain that it took many years to make the shift from a geocentric model to a heliocentric model. Ask: "Why might this be?" "What pieces of evidence do you think might be hard to throw out?"

If students are not volunteering answers, ask them "Can we see or feel the Earth moving? Can we see the Sun moving?" Help the students to realize that our senses clearly tell us that the Earth is standing still and we can see the Sun and planets moving. Explain that this makes it hard to accept a model that says, "Actually, the Earth is moving but we cannot feel it and the Sun is still and in the center." Based on our senses, which is all science had to count on for observational evidence at the time, the heliocentric model simply does not make sense.

Step 10: Pieces That Fit Into Old and New Frames

Ask: "When moving from Frame #1 to Frame #2 did you use some of the same pieces in both?" (*Yes*)

Explain that in science, like in the activity, some pieces of evidence do fit into both models but they may be put together differently.

Ask: "When moving from a geocentric to heliocentric model, can you think of examples of pieces of evidence that they would have kept?"

It may help to show the students the two models and ask them to note what stayed the same. Two of the more explicit examples include the general circular motion of the planets and the Moon revolving around the Earth.

Step 11: Collecting New Pieces of Evidence

Ask: "In this example, what might the "new pieces of evidence" represent?" "Can you remember from the last activity what kind of information helped to support the heliocentric model?"

One example that was discussed was how the invention of the telescope allowed Galileo to observe things that previously could not be seen. The information he collected with the new technology added evidence to support the heliocentric model. Also, a less explicit example is Copernicus' calculations which showed that the movement of the Sun, Moon, and planets could be more accurately predicted with the heliocentric model. Also, more recent major technological advancements have allowed us to take pictures from space that support that the Sun is at the center of our solar system.

Review, Extend, Apply

Step 12: Are Frames of Science Models Always Completely Filled In?

Ask: "Were you able to complete Frame #2?" (*no*) "What does this mean in terms of what happens in science?" "Do you think a frame can ever be entirely complete?"

The empty space in Frame #2 indicates that there is still some evidence missing. Explain to the students that in science, a frame is hardly ever entirely complete.

Ask: "Was Frame #1 likely to be an accurate representation of science?" (*The students should answer "no" because most frames are not entirely filled in.*) "If a frame is not entirely filled in, does it mean that explanatory model is wrong?" "Can we believe in the heliocentric model?"

Invite students to respond on both sides of the question. This question will hopefully prompt an interesting discussion about the nature of science in terms of the tension between the tentative nature of explanatory models and what can be accepted more or less as "fact". Guide the discussion to help students to realize that scientific models are tentative but that does not mean everything should be completely doubted. For example, with the major advancements in technology, there is now overwhelming evidence for a heliocentric model of the universe.

In conclusion, ask: "Can you think of any examples from current day science that remind you of the shifts in how we frame science?" (*Possible examples include ideas about climate change; the causes of autism; and how we view the nature of intelligence.*)

Resources for Section 3

Scientific Collaboration

A Story from Pharmaceutical Research

Laura, Ming, Robert and Shantelle are chemists. Laura is the leader of the team, Ming and Shantelle have been working with Laura for several years, and Robert is new to the group. They are just one team in a large group working on developing a drug that can cure a certain type of cancer. They meet weekly to discuss their work. At this week's meeting, they are catching each other up with what each of them has been doing. They are also preparing for their presentation to their larger group at next week's group meeting.

Laura: OK, so let's check in and see what's happening. Robert, let's start with you.

Robert: The first reaction I did worked out beautifully. You should see the resulting compound! I've sent the compound to Pat in Biology so he can test it on some real cells to see how active the compound is.

Ming: Robert, that's great. I remember you weren't sure how to approach that reaction. Sounds like you figured it out. Great job!

Robert: Thanks!

Laura: Do you think Pat will have results for us by the time we have our big group meeting next week? It would be really good to be able to present those results to the larger group.

Shantelle: Right: depending on how active the compound is on the real cells that might change what our group works on next.

Robert: Yeah, I know. I asked Pat if there was any way to get the results by next week's meeting. He said he would start testing the compound as soon as possible, but he didn't know if the results would be available in time.

Shantelle: I guess that's just part of the biology, huh?

Robert: Yes, and also, his team is involved with a major project as well, so he's working pretty hard on his own work.

Ming: That's OK. Even if we don't have the results, we can still tell the group that the compound has been submitted for testing, which is still progress.

Laura: That's right.

Ming: What about the second reaction you were working on? You were wanting to see if you could get it to work?

Robert: Yeah. Unfortunately, I couldn't get that second reaction to work out. I just don't know what's happening.

Laura: Have you checked the literature to see if other chemists have tried this reaction?

Robert: Yes, I did check the literature. There was a group in France that worked with similar chemicals, and they got a very interesting result. Since the chemicals they used were similar, I thought maybe I could get a similar interesting result with our chemicals. But it didn't work. This is definitely not what I was planning on!

Ming: Hey, that's all right, Robert – that's the way the science works sometimes.

Shantelle: Right! Do you remember that last reaction I was trying to work up a couple of weeks ago? We were talking about that one for weeks!

(They all nod their heads: they remember!)

Shantelle: I finally asked Sam for her ideas. You know Sam, from Team 3 down the hall? She suggested a different way of looking at the problem, which was completely different from the way I had been thinking about it. Once I looked at the reaction in that new way, I figured out how to get it to work.

Robert: Ah, so maybe I need to look at this in another way? Maybe I should check with somebody else?

Laura: It's possible. It's fine to check with us first, especially since, as a team, we know what each of us is working on, and so we might have a better idea of what to suggest. But we might get stuck, too! It's often helpful to ask someone else and gain a fresh perspective on the problem.

Robert: OK, good to know. Thanks!

Laura: Let's finish with all of our quick updates, then, Robert, we can really discuss your second reaction in detail, and see if there's anything we can figure out about it.

Robert: Sounds good!

Background Information Cards for *Zea* Video Activity:

(Cut along dashed lines and then fold along solid lines)

Group 1: A poultry specialist filmed this video for his research.

Group 2: This video was filmed in a lab for microbiology research.

Group 3: An astronomer who is interested in objects in outer space gave this video to me.

Name________________________________ Date________________

Questions to Think About

Here are some questions to think about while watching the film. We will be discussing these after the film.

1) Can scientists disagree? If so, what are the sources of disagreement? What about in this particular case with Judah Folkman?

2) What allowed Judah Folkman to see that the blood vessels were an important piece of evidence in learning more about cancer when many of the lab researchers did not?

3) How did confirmation bias play a role in this situation? Who, if anyone, exhibited confirmation bias?

Schema huius præmissæ diuisionis Sphærarum .

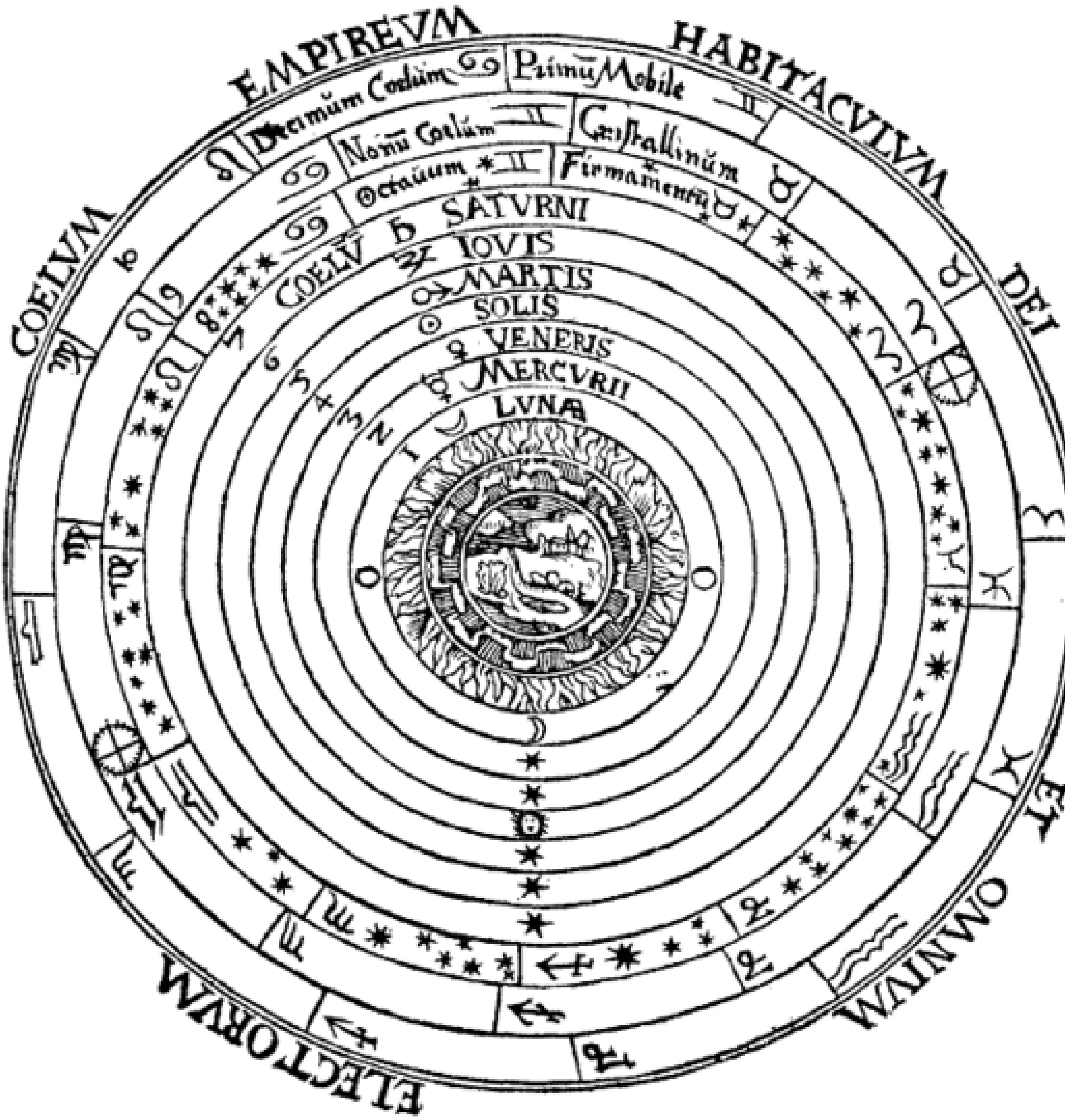


Fig. 1: The Geocentric Model (before Ptolemy)

Photo Credit: En.Wikipedia.org

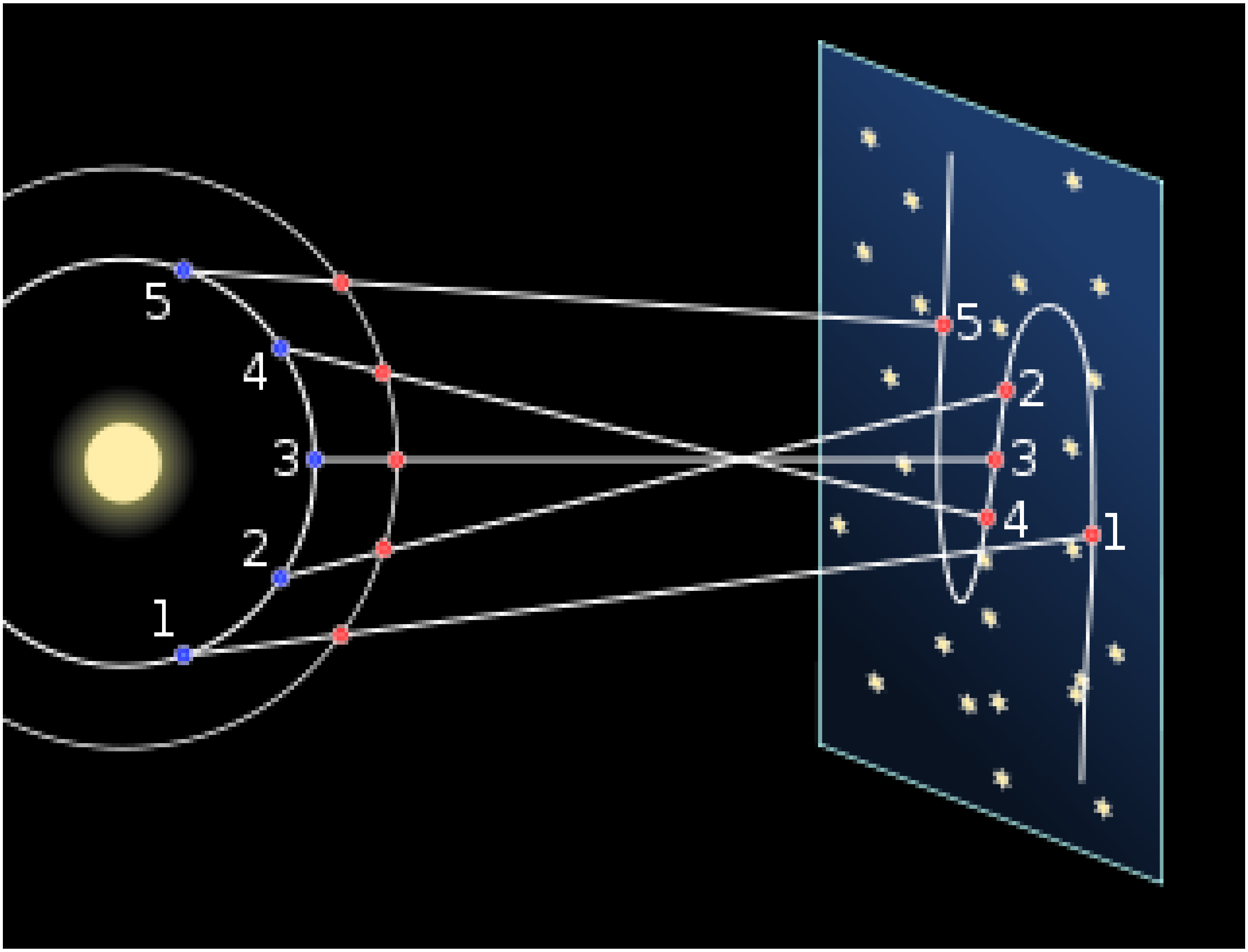


Fig. 2: Retrograde Motion

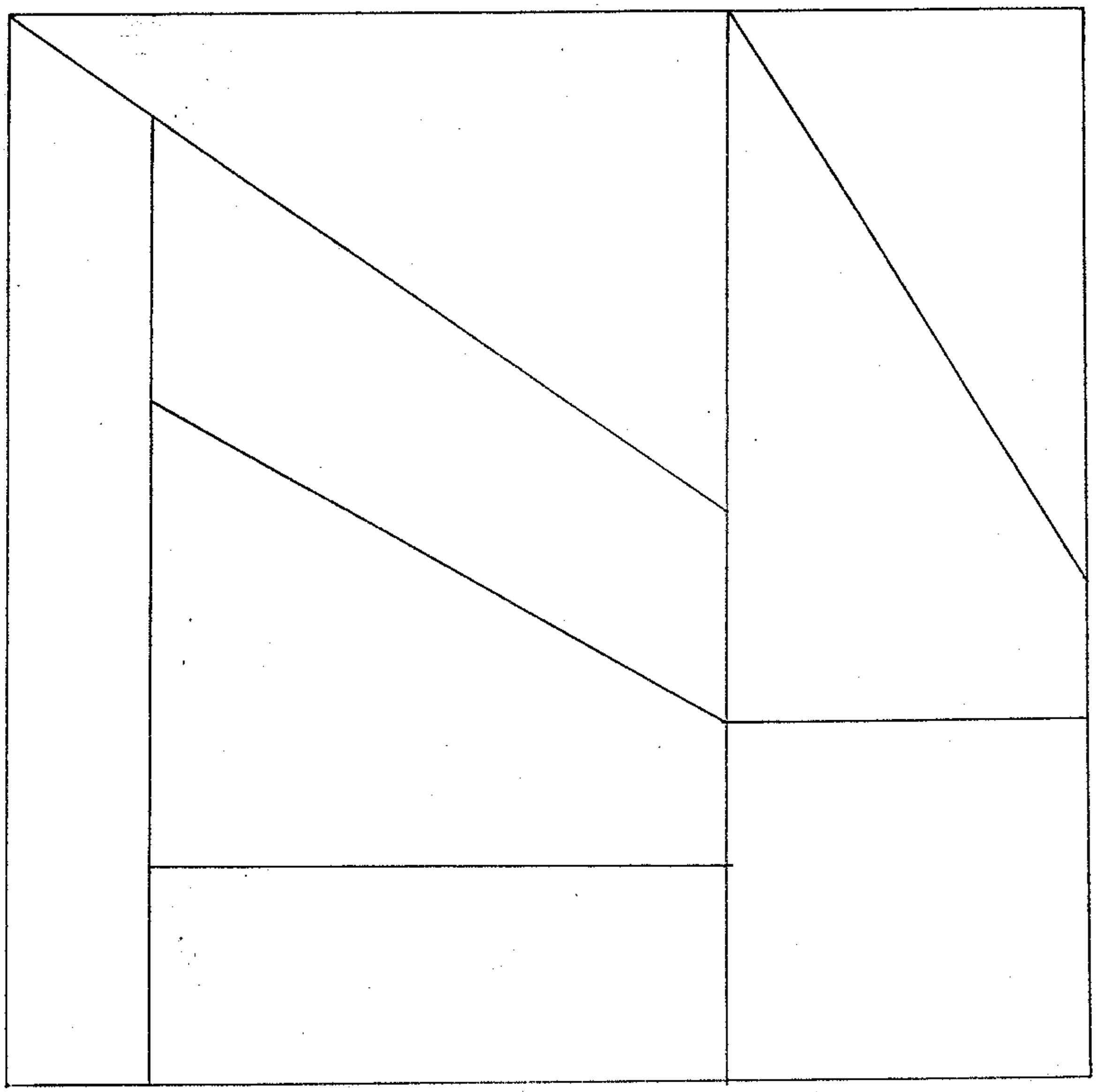
Photo Credit: En.Wikipedia.org

Frame #1

Frame #2

Pieces of Evidence

(Cutouts for Frame #1)



New Pieces of Evidence

(Additional Cutouts for Frame #2)