8

Effective Physics Analogies

Allan G. Harrison

The abstract nature of physics concepts particularly challenges teachers and students. For instance, how do we describe forces, in particular, forces that act at a distance, like gravity, magnetism, and electric force? How can we explain refraction? A ray of light bends toward the normal as it passes from air to water because it slows down, but why does it slow down and how does this slowing down change the direction of a photon? And how do we easily explain nuclear decay and radioactivity? Sophisticated quantum explanations are available to physicists, but where are the everyday explanations that school teachers can use with elementary and middle school students?

The answer, of course, is to use analogies and models.

In *A Brief History of Time* (Hawking, 1988) at least 74 everyday analogies were used to explain astrophysics and quantum ideas; in *Six Easy Pieces*, Richard Feynman (1994) employed 12 analogies to explain "Atoms in Motion" (his first chapter); and history shows that Robert Boyle, Christian Huygens, Johannes Kepler, and James Clerk Maxwell all used analogies to solve conceptual problems. So remember, whenever you invent or modify an analogy to help your students' learning, you're in excellent company.

Here follow three particularly valuable groups of analogies as they apply to high school physics classes:

1. Analogies for Light

A ray of light changes direction when it passes from air into water because it slows down. Refraction of light rays is commonly compared to the way water waves change direction. This analogy works because students can see water waves slowing down and changing direction as the waves move from deep water into a shallower region. Of course, this phenomenon has to be demonstrated before the analogy between water waves and light waves can be made. Ripples in a pond or tank are an excellent way to demonstrate refraction of water waves. The analogy between water waves and light waves is productive because it also explains the diffraction of light. Student understanding is advanced even further when the water wave analogy is augmented by the analogy of the pair of wheels rolling from a smooth to a rough surface, featured later in this chapter and in Treagust, Harrison, Venville and Dagher (1996).

2. Field Metaphors and Analogies

Forces that act at a distance are best explained by talking about gravity and magnetic and electric fields. The field concept is a metaphoric analogy based on agricultural, battle, and sport fields, areas in which crops, battles, or games are confined. In agriculture, plants, animals, and soil are intimately related, and each is affected by what happens in other parts of the field. There are specific rules and relationships that apply inside it. For instance, on a sports field or battlefield, the addition or loss of a star player or the introduction or destruction of a major weapon affects all parts of the field. Players and soldiers know to some degree what each other is doing and respond to overall changes in the ebb and flow of power. The Field Analogy explains how a magnet affects every magnetic substance in its field of influence. A magnetic field models the way that magnetism works within and around a magnet. Other than the field concept, there is no effective way to explain force at a distance. Magnetic and electric fields puzzled Faraday and occupied Maxwell for many years. Maxwell's mathematical equations emerged from the analogical models of weights, pulleys, and strings that he used to model forces acting at a distance (Nersessian, 1992).

3. Analogical Models for Electricity

More analogies and models have been used to explain electrical circuits than for any other science concept. Electricity is used everywhere, yet it is so counterintuitive. For example, in series circuits, electric energy is shared between lightbulbs like water is shared between sprinklers along a hose. This analogy suggests that as lightbulbs are added to a series circuit, more current should flow, but the reverse happens. This is a question that only The Electric Field Analogy can help solve.

But there is another paradox: Add lightbulbs to a series circuit, and they all get dimmer; add lightbulbs side by side in a parallel circuit, and all are equally bright (within limits). The analogy that works is one that shows that parallel circuits actually are independent circuits. The school hall with two or three separate sets of doors satisfies this need. People leave the hall two or three times faster when two or three doors are opened. Independent exits are like independent parallel circuits.

The other counterintuitive conception for electric circuits is the problem of why the current isn't used up. Lightbulbs grow dim after a while and batteries go flat. Something must be used up. Grayson (1994) says the problem comes from confusing *current* with *energy*—current is conserved while the battery's energy is used up. This is right, and students more readily exchange the misconception of consumed current for the understanding that energy is transferred when multiple current conservation analogies are employed. Students need the correct terminology, and they need logical explanations. Analogies provide these explanations. And multiple analogies are recommended for explaining electricity concepts.

The most popular electricity analogies are those that employ water circuits and water flow (e.g., Hewitt, 1999, p. 535). Water circuit analogies are useful for demonstrating that electricity flows, *but that's all.* The downside of these analogies is the student conclusion that electricity is a fluid and that electricity leaks out onto the carpet from electric sockets that have no plugs in them. The incorrect inference that electricity is a material fluid supports the idea of current being used up because water is rarely recycled in the students' homes; it is used up and lost. Why shouldn't they conclude that current is used up?

Science educators should use The Continuous Train, Bicycle Chain, and Student M&M's Circle Analogies to reinforce the notion that current is conserved, not consumed (Osborne & Freyberg, 1985). To teach electricity concepts effectively, I recommend a set of two or three analogies drawn from the list below, which is numbered 8–14 because these analogies are found in the second half of this chapter:

8. The Water Circuit Analogy for Electric Current
9. The Water Pressure Analogy for Voltage
10. The Shared Water Flow Analogy
11. The School Gymnasium Analogy for Parallel Circuits
12. The Continuous Train Analogy for Current Conservation in a Series Circuit
13. The M&M's Circle Analogy for Electric Current
14. The Field Analogy for Electric Circuits

As you see, these seven analogies include the Water Circuit Analogy, but *it should never be used on its own*—it engenders too many misconceptions.

First, here are seven additional physics analogies:

1. The Dominoes and Books Analogy for Conduction of Heat
2. The Gravity Warps Space-Time Analogy for Bending Starlight
3. The Supernova Cola Analogy for Exploding Stars
4. The Matches, Mousetraps, and Dominos Analogies for Nuclear Fission
5. The Eye Is Like a Camera Analogy
6. The Pair of Wheels Analogy for the Refraction of Light
7. Bridging Analogies for the Balanced Forces of a Book on a Table

The Dominoes and Books Analogy for Conduction of Heat

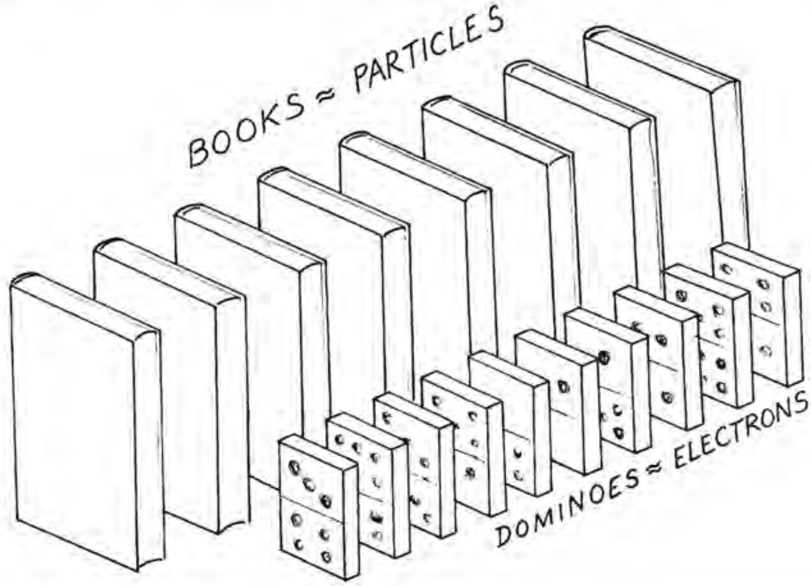
Heat transfer by conduction is easy to feel and demonstrate. If you simultaneously heat the ends of steel, copper, and aluminum rods, you can measure the rates that heat travels along them. Another way is to hold the ends of a wooden skewer and a piece of wire in a candle flame. You quickly drop the wire but you can hold the wooden stick even when it's on fire.

Mrs. Jones had her Grade 8 students feel the water tap, bench top, a sweater, and a pencil, asking, "What do they feel like?" Knowing that the lesson was about heat, students said, "[The] faucets feel colder than the bench top and that's cooler than the pencil and my sweater feels warm." Mrs. Jones handed out some thermometers and asked the students to try and measure the temperature of the objects they had felt. Discussion followed on how to lay the thermometer bulb on the objects and for how long to make it a fair test. Most students agreed that the objects that felt different were in fact about the same temperature. They talked about experimental error; then Mrs. Jones directed the class to a demonstration she had set up while they had used their thermometers (see Figure 8.1).

For a couple of minutes they talked about metals—iron, copper, and aluminum. "Which one conducts heat fastest . . . what's slowest?" Some students also asked, "How does a metal conduct heat and why's wood a bad conductor?" Anticipating this question, Mrs. Jones turned to her books and domino analogy.

The class had talked about kinetic theory, so the students were familiar with particle ideas. Mrs. Jones said that the books represented the atoms or molecules that make up the metals and wood. The dominoes represented electrons that are free to move around in metals but not free to move in wood or plastic.

Figure 8.1 The Dominoes and Books Analogy for Metal Conduction



Mrs. Jones said, "If I push this end book over, what happens?" She did so, and each book fell onto the next book, pushing it over and so on for about 20 books. She stood the books up again and then asked two girls to help her. "When I say 'go,' I want Gail to push the first book over like I just did and Sal to push the first domino over at the same time." When she said "go," the girls pushed over the end book and domino. The line of books fell slowly but the dominoes fell nearly three times faster. She then used this analogy to explain conduction:

Mrs. Jones: Metals are different from other sorts of substances because their electrons are free to move. In metals there are lots of free electrons, and this is why metals are very good conductors. In metals we've got our big particles—these books are like atoms—and the dominoes, the little ones, represent free electrons. Little dominoes move lots faster than big books. Now when I heat one end of the metal, as well as making the particles vibrate, the free electrons also vibrate, so we've got a double way of passing on the vibrations. Nonconductors like wood and plastic don't have free electrons, only very big

	molecules, so in metals, the vibrations or heat travels much faster. . . . You saw that the books fell slowly and the dominoes fell quickly. It's the free electrons that make metals good conductors.
Mrs. Jones:	What state of matter do you think would be the worst conductor?
Student:	Gases
Mrs. Jones:	That's right, gases. Why are gases the worst conductor?
Student:	Because the particles are so far apart that they don't touch each other.
Mrs. Jones:	That's good. [They are] so far apart they can't touch each other when they vibrate. Gases are like having one book here, and the next book might be right at the end of the bench. . . . So it does not matter how much I heat this gas particle, there is no way it is going to pass on its vibrations. So metals are the best, then solids, then liquids, and gases are pretty poor.

The Dominoes and Books Analogy for Conduction of Heat		
Focus	**Concept**	Conduction of heat relies on particles. Students can visualize solids as close particles that jostle each other and transmit heat energy from one particle to another; metals conduct heat quickly while wood, plastic, and cloth are poor conductors because of the difference in structure.
	Students	Students are familiar with lines of people jostling each other and that materials are good or poor conductors of heat.
	Analog	Lines of dominoes, close but not touching, will all fall over if the first domino falls onto the next one. Books stood up like dominoes also fall in a line if the first is disturbed but much less quickly.

The Dominoes and Books Analogy for Conduction of Heat (Continued)

Action	**Likes—Mapping the Analog to the Target**	
	Analog—Dominoes and books	**Target—Enzymes and substrates**
	Dominoes standing up that can fall over	Free electrons that can move around
	Books standing up that can fall over	Atoms and molecules that vibrate
	Dominoes falling over quickly one after another, in a line	Free electrons speeding up when heat is absorbed and moving around bumping others
	Books falling over slowly, one after another, in a line	Atoms vibrating faster when heat is absorbed and jostling atoms next to them
	Fast-falling dominoes compared to slow-falling books	Good heat conductors compared to poor ones.
	Slow-falling books (no dominoes)	Nonconductors having only vibrating atoms or molecules
	Unlikes—Where the Analogy Breaks Down	
	• There are many, many more electrons and atoms than dominoes and books—remember, the analogy is a gross oversimplification. • Dominoes and books fall once, one way, and in a straight line; electrons and atoms vibrate continuously in all directions all the time. • The difference in size between electrons and atoms is much greater than the size difference between dominoes and books.	
Reflection	**Conclusion**	Metals conduct heat well because they have free electrons; wood, plastic, and cloth are poor conductors as they lack free electrons. Was this concept understood when the analogy was demonstrated once or twice?
	Improvements	Did I spend enough time building the phenomenon of conductivity? Were the students receptive to the analogy?

The Dominoes and Books Analogy for Conduction of Heat (Continued)	
	Did I carefully negotiate the shared and unshared attributes, and did we draw a suitable conclusion?
Science Content Standard B, Physical Science, Grades 5–8: "Properties and changes of properties in matter; Transfer of energy." The Dominoes and Books Analogy shows that conduction is a "change [that] involves energy transfer" and that substances have characteristic properties such as conductivity (NAS, 1996, p. 154–155).	
Suggested teaching strategies	Prepare for the analogical explanation by having students assess a variety of objects for coldness, establish that coldness is a function of conductivity, and demonstrate the analogy when students ask *how* and *why* some materials are good conductors and others are not.
Resources	Thermometers, 20 similar sized books (e.g., encyclopedia set). Two boxes of dominoes.
Applications	This is suitable for Grades 5–8 and is a useful and needed explanation in inquiry science on energy or heat topics.

The Gravity Warps Space-Time Analogy for Bending Starlight

Einstein's 1915 General Theory of Relativity predicted that very large objects like the sun should curve space-time. This means that the sun's powerful gravity should change the direction of photons (light rays) that pass close by. The closer light rays are to the sun, the stronger the effect. The idea was received with skepticism; but the theory and its math were sound and the prediction was clear: light rays will change direction when they pass through intense gravitational fields that curve space-time.

Scientists argued about the prediction, and the best way to deal with the idea was to test it. Arthur Eddington (1922) planned to measure the deviation of starlight as it passed close to the sun. But he had a problem: the star's light needed to skim past the sun and still be observable on Earth and its deviation measured. But you can't normally do this. The sun is so bright that stars cannot be seen in daylight, least of all ones very close to the sun.

Eddington (1922) knew that stars almost in line with the sun can be seen during a total eclipse. So if the sun was blanked out, it would be possible to measure where a star appeared to be, compared to where astronomers knew it should be (remember, the sun moves relative to the stars). If Einstein was right, the difference between the apparent and calculated position should match the predicted relativistic deviation.

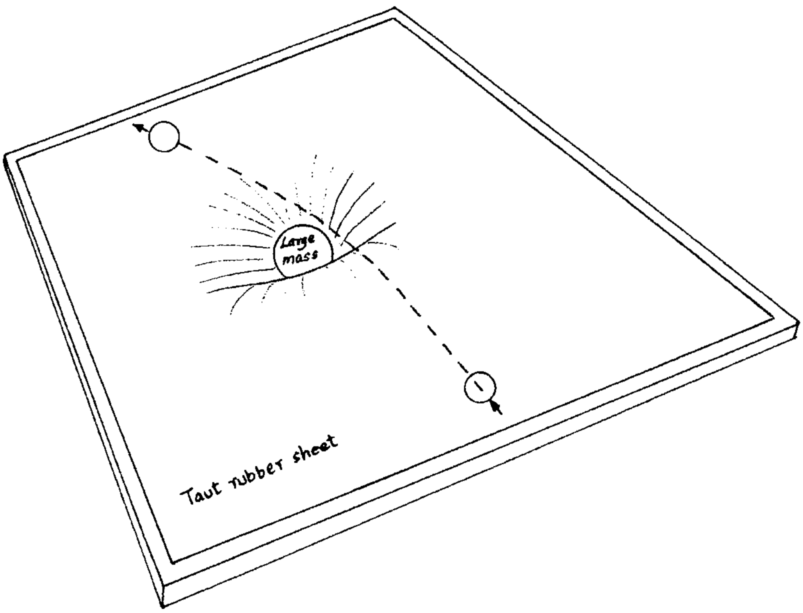
In 1919 Eddington went to West Africa where an eclipse was total, and he measured the position of a star almost in line with the sun and compared it to where it should be. Within the limits of experimental error, the deviation matched the prediction. "Einstein's theory is completely confirmed. The predicted displacement was 1".72 and the observed 1".75 ± .06" (Eddington as quoted by Bronowski, 1973, p. 254; Eddington, 1922, pp. 110–122).

We just can't demonstrate the change in direction of a ray of light as it passes a massive object like the sun. And eclipses are rare. Thus a model or analogy is important and useful. The analogy is best explained using a diagram (see Figure 8.2).

The flexible sheet is a crude analogy for space-time. The change in direction of the rolling ball is much greater than the change in direction experienced by a light ray passing a massive object like the sun.

Like most analogies, it is important to discuss with students ways in which the analog (the rubber sheet distorted by a heavy ball) is *like* the target and the ways in which it is *unlike* it. Remember that the difference in the scale of the sun and a photon is far greater than the difference between a large stationary ball and a smaller rolling ball.

Figure 8.2 A Rolling Ball Changes Direction as it Rolls Past a Heavy Ball That Distorts a Flexible Sheet



The Gravity Warps Space-Time Analogy for Bending Starlight		
Focus	**Concept**	A gravitational field is not a mysterious force of attraction between masses but is a feature of space itself. All objects modify or curve the space around them. Very large objects modify the path of nearby objects and light itself (photons).
	Students	Students will be aware that if they try to run across a downhill slope, their path will deviate down the slope. The same happens if they try to roll a ball across a slope—it bends downhill.
	Analog	This analogy should be demonstrated. A large sheet of thin plastic or rubber sheeting (up to 1m square) is stretched across a frame (Figure 8.2). A lead sinker is placed in the center of the sheet to make a depression. A small ball (marble) is rolled across the sheet so that it passes near the large mass. The students can see its path bend toward the large mass.
Action	**Likes—Mapping the Analog to the Target**	
	Analog—Heavy ball on flexible sheet	**Target—Large objects warping space**
	Flexible sheet of plastic or rubber	Space-time
	Lead sinker or heavy ball (baseball)	Sun or large star
	Depression in the plastic or rubber sheet	Curved space-time near massive object
	Curved trajectory of rolling marble	Deviation in the path of light past a massive object
	Marble rolling down slope of the depression	Gravitational field effect on space-time

<table>
<tr><th colspan="3">The Gravity Warps Space-Time Analogy for Bending Starlight (Continued)</th></tr>
<tr><td rowspan="2"></td><td colspan="2">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="2">• The flexible sheet is two-dimensional; space is three-dimensional.
• The magnitude of the effect in the analogical model is much greater than that experienced in gravitational fields.
• A marble is much larger than a photon and, unlike the photon, it has mass</td></tr>
<tr><td rowspan="2">Reflection</td><td>Conclusion</td><td>Was the demonstrated analogy convincing? Could the students make the link between the two-dimensional sheet and three-dimensional space? Did they need other analogies (ball rolling across a slope) to visualize the effect of curved space-time?</td></tr>
<tr><td>Improvements</td><td>Vary the size of masses and elasticity of sheet. Was more discussion required? Is this analogical model best used as an advance organizer, an embedded activator, or to summarize the concept?</td></tr>
<tr><td colspan="3">Science Content Standard B, Physical Science, Grades 9–12: "Interaction of matter and energy." This analogy involves motion and forces, gravity and matter-energy interactions (NAS, 1996, p. 180–1). The Gravity Warps Space-Time Analogy explains mass-energy interactions that support the idea that relativity is more universal than Newton's laws.</td></tr>
<tr><td>Suggested teaching strategies</td><td colspan="2">Demonstrate a marble rolling past a heavy ball depressing a plastic or rubber sheet. Role-play demonstrations could include a student running past a group of students who grab the passing student, pulling the student toward them to change the running student's path. Or have students run across a downhill slope; their paths will curve down the slope. Another analogy is the way a young man's path deviates toward a group of girls.</td></tr>
<tr><td>Resources</td><td colspan="2">Plastic or rubber sheeting, frame, large mass, small ball or marble. Description of the fact that large masses curve space-time and explanation of Eddington's (1922) experiment and its success. Take care not to claim that Eddington's experiment proved the general theory of relativity—it only provided strong supporting evidence.</td></tr>
<tr><td>Applications</td><td colspan="2">High school physics.</td></tr>
</table>

The Supernova Cola Analogy for Exploding Stars

Large stars end their life with a cataclysmic bang. This bang is called a supernova. A star of about 2 solar masses and upward produces so much energy and light when it dies that it momentarily outshines the galaxy in which it resides. Remember that galaxies like ours (the Milky Way) contain about 100,000,000,000 stars (or suns). A large supernova outshines all of these for a few moments.

A star greater than 1.5 solar masses (the Chandrasekhar limit) collapses into a black hole. Middling stars, above 1.5 solar masses, turn into neutron stars, and many of these are pulsars (stellar lighthouses, or better, stellar radio stations). Our sun will not blow up this way—it will turn into a red giant and then a white dwarf.

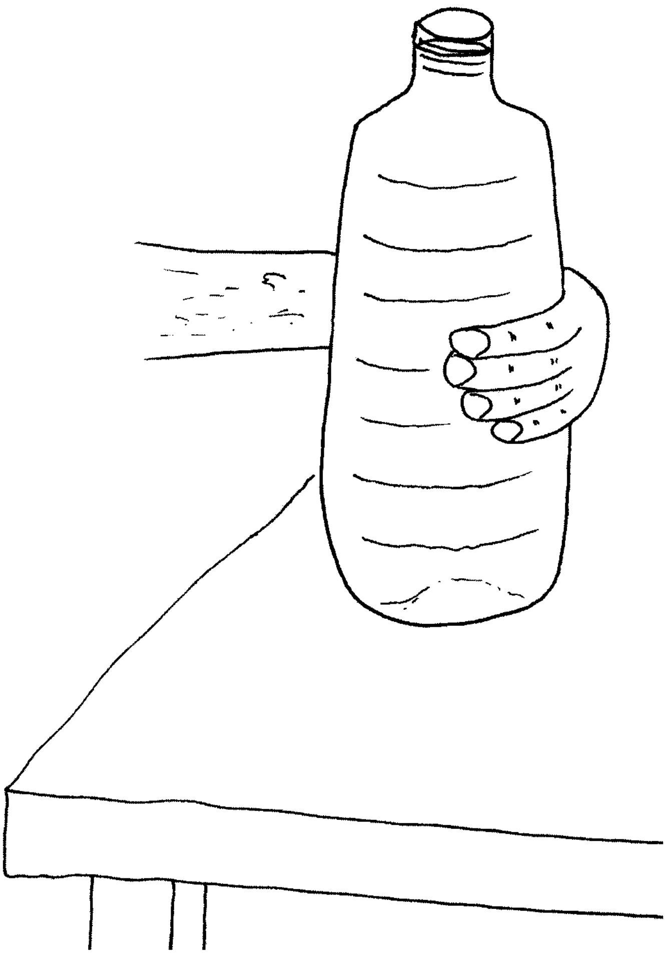
In a few milliseconds at its life's end, a star exceeding the Chandrasekhar limit collapses to roughly one one-hundred thousandth of its diameter. All the outer gas is blown away as a nebula, and the inner core collapses to become a neutron star. If our sun were to collapse this way (it's a bit too small to do so), it would shrink from approx 1,500,000km diameter to about 15km diameter.

The power that blows off the outer gas and crunches the inner core into a neutron star comes from the gravitational collapse that occurs when a star runs out of energy. This happens when most of the silicon fuses into iron. At this point, no fusible fuel is left to maintain the outward radiant energy pressure that balances the inward-acting gravity. The star loses its equilibrium and collapses on itself. The imploding shock wave (driven by intense gravity) hits the brick wall of maximum crunch (density) and bounces back outward, blowing away all the noncore gases. This is the stuff that rocky planets are later made of.

We can demonstrate a shock wave's power using a cola bottle (Figure 8.3). Fill the cola bottle with water, hold it in your hand 300–400mm above the bench, and bang it down bottom first on the bench. The water suddenly decelerates, creates a shock wave that continues on, hits the bottom, rebounds, and blows much of the water up and out the spout. Take care and use only a strong plastic bottle. You may need a raincoat.

This model can also be used to demonstrate momentum and longitudinal waves.

Figure 8.3 The Supernova Cola Analogy for an Imploding Star



<table>
<tr><th colspan="3">The Supernova Cola Analogy for Exploding Stars</th></tr>
<tr><td rowspan="3">Focus</td><td>Concept</td><td>Shock waves are immensely powerful. Shockwaves occur when bombs go off, earthquakes happen and stars blow up as supernovas. Students are not familiar with wave power—they have heard of tsunamis, but few have seen the power of a small shock wave, much less a stellar one.</td></tr>
<tr><td>Students</td><td>Students are familiar with the fact that if you bang an open can of cola or a full cup down on a table, some of the liquid spurts out the top.</td></tr>
<tr><td>Analog</td><td>Exaggerating the experience shows what shock waves can do. If you bang a full bottle of cola (with the lid off) down on a solid bench, much of the liquid is ejected out the spout. You bang the bottle downward, but the liquid takes off in the opposite direction. Why? Because the liquid suddenly stopping moving downward generates a shock wave that reflects off the bottom of the bottle and blows the liquid upward. This is like a star blowing up when it runs out of energy and collapses inward.</td></tr>
<tr><td rowspan="8">Action</td><td colspan="2">Likes—Mapping the Analog to the Target</td></tr>
<tr><td>Analog—Cola bottle fountain</td><td>Target—Supernova explosion</td></tr>
<tr><td>Plastic cola bottle</td><td>Star bigger than our sun</td></tr>
<tr><td>Cola in the bottle</td><td>Star's gases (mostly the outer half)</td></tr>
<tr><td>Rapid downward motion</td><td>Star's gases collapsing under intense gravity</td></tr>
<tr><td>Shock wave generated when bottle stops moving</td><td>Shock wave generated when gases can collapse no further</td></tr>
<tr><td>Shock wave reflected off bottle's bottom</td><td>Shock wave reflected off maximum density</td></tr>
<tr><td>Cola blown out of the top</td><td>Gases blasted off the star's outer half</td></tr>
</table>

The Supernova Cola Analogy for Exploding Stars (Continued)		
	Unlikes—Where the Analogy Breaks Down	
	• Cola is a cool liquid; stars are made of very hot gases (or plasma). • Stars are many orders of magnitude bigger than a bottle of cola. • Cola just sprays out into the air; star gases become a nebula and can form planets.	
Reflection	**Conclusion**	Was the demonstration successful, and could the students visualize the downward momentum reflecting off the bottom of the can or bottle and blowing the cola upward? Can you bang the bottle down fast enough?
	Improvements	Should we play with ropes and slinky springs to show wave reflection before doing the cola bottle experiment? Can we apply these wave reflection concepts to tsunamis? Videoing an excellent cola demonstration and replaying it in slow motion will help.
Science Content Standard B, Physical Science, Grades 9–12: "Interactions of matter and energy." This analogy focuses on motion, forces, and gravity (NAS, 1996, pp. 180–181). The Supernova Cola Analogy demonstrates that when a star's forces are unbalanced, parts of it explode and are blown away.		
Suggested teaching strategies	Establish that some stars blow off much of their mass as nebulae. Play with ropes and slinky springs and show that waves reflect. Carefully prepare and conduct the banged-down cola bottle experiment. Carefully map the process to star implosion. A videotaped version of the experiment is useful at this point.	
Resources	Supernova and nebula diagrams, cola bottle full of cola or water, solid bench, strong student or teacher, video camera.	
Applications	Astrophysics in high school; for showing the power of wave reflections	

The Matches, Mousetraps, and Dominoes Analogies for Nuclear Fission

Nuclear fission belongs to the group of submicroscopic concepts that are best explained by analogy. Three analogies are popular: the block of matches, the mousetraps in an aquarium, and the lines of dominoes (Hewitt, 1999, p. 629).

When a high-speed neutron collides with a uranium-235 (U-235) nucleus, the new nucleus becomes unstable, deforms, and splits into krypton-91 + barium-142 + 3 high-speed neutrons. If, on average, one of these neutrons collides with another U-235 nucleus and it splits, then fission is sustained. This is how a nuclear reactor works. However, if two of the neutrons collide with two atoms of U-235, then one fission becomes two, two become four, and the process spreads exponentially. This is what happens in an atomic bomb. In a nuclear reactor, the U-238 is enriched so that it contains 3%–4% U-235, and at this concentration, the maximum rate is just over one neutron captured per fission. The reaction can run out of control (e.g., Chernobyl), but the fission rate cannot turn into a bomb (e.g., Hiroshima). If 90% of the uranium is U-235, an explosive chain reaction is possible.

If you stick 100 matches into a block of plasticine so that the match heads are 5mm apart and you ignite the match on the corner, the whole lot bursts into flame (see Figure 8.4). Take care or you can get burned. Do this in a sand tray, and of course be vigilant for the students' safety. Many children have done this by striking the end match in a book of matches—it all catches fire.

If you set 30–40 mousetraps and place them side by side in a small, empty aquarium, you can simulate a chain reaction (see Figure 8.5). Roll up 100, 10cm squares of paper and place 2–3 on each mousetrap. The paper ball should sit on the wire U-shape—the piece that springs over and hits the mouse. When all the traps are set with paper balls, throw more paper balls into the aquarium until one sets off a trap. Many other traps will be set off in a chain reaction. This analogy is better than the matches analogy because not all the mousetraps are set off.

Branching lines of dominoes also are a useful analogy for nuclear fission. The advantage is that students can make their own models of fission, and this model is very safe. All you need is 1–2 sets of dominoes. See Figure 8.6.

Figure 8.4 The Matches Analogy for Nuclear Fission

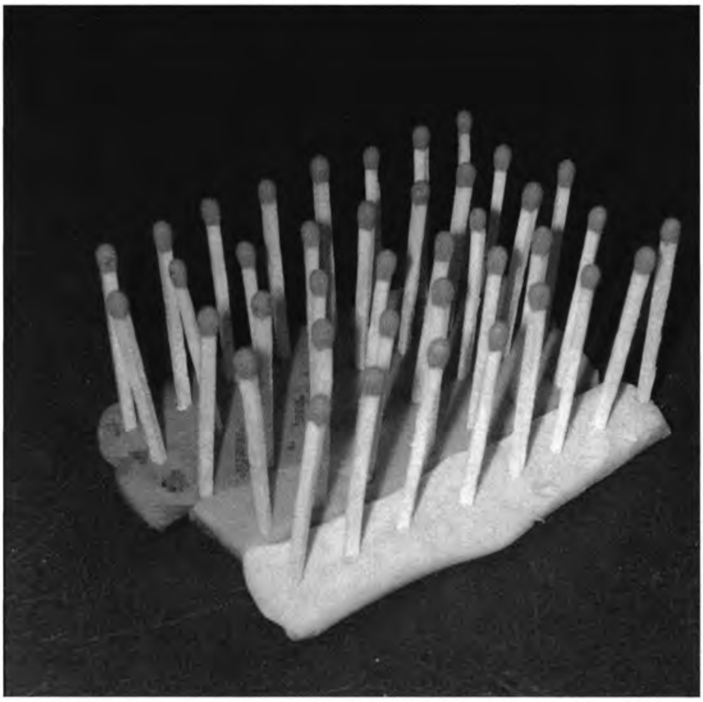


Figure 8.5 The Mousetrap Analogy for Nuclear Fission

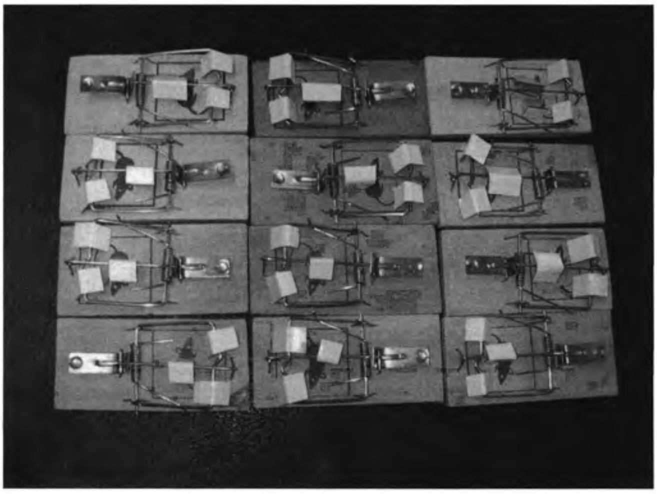
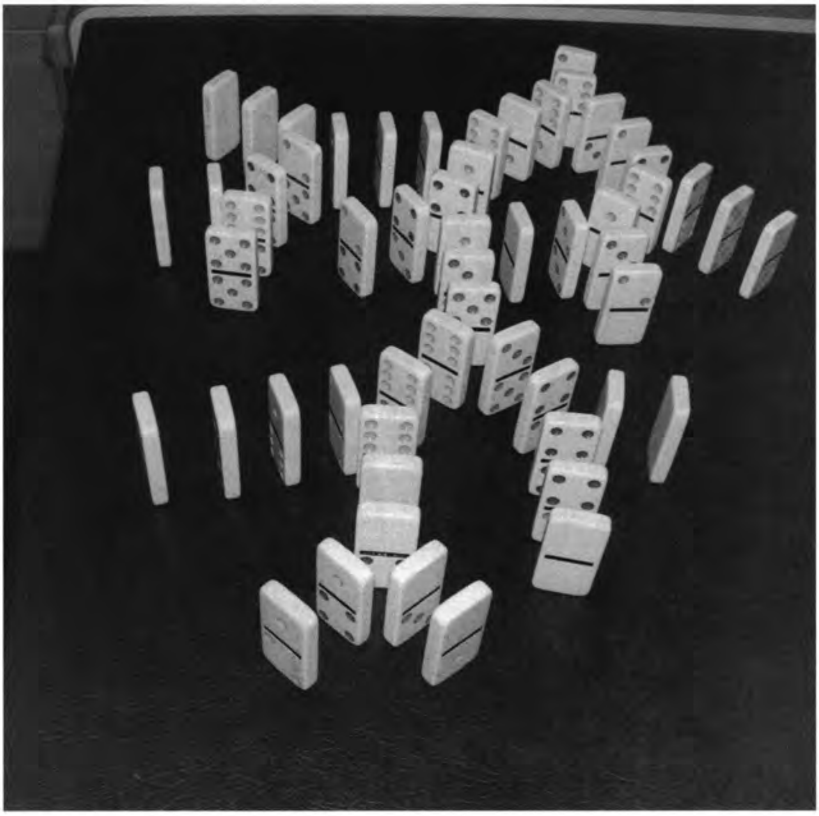


Figure 8.6 The Dominoes Analogy for Nuclear Fission



The Matches, Mousetraps, and Dominoes Analogies for Nuclear Fission		
Focus	**Concept**	Nuclear fission and chain reactions are nonobservable but key concepts—students are surprised how quickly an atomic reaction can spread. The reaction's speed and extent helps explain the vast amount of energy that can be released.
	Students	Students are interested in atomic bombs and nuclear power plants. Modeling a chain reaction is a great teaching moment. Children who have accidentally lit a book of matches know the power of a chain reaction.

The Matches, Mousetraps, and Dominoes Analogies for Nuclear Fission (Continued)		
	Analog	Ignition spreads rapidly among closely packed match heads—this is like an exponential chain reaction. The same happens when one mousetrap among 30–40 traps goes off. You can liken falling dominoes to a chain reaction, especially if the dominoes branch out like a tree.
Action	**Likes—Mapping the Analog to the Target**	
	Analog—Matches, mousetraps, and dominoes	**Target—U-235 and neutrons**
	Matches can ignite rapidly.	U-235 hit by a neutron splits into pieces immediately.
	Matches must be close to ignite each other.	U-235 atoms must capture a neutron.
	Match ignition spreads exponentially.	U-235 fission spreads exponentially.
	Energy is released.	A huge amount of energy is released.
	Mousetraps are set off when bumped.	U-235 fissions when hit by a neutron.
	Close mousetraps can set off each other.	Close U-235 atoms can capture a neutron.
	Balls of paper	Neutrons
	Unlikes—Where the Analogy Breaks Down	
	• There are many, many more U-235 atoms than matches, mousetraps, and dominoes—the analogy is a gross oversimplification. • U-235 atoms release 3 neutrons; matches, mousetraps, and dominoes mostly affect just one other object.	
Reflection	**Conclusion**	Summarize with a conclusion like, "Nuclear fission and chain reactions are like one match's ignition spreading to ignite all the nearby matches." Ensure that students know where this analogy breaks down because spectacular analogies often mask the unshared attributes.

The Matches, Mousetraps, and Dominoes Analogies for Nuclear Fission (Continued)		
	Improvements	Do I need just the matches analogy or should I perform two analogies—matches to show how a fission bomb works and the dominoes to show how a nuclear power reactor is similar but nonexplosive.
Science Content Standard B, Physical Science: Grades 9–12, "Interactions of matter and energy" (NAS, 1996, p. 180). The Matches, Mousetraps, and Dominoes Analogies demonstrate a chain reaction in a critical mass of fissile material. Mass is converted to energy, but the matter-energy sum remains constant.		
Suggested teaching strategies	Ask if students have ever accidentally ignited a book or box of matches. Discuss chain reactions and how they can spread rapidly—add a video of an explosive grass fire. Take great care with the matches demonstration (do a risk analysis) and link it to the mousetraps or dominoes analogy. Discuss atomic bombs and nuclear reactor differences.	
Resources	Plasticine, 100 matches, aquarium, 30–40 mousetraps, 100 paper balls, several boxes of dominoes.	
Applications	Suitable for students in Grades 9–12 and is a useful and needed explanation in inquiry science.	

The Eye Is Like a Camera Analogy

The eye is like a camera in some telling ways (see Glynn, 1991) and is featured in a number of science books. Two assumptions are often made by teachers when this analogy is used: (1) that students know how cameras work and (2) that students understand image formation with pinholes and convex lenses. This was a reasonable assumption when cameras were simple, but that is no longer the case. Digital and video cameras are a world away from simple 35mm cameras.

Students will have prior knowledge of camera optics only if they have made a pinhole camera and had experience with lenses that form real images of lightbulbs and candle flames. It is important that students understand the optics of simple image formation. Without pinhole camera or image formation with convex lenses experience, the eye analogy should not be used. It is arguable whether the camera teaches about the eye or the eye teaches about the camera.

The prior conceptual knowledge that students need can be summarized as follows:

- Rays of light actually converge on the fine detail of an in-focus real image. For example, images are formed when lenses cause rays of light to converge onto a point on a screen (e.g., overhead projector).
- Only light sources can produce focused images (e.g., candle flames, lightbulbs, intense light through overhead transparencies, data projectors).
- Light rays are bent in an orderly way as they pass through convex lenses.
- The following table shows some of the ways a camera's functions can be used to teach about the eye.

Ways in Which a Camera Is Like an Eye

Camera Structure or Function	*Eye Structure or Function*
Convex lens focuses light on film.	Cornea and lens focus light onto the retina.
Lens changes position to focus on near and distant objects.	Lens changes shape to focus on near and distant objects.
Aperture size controls exposure brightness.	Pupil controls brightness of light on the retina.
Black interior prevents multiple reflections.	Black interior prevents multiple reflections.
Lens cap protects the lens.	Eyelids protect the cornea.
Image captured on film or chip.	Image captured on the retina.

Ways in Which a Camera Is Unlike the Eye

Camera Structure or Function	*Eye Structure or Function*
One lens at the front of the camera	Two lenses—cornea at the front (not adjustable) and adjustable lens behind it
Captures single or repeated images	Captures continuous images
Limited range of light brightness	Works in vast range of brightness

The Eye Is Like a Camera Analogy		
Focus	**Concept**	Both the camera and the eye form images (on film and the retina, respectively). Real images are formed when light rays from a source point focus on an image point. This difficult concept can be demonstrated using a Hodson light box and thin convex lenses.
	Students	Do students understand how images are formed? Have they seen images of lightbulbs or candle flames in a pinhole camera? Are they familiar with cameras and know how they work?
	Analog	Light rays from a luminous or illuminated object passing through a convex lens can be focused onto a screen, film, or retina. This happens in both cameras and eyes.
Action	**Likes—Mapping the Analog to the Target**	
	Analog—Camera	**Target—Eye**
	Convex lens focuses light on film.	Cornea plus lens focus light onto the retina.
	Lens moves to focus on near and distant objects.	Lens shape changes to focus on near and distant objects.
	Aperture size controls exposure brightness.	Pupil controls brightness of light on the retina.
	Black interior prevents multiple reflections.	Black interior prevents multiple reflections.
	Lens cap protects the lens.	Eyelids protect the cornea.
	Image captured on film or chip.	Image captured on the retina.
	Unlikes—Where the Analogy Breaks Down	
	• The eye has a fixed lens (the cornea) and a variable lens, whereas a camera can have 6–10 differently shaped lenses in its lens system. • Cameras capture single or repeated images; the eye is a continuous imaging device.	

The Eye Is Like a Camera Analogy (Continued)		
	• The eye responds to a wider range of brightness than cameras; however, some charged couple device cameras are becoming more eyelike; especially when the image is transmitted along a wire (like the optic nerve).	
Reflection	**Conclusion**	Was the analogy structurally and functionally convincing? Were diagrams of eyes and cameras sufficient or do students need to make model cameras and dissect eyes (or take models apart)?
	Improvements	Depending on the age and sophistication of the students, is it useful to compare the structure and function of digital cameras to the eye. Which analogy works best: the camera is like the eye or the eye is like the camera?
Science Content Standard B, Physical Science, Grades 5–8: "Transfer of energy," light interacts with matter (NAS, 1996, p. 155) and Content Standard C, Life Science: Grades 9–12: "Matter, energy and organization in living systems" (p. 186). The Eye-Camera Analogy shows how light rays are bent to form images.		
Suggested teaching strategies	Students should be familiar with convex lenses. They could make pinhole cameras and model eyes (round-bottomed flasks with convex lens stuck onto the front and filled with fluoroscein solution). An eye dissection could be added. At some stage the comparison between the camera and the eye should be elaborated. Eyes and cameras are analogies of each other.	
Resources	Model eye, materials to make model eye, cow's eye, dissection equipment, a selection of cameras (pinhole, box, SLR, digital, video).	
Applications	High school.	

The Pair of Wheels Analogy for the Refraction of Light

Mrs. Kay was using a light box to show that rays of light change direction when they pass from air to glass and vice versa. When light entered the block vertically, it passed straight through without bending; when it entered the glass obliquely (top image of Figure 8.7), it bent to the left and when it left the glass it bent to the right.

The concept states that when a ray of light passes from a less dense to a more dense transparent substance, the ray of light bends toward the normal. When a ray of light passes from a more dense to a less dense substance, it bends away from the normal. Mrs. Kay went on to say,

> Let me show you an analogy. I'm going to coat this pair of wheels with orange fluorescent paint. The wheel tracks will represent the ray of light. The wheels are like the two edges of the ray of light as it starts off; it's deliberately wider because it's hard to see the reason for the bending if it's too narrow [she points to the light ray bending through the glass block]. When the track's wider it's easier to see the reason for the bending.
>
> First we'll roll the wheels from the paper onto the carpet at right angles. The wheels are like the ray of light going straight through the block along the normal [path]. Push it straight . . . both wheels slow down at the same time, so it doesn't change direction. It's the same with a light ray; if the light ray goes through at right angles, it slows down, but it doesn't change direction.
>
> Now push the wheels . . . so the wheels roll from the paper onto the carpet at an angle. . . . See, it's bent, and the light did much the same thing, didn't it? When the light passed through our block at an angle, the light also bent. Why does it bend like that?

Discussion:

Sally: When the wheel is on a smooth surface, it's going faster.

Mrs. Kay: It's to do with speed. That's the point I wanted to make. When the wheels cross from the card to the carpet, which wheel slows down first?

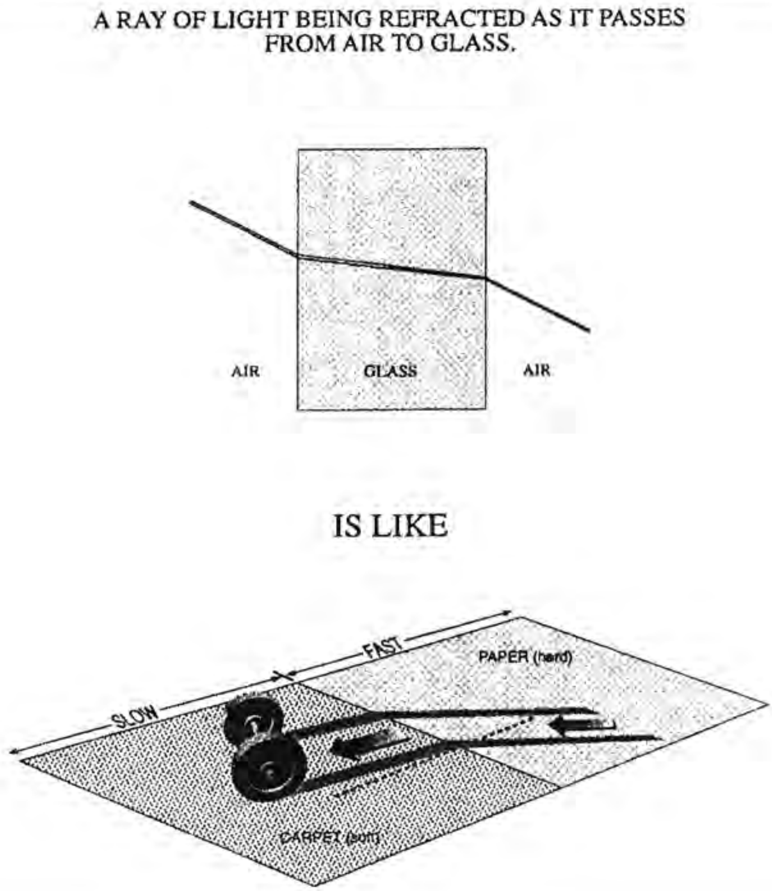
Fiona: The one on the carpet.

Mrs. Kay: The one going onto the carpet slows down first because there's more friction on the rough surface. If you can think of the ray of light as being not quite as thin as it looks, one edge of the light would hit the block before the other side.

Beth: Yes. Yes.

Mrs. Kay: It's the same with light: one edge of the ray slowed down before the other, so the wheel that hit the carpet first slows down first, so it's covering less distance than the faster one

Figure 8.7 The Pair of Wheels Analogy for Refraction of Light



still on the paper, and when that one hits the carpet as well, the lines become parallel again because they return to the same speed. So the path bends because the wheels and the light travel more slowly in a dense medium, or in this case, on a rougher surface.

<table>
<tr><th colspan="4">The Pair of Wheels Analogy for
the Refraction of Light</th></tr>
<tr><td rowspan="3">Focus</td><td>Concept</td><td colspan="2">Students are familiar with the bending of light as it passes through glass or water. Refraction is easily demonstrated with a glass block, a prism, and a light box. The phenomenon itself, however, is difficult to explain.</td></tr>
<tr><td>Students</td><td colspan="2">Students may be aware that light is wavelike, and they may have seen waves change direction at the beach or in a ripple tank. They may know that this bending is related to waves slowing down or speeding up. Some students will confuse reflection of light and refraction of light.</td></tr>
<tr><td>Analog</td><td colspan="2">Many students have experienced the change of direction that results when one wheel of a stroller, toy car, or car rolls off a hard surface onto a soft surface, like sand, carpet, or grass. The change of direction occurs because the wheel on the hard surface rolls easily while the one on the soft surface slows down. This phenomenon can be demonstrated (and practiced by the students) by rolling a pair of Lego wheels obliquely from a hard surface onto a softer surface. As one wheel slows, the pair of wheels changes direction. To show the change of direction, coat the wheels with bright poster paint.</td></tr>
<tr><td rowspan="5">Action</td><td colspan="3">Likes—Mapping the Analog to the Target</td></tr>
<tr><td colspan="2">Analog—Wheels</td><td>Target—Refracted light</td></tr>
<tr><td colspan="2">Wheel tracks</td><td>Ray of light</td></tr>
<tr><td colspan="2">Perpendicular path shows no deviation</td><td>Vertical ray does not change direction</td></tr>
<tr><td colspan="2">Oblique path bends toward vertical</td><td>Oblique ray bends toward normal</td></tr>
</table>

<table>
<tr><th colspan="3">The Pair of Wheels Analogy for the Refraction of Light (Continued)</th></tr>
<tr><td rowspan="4"></td><td>Tracks change direction as one wheel slows

Wheels slow because the carpet increases friction.</td><td>Ray bends because it slows

Light slows because glass is optically more dense than air.</td></tr>
<tr><td colspan="2">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="2">• Light rays are very narrow, whereas wheels are quite wide.
• Two wheels are needed to represent one narrow ray of light.
• Optical density of glass slows the light, whereas friction slows the wheels.
• Photons of light are not connected to each other, but the wheels are joined by an axle.</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td rowspan="2">Reflection</td><td>Conclusion</td><td>Was the model of refraction clear to the students; did they find it convincing? A good test of understanding is whether they can use the model to explain bending away from the normal as light leaves glass.</td></tr>
<tr><td>Improvements</td><td>Do I need to show water waves bending in a tank or on a video before using this model? Should I perform the analogy in both directions? Should I leave them to think through the reverse process?</td></tr>
<tr><td colspan="3">Science Content Standard B, Physical Science, Grades 9–12: "Interactions of energy and matter" (NAS, 1996, p. 180); light waves change speed and direction when they interact with matter. The Pair of Wheels Analogy and its associated modeling is inquiry science and supports Science Content Standard A: "Abilities necessary to do scientific inquiry" use explanations and models and "cognitive . . . skills [to formulate] scientific explanations" (p. 175).</td></tr>
<tr><td>Suggested teaching strategies</td><td colspan="2">If there is enough equipment, let the students repeat the analogy in groups. Show bending toward the normal as a demonstration and ask the students to find what happens when they roll the wheels the opposite way. Be sure the wheels turn easily on their axle.</td></tr>
<tr><td>Resources</td><td colspan="2">Light box, square and triangular prisms, paper, and carpet (both A3 size, or about 11.5 by 16.5 inches), poster paint, shallow tray, Lego wheels.</td></tr>
<tr><td>Applications</td><td colspan="2">High school: refraction of light and inquiry: how do we know how phenomena like refraction work?</td></tr>
</table>

Bridging Analogies for the Balanced Forces of a Book on a Table

When holding a book, most people agree that the book applies a downward force (weight) that is balanced by the upward push from their hands. The forces are balanced if the book does not move. When the book is placed on a table, many people say that there is now only one force acting, namely, the downward weight of the book. This alternative conception agrees with Aristotle's idea that objects seek stable and passive positions. The table is like the earth's surface, the place where everything belongs and comes to rest. Newtonian physics insists that stationary objects, like books on a table, do not move because the upward and downward forces are balanced: The table applies an upward force equal to the book's weight.

John Clement (1993) found that "76% of a sample of 112 high school students indicated that a table does not push up on a book lying at rest on it"; but "96% of these students believed that a spring pushes up on one's hand when the hand is pushing down on the spring" (p. 1243). He suggested that knowing that hand and spring forces are balanced could be used to explain why the table must apply a reaction force to a book sitting on it.

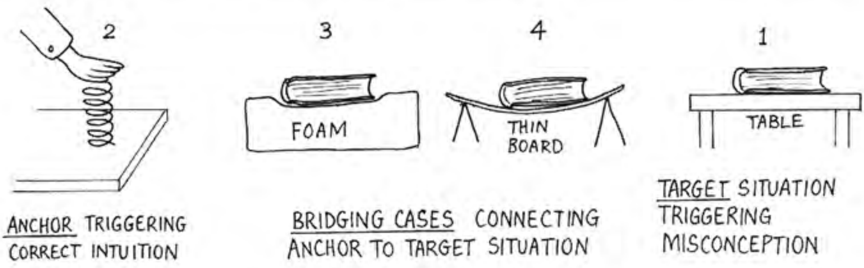
But students don't readily connect the forces they can feel when squeezing a spring with the book sitting on a table. After all, they can feel the spring pushing back on their hand, and the hand and spring tend to move a small amount. The book sits still.

Clement (1993) suggested that a series of analogies would help students connect their experience with their hands on the spring (called the *anchoring concept*) with the problem of the book on the table. The series of analogies he used works like the pillars of a bridge—each holds up a small part of the idea—hence he called the strategy a bridging analogy. The pillars of the bridge are shown in Figure 8.8. Students experience each analogy in order and the result is that most do connect the balanced forces of the hand and spring to the book on the table.

Start with the book-on-the-table problem: is there an upward force from the table balancing the book's weight? When most disagree or are not sure, introduce the anchoring concept using bulldog clips and rubber bands. Students feel their push and pull and the reaction forces. The book on a pillow can be done by the whole class—use freezer zip bags half-full of air and science books. Make the model table using thin plywood and then show how it's like the book on the table. It works for most students.

Bridging analogy strategies can be applied to friction, cells, genes and DNA, particles, concepts in math, and acid-base models, to name a few. When we first met bridging analogies, we thought that they were rare, but examples keep cropping up. Why do they work so well? Because they are scaffolds that help students work from an anchor to an abstract problem solution in small steps.

Figure 8.8 Balanced Forces Between a Book and a Table Is Like the Balanced Forces Between a Hand and a Spring



Bridging Analogies for the Balanced Forces of a Book on a Table		
Focus	**Concept**	Objects like rigid chairs and tables exert an upward reaction force on objects sitting or placed on them. Objects such as books do not move because the upward and downward forces are balanced.
	Students	Most students recognize the balanced forces involved in squeezing a spring or holding up books in their hands and situations where a load deforms its underlying support (e.g., a flexible table or padding).
	Analog	Balanced forces in squeezing a spring and stretching a rubber band act as anchors for sequential analogical supports (book on a cushion or air-filled bag, flimsy table bending under book's weight). In a stepwise way, each analogy bridges (scaffolds) the gap between palpable forces of spring and hand and those of a book on the table and the table, which must be imagined.
Action	**Likes—Mapping the Analog to the Target**	
	Analog—Spring held between fingers	**Target—Book on a table**
	A compressed spring exerts force back on a hand (balanced forces are felt).	Book has downward weight but no deformation can be seen or felt.

<table>
<tr><th colspan="4">Bridging Analogies for the Balanced Forces of a Book on a Table (Continued)</th></tr>
<tr><td rowspan="5"></td><td colspan="2">Stretched rubber band has balanced forces that can be felt.</td><td>Book's weight acts downward on table; table pushes back.</td></tr>
<tr><td colspan="2">Book's weight deforms an air bag; shows balanced forces.</td><td>Book's weight acts downward on table; table pushes back.</td></tr>
<tr><td colspan="2">Flimsy table bends under book sitting on it.</td><td>Table must push back on the book on it.</td></tr>
<tr><td colspan="3">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="3">• The table exerts a reaction force but does not visibly bend under the book's weight. The analogies could be called examples.</td></tr>
<tr><td rowspan="2">Reflection</td><td>Conclusion</td><td colspan="2">Were the bridging analogies carefully sequenced? Do I need to include more examples? Did I let the students tell me how they interpreted the bridging analogies? Did I give them adequate thinking time?</td></tr>
<tr><td>Improvements</td><td colspan="2">Did I demonstrate what the students could have done themselves? Do I need to revisit this idea in later lessons? If bridging analogies worked with reaction forces, can I use them elsewhere for other science concepts, say concepts in mathematics?</td></tr>
<tr><td colspan="4">Science Content Standard B, Physical Science, Grades 5–8: "Motions and forces" (NAS, 1996, p. 154). This analogy helps students understand "forces in equilibrium, especially if the force is associated with static inanimate objects, such as a book resting on the desk" (NAS, 1996, p. 154).</td></tr>
<tr><td>Suggested teaching strategies</td><td colspan="3">This is an excellent example of scaffolding and agrees with Vygotsky's (1986) sociocultural learning theory. In what other situations can effective sets of bridging analogies or examples be strung together?</td></tr>
<tr><td>Resources</td><td colspan="3">Table, book, chair, students, springs, bulldog clips, rubber bands, freezer zip bags, thin plywood and supports</td></tr>
<tr><td>Applications</td><td colspan="3">Middle school where balanced forces are not obvious; understanding action and reaction forces is a desired outcome.</td></tr>
</table>

Electricity Analogies for Current, Voltage, and Resistance

When planning inquiry science, teachers choose topics that are interesting, raise curiosity, and are open-ended. Electricity meets all these criteria and is safe when done with batteries. Building electric circuits therefore is an excellent inquiry context for students in Grades 1–12.

Inquiry Science

There are three ways inquiry science can be open-ended:
Ideally, students should

1. Suggest the problems to study and investigate;
2. Design the experimental methods and collect the data; and
3. Interpret the data and propose some theories and models (Hackling & Fairbrother, 1996).

Building analogical models helps students focus on the concepts being studied. Repeated cycles of proposing, testing, and revising analogical models is authentic science. While some science topics are too far removed from everyday life for students to suggest the problems and methods and interpret the results; electricity is different. Students use various electronic devices, play with battery-powered toys, dismantle flashlights— and some make electric gadgets.

Teachers like electricity because it is cheap to run, the materials are easy to obtain, and students can't hurt themselves with lightbulbs, wires, switches, and batteries. Young students (Grades 1–4) are really excited when their circuits work, and older students (up to Grade 12) are challenged when circuits do unexpected things. Electricity provides opportunities to test many different connections and introduces concepts like voltage, current, and resistance. Making sense of these concepts involves high-level thinking, especially when the students know that they can experiment, see expected and unexpected things happen, try again, and revise their models.

Some of the problems you can encounter when teaching electricity, and the strategies for dealing with them, are described in Osborne and Freyberg (1985) and Driver et al. (1994).

Electric current, voltage, and series and parallel circuit differences are hard to explain, so teachers regularly use analogies and models to help students understand what is happening. Like inquiry activities, analogies work best when the students are involved in the planning and thinking. Learning gains are high when students develop and map their own analogies (Cosgrove, 1995; Zook, 1991), but students need guidance if they are to avoid common alternative conceptions. Electricity analogies mislead students when the analogy is taken too far. This is why it is better to use multiple analogies than stretch only one. This holds for both teacher and student analogies.

Common Electricity Analogies

The analogies and models that appear in the following pages are

1. The Water Circuit Analogy for a simple series circuit
2. Voltage is like water pressure
3. The analogy of doors in the assembly hall for parallel circuits
4. The Continuous Train Analogy to show conservation of current
5. The student circuit that runs on M&M's
6. The Shared Water Flow Analogy for multiple lightbulbs and motors in a series circuit
7. The Field Analogy for multiple lightbulbs in a series circuit

Three of these analogies—the water circuit, continuous train, and M&M's—are multiple analogies that address the common alternative conception that current is used up in electric circuits, as has been touched on earlier. Many science teachers have studied this problem (e.g., Grayson, 1996; Tasker & Osborne, 1985) and the analogies we have chosen can change students' conceptions. Some of the analogies are our own; others we've collected and brought together in this book.

What Students Know

Students know that batteries in flashlights, toys, and handheld electronic games go flat. They know that something is used up, and when they look for something to have been consumed, what's more obvious than the electric current flowing around the circuit? It's right that students should think that something is used up because batteries have to be replaced or recharged. Consequently, most of our analogies and models are designed to show that the electrons or electric current is conserved rather than consumed. When we say that the energy is used up, we mean it in the sense that the battery loses energy. Energy can only be changed into another form; it's never used up. It's important to discuss and clarify the expressions we use.

But students are hard to convince, and that's good, because that's how they learn and remember concepts. Effective analogies that show that current is conserved and energy is converted also need to be accompanied by explanations of why the current decreases as battery energy is used up.

The Water Circuit Analogy for Electric Current

Think about this conversation between John and his teacher. Miss Davis asks John, "Can you put these [electricity terms] and ideas together and explain how an electric circuit works?" John: "Ah, no. That's the problem. I can't get a picture in my head of how this electricity stuff works" (Glynn, 1991, p. 186). As they talked, Miss Davis reminded John of the water circuit in the class aquarium, and she used the water circuit as an analogy for an electric circuit. Instead of retelling the whole story, we have sketched the aquarium water circuit and summarized Miss Davis's conclusions.

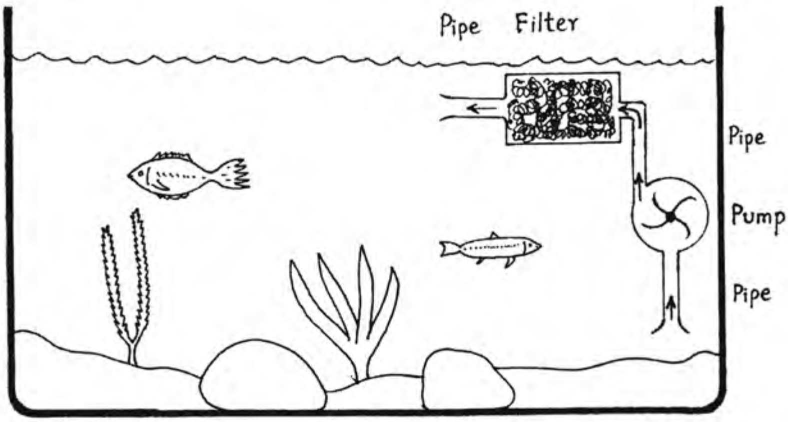
Figure 8.9 models a classroom aquarium—the pipes, pump, and filter all enlarged. The pump draws water from the aquarium through a pipe and pushes the water under pressure through another pipe into the filter containing a fine mesh that resists the water flow. The water flows through another pipe back into the aquarium.

The aquarium is the familiar object for the analogy and can be replaced by a swimming pool and its filtration system. Both use a closed water circuit that can be understood by the students. If your students cannot visualize the filtration circuit, show them a functioning aquarium, use an overhead transparency, or talk about swimming pool filters.

This is an effective analogy for a simple series circuit, provided the teacher and students realize that water is a liquid substance and electricity is not. Three alternative conceptions can arise from this analogy. Students see a fixed amount of liquid coming out of the pump; they may conclude that a battery produces a fixed flow of electricity and may also come to the following conclusions:

- Electricity will leak out of a switched-on power outlet if no appliance is plugged in to it.
- Two parallel circuits connected to the same battery share the electric current from the battery and each get half the current (in fact, twice as much current flows when two parallel circuits are connected to one battery).
- Two or three lightbulbs in series receive the same current (they do) and will glow equally brightly (they do not, because they share the voltage).

Figure 8.9 The Aquarium Water Circuit Analogy for a Simple Series Circuit



The Water Circuit Analogy for Electric Current		
Focus	**Concept**	Electricity only flows in complete, unbroken circuits. The electron flow is not used up, and work is done as the electricity flows around the circuit.
	Students	Up to 40% of the class may think that current is partly used up in a circuit. Most students have seen an aquarium with a water filter in it. Their teacher may have explained the need to circulate water through a filter to keep the water clean and the environment healthy. They may know how a swimming pool filtration system works.
	Analog	An aquarium filter system draws water in through a pipe, a pump pushes it through another pipe into a filter that resists water flow, and then the water exits through another pipe into the aquarium.

<table>
<tr><th colspan="3">The Water Circuit Analogy for Electric Current (Continued)</th></tr>
<tr><td rowspan="12">Action</td><td colspan="2">Likes—Mapping the Analog to the Target</td></tr>
<tr><td>Analog—Aquarium water circuit</td><td>Target—Simple series circuit</td></tr>
<tr><td>Water</td><td>Electricity</td></tr>
<tr><td>Flowing water</td><td>Electric current</td></tr>
<tr><td>Pipes carrying water</td><td>Wires carrying electricity</td></tr>
<tr><td>Pump pushing water (pressure)</td><td>Battery pushing electrons (voltage)</td></tr>
<tr><td>Pump pressure</td><td>Battery voltage</td></tr>
<tr><td>Filter (resists water flow)</td><td>Thin wire in lightbulb—resistance</td></tr>
<tr><td>No water lost</td><td>Current is conserved</td></tr>
<tr><td colspan="2">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="2">• Water is a material liquid; electricity is a flow of charge in an electric field.
• Water can flow in an incomplete circuit; electricity always needs a complete circuit.
• Water flow depends on the pump output and pressure; electric current flow is determined by the entire circuit (the circuit must be looked at as a whole).</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td rowspan="2">Reflection</td><td>Conclusion</td><td>Did the students understand the ways a water circuit is like an electric circuit and the ways in which it is different? Do I need to check their knowledge next class? Did I emphasize the need to see the circuit as a whole?</td></tr>
<tr><td>Improvements</td><td>Next time, I could set up a working aquarium for the students to examine; I could use the water circuit alongside the students sharing M&M's analogy or the Continuous Train Analogy.</td></tr>
<tr><td colspan="3">Science Content Standard B, Physical Science, Grades 5–8: "Transfer of energy" (NAS, 1996, p. 155); "energy is an important property of substances and . . . most change involves energy transfer" (NAS, 1996, p. 154). The Water Circuit Analogy shows that current is conserved and energy is transformed throughout an electric circuit.</td></tr>
</table>

The Water Circuit Analogy for Electric Current (Continued)	
Suggested teaching strategies	Students make simple circuits: 1 battery + 1 lightbulb; 1 battery + 2 lightbulbs (series & parallel). Agree on what happens. Examine (even set up) an aquarium with water filter—can the students say what is needed to analogize the electric circuit? Prepare cues and questions to compare electric circuit to a functioning aquarium or pool filtration system. Discuss how the water circuit and electric circuits are similar and how they differ.
Resources	Lightbulbs, batteries and wires; aquarium with filtration circuit or parts to make one; overhead transparency.
Applications	Middle school. Best used to develop the concept of complete circuits and current conservation. Most effective when used as part of a set of multiple circuit analogies.

The Water Pressure Analogy for Voltage

Voltage in electric circuits is difficult to visualize and explain. Batteries are labeled in volts: 1.5V, 6V, 12V, and so on. This is a measure of the force with which the battery can push electrons around a circuit. Scientists prefer to talk about potential difference (PD) and PD is measured in volts (V). The potential difference between two points in a circuit measures the potential of the current to flow between the points. The higher the PD, the better the current flows. PD is sometimes called *electrical pressure*.

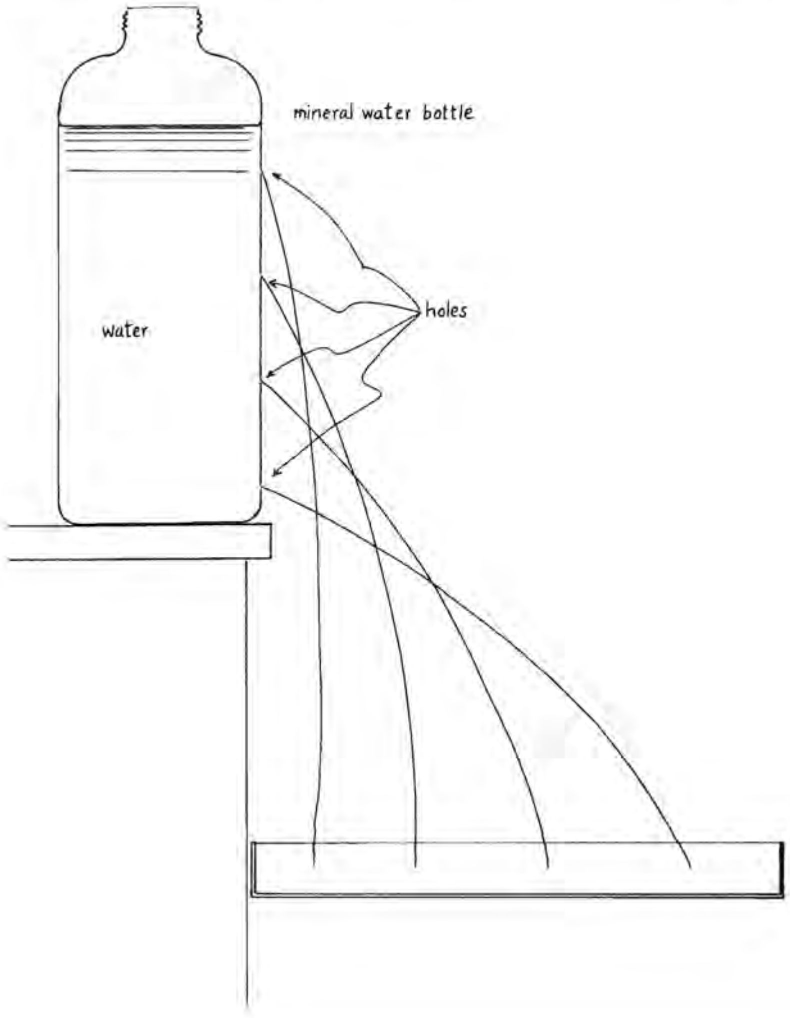
Voltage affects the work an electric current does when it passes through a lightbulb, motor, or heater. If you double the PD with which a current is pushed through a lightbulb, you double the amount of work it does. Likewise, if you have a 12V battery and double the current flowing, you also double the work done or energy released. A circuit's capacity to do work is a multiple of the volts times the amps (the energy released is a multiple of amps × volts × time).

So how do we describe and explain PD (and voltage)?

A common model is The Water Pressure Analogy. Figure 8.10 shows a tall water bottle with holes at four levels. The pressure in the water depends on the depth: If the depth is doubled, the pressure is doubled. The pressure controls the amount and force with which water flows through the holes, assuming all the holes are the same size.

Similarly, if you have a circuit that is driven by a 6V battery, a certain current flows. If you double the PD to 12V, the current doubles (provided the bulb does not blow out).

Figure 8.10 The Water Pressure Analogy for Potential Difference and Voltage



In the water bottle model, the direction of the outflow and how far it spurts can be likened to PD or battery voltage. The greater the depth, the higher the pressure, and greater the flow. Electricity works like this—but remember, electricity isn't a fluid substance.

Another use of this analogy is to compare the bottle to four flashlights—each with one, two, three, or four batteries. This comparison can mislead, however, unless you negotiate the variation in the brightness or the length of time the flashlight will shine. Perhaps this is a problem you could ask the class to work on in groups, report back, and debate the conclusions.

The Water Pressure Analogy for Voltage		
Focus	**Concept**	PD is measured in volts and is difficult to visualize. Understanding PD is crucial when working with electric circuits because it is a key element in Ohm's Law and in energy and work calculations.
	Students	Students are familiar with water pressure and depth, and this concept is easily demonstrated. They know that a hole low down in a tank or bottle leaks water faster than a hole higher up.
	Analog	Different batteries have different PDs (volts). This is like a water tank or bottle with holes at different levels. The greater the PD, the greater the current flow; the deeper the hole, the more water it lets out.
Action	**Likes—Mapping the Analog to the Target**	
	Analog—Water flows out holes at different depths at different rates	**Target—PD (volts) determines circuit current**
	Water tank or bottle	Battery, dynamo
	Hole for water to escape	Battery in a circuit so current can flow
	Deeper the water over the hole	Higher the PD or voltage
	Deeper hole, more water flows	Higher PD, more current flows
	Flow rate proportional to depth	Current flow proportional to PD
	Unlikes—Where the Analogy Breaks Down	
	• The water flow analogy encourages students to think of electricity as a material substance—it is not. • Water flow rates decline as the tank or bottle empties; a battery may demonstrate reduced PD across its terminals but it is not empty.	

The Water Pressure Analogy for Voltage (Continued)		
Reflection	**Conclusion**	Were the likenesses between PD and pressure (depth and voltage) clear? Were middle ability students able to use the analogy to restate the concept of PD in their own words? Did formative assessment help the students map the analogy and recognize where it broke down?
	Improvements	Do I need better cues, questions, and need-to-know information? Should I look for a better analogy next time?
Science Content Standard B, Physical Science, Grades 5–8: "Transfer of energy" (NAS, 1996, p. 155). The Water Pressure Analogy is useful for explaining electrical pressure or PD (voltage) in all or part of a circuit. PD is like water pressure but the analogy breaks down when the fluid flow idea is taken too far.		
Suggested teaching strategies	Students should experience differing currents in circuits with differing PDs (volts); make circuits and develop student models that need to explain PD, then introduce the model. Given the opportunity, students may suggest a depth and pressure model. If you have enough bottles, allow groups to make and measure water flow.	
Resources	Batteries or power packs with different PDs, ammeters, voltmeters, lightbulbs, motors, and bottles with 3 or 4 holes (see Figure 8.10).	
Applications	Suitable for middle school and secondary students. Encourage older students to develop quantitative definitions for PD.	

The Shared Water Flow Analogy

Imagine a crowd of people walking along a two-lane road—there are many pathways for each pedestrian and few people cut across each other's path. The wide road is like a thick wire and electricity flows easily with little resistance. If a short length of the road is narrowed by sewer construction and people can only pass two abreast, this section is like a thin filament in a lightbulb that has a high resistance. Less electricity flows along a thin wire in the same way as fewer people can pass the sewer construction.

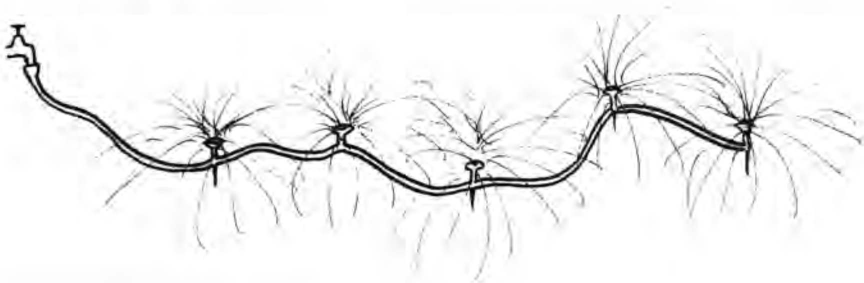
As the flow becomes congested, people jostle and bump each other, and they have to walk faster so everyone can get through. This makes some people hot and angry and is like the thin filament heating up and glowing.

This analogy explains current flow in a one-lightbulb + battery simple circuit; but it does not adequately explain why, in a series circuit, the brightness of each globe diminishes as lightbulbs are added but not more batteries. Analogies that demonstrate a sharing of water flow are sometimes used, but these require great care as they contain strong alternative conceptions. The Shared Water Flow Analogy goes like this:

In summer our neighbor sometimes waters her lawn with a hose that has 3 or 4 sprinklers along its length (see Figure 8.11). If there are 2 sprinklers, the water spurts out 3.5m; if there are 3 sprinklers the water spurts 3m, and for 4 sprinklers, 2.5m. This is a bit like a circuit with 2, 3, or 4 lightbulbs connected in series with a 6V battery. If there are 2 lightbulbs, each glows brightly, if 3, the lightbulbs are medium bright, and for 4 lightbulbs, the light is dull. Sprinklers spray less distance when more sprinklers are on the hose, and when there are more lightbulbs in the circuit, the lightbulbs are less bright. The hose can supply only a fixed volume of water per second, and the battery can supply only a certain amount of energy per second. Increasing the number of sprinklers and lightbulbs means that each gets less water and electrical energy, respectively.

This analogy can mislead because more sprinklers increases the water flow in the hose (the resistance to water flow actually decreases), but in the electric circuit, each bulb delivers less light (because the electricity flow actually decreases with increased resistance). There is another weakness; it does not matter whether the sprinklers on the hose are in series or on side-by-side branches—the flow is the same in each. Lightbulbs in a line (series) glow much less brightly than lightbulbs side by side in parallels.

Figure 8.11 Resistance in a Multilight Series Circuit Is Like Multiple Sprinklers on a Hose



<table>
<tr><th colspan="4">The Shared Water Flow Analogy</th></tr>
<tr><td rowspan="3">Focus</td><td>Concept</td><td colspan="2">When you add lightbulbs to a series circuit, the current flow drops, and the current and energy are shared between the lightbulbs.</td></tr>
<tr><td>Students</td><td colspan="2">Students are familiar with water pressure and may have seen people watering their lawns using a hose with sprinklers placed along it. The sprinklers usually share the water flowing through the hose.</td></tr>
<tr><td>Analog</td><td colspan="2">Water flowing through a hose with 3–5 sprinklers is like a series circuit with 3–5 lightbulbs. Add sprinklers and the diameter of the spray reduces; add lightbulbs and the brightness of all lightbulbs diminishes.</td></tr>
<tr><td rowspan="10">Action</td><td colspan="3">Likes—Mapping the Analog to the Target</td></tr>
<tr><td colspan="2">Analog—Water flow from each sprinkler is an equal share of the water</td><td>Target—Brightness of each globe is an equal share of the energy</td></tr>
<tr><td colspan="2">Sprinkler</td><td>Lightbulb</td></tr>
<tr><td colspan="2">Water spraying out of sprinkler</td><td>Lightbulb glowing</td></tr>
<tr><td colspan="2">Diameter of the sprinkler's spray</td><td>Brightness of the bulb</td></tr>
<tr><td colspan="2">Add sprinklers, spray diameter reduced</td><td>Add lightbulbs, brightness drops</td></tr>
<tr><td colspan="2">Sprinklers share the water flow.</td><td>Lightbulbs share electric current and energy.</td></tr>
<tr><td colspan="3">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="3">• The water flow analogy encourages students to think of electricity as a material substance—it is not.
• Increasing the number of sprinklers on a hose increases total water flow; adding lightbulbs to a series circuit reduces the total current and energy flow.</td></tr>
<tr style="display:none"><td colspan="3"></td></tr>
<tr><td>Reflection</td><td>Conclusion</td><td colspan="2">Did students understand that The Sprinkler Analogy only shows that added lightbulbs share the current and energy in a series circuit? Did they realize that adding sprinklers makes the total water flow increase but adding lightbulbs reduces the total current and energy flow?</td></tr>
</table>

The Shared Water Flow Analogy (Continued)		
	Improvements	Do I need to demonstrate the sprinklers on a hose alongside a comparable electric circuit and show the effects of adding sprinklers and lightbulbs?
Science Content Standard B, Physical Science, Grades 5–8: "Energy is transferred" (NAS, 1996, p. 155); "energy is an important property of substances and . . . most change involves energy transfer" (NAS, 1996, p. 154). The Shared Water Flow Analogy shows that electric current does varying amounts of work throughout the electric circuit. Physical Science, Grades 9–12, benefit from this analogy when it is used to explain Ohm's Law and "moving electric charges" (p. 180).		
Suggested teaching strategies	Students need experience with 2, 3 or 4 lightbulbs in series with a 6V battery to see that increasing the number of lightbulbs leads to decreased brightness. Lead students to the question, Why does this happen? Intuition suggests the sharing of a finite resource, and The Sprinkler Analogy explains current phenomena in everyday terms. The main value of the analogy is its ability to raise the question, Why are the lightbulbs duller than expected? This paves the way for The Field Analogy.	
Resources	6V battery, lightbulbs and wires; hose with 3 or 4 sprinklers—best if sprinklers can be added.	
Applications	Suitable for middle and high school students. Most effective when followed by The Field Analogy.	

The School Gymnasium Analogy for Parallel Circuits

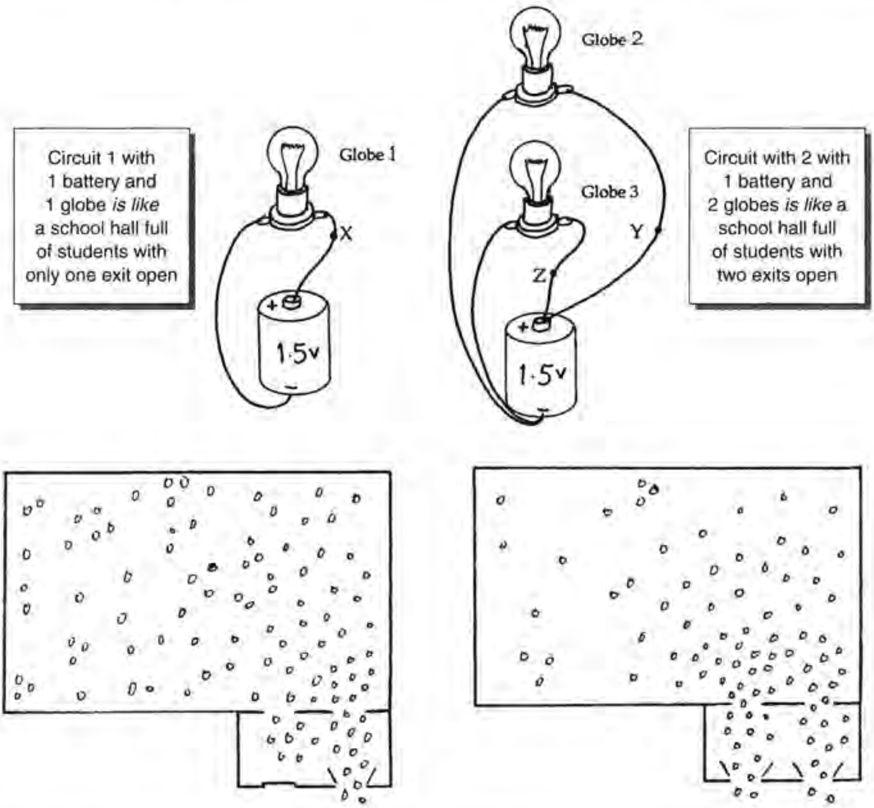
Compare Circuits 1 and 2: 1 battery + 1 globe and 1 battery + 2 lightbulbs in parallel. The lightbulbs are all equally bright, and the battery in Circuit 1 lasts twice as long as the battery in Circuit 2. Why do lightbulbs 2 and 3 glow as brightly as globe 1, and why does the Circuit 2 battery last only half as long as Circuit 1's? The opposite happened when lightbulbs 2 and 3 were connected in series. This can be explained using The School Gymnasium Analogy (see Figure 8.12).

Students can leave the gym with two open exits twice as fast as is possible with only one exit open. This analogy can be modified to have halls with

1 or 3 exits open, to model circuits with 1 and 3 lightbulbs in parallel, *or*

2 or 3 exits open, to model 2 and 3 lightbulbs connected in parallel.

Figure 8.12 The School Gymnasium Analogy for Parallel Circuits



A variation on this analogy can be used to simulate a series circuit (or mixed parallel-series circuits). If there are a series of doors that each line of students has to pass through, the rate of escape drops off—the more doors, the slower the line flows. This is like several lightbulbs connected in a line (in series). The slower flow of students is analogous to the slower the current, the dimmer the lightbulbs.

Alternative Strategy

If you have an imaginative class that has regular experience with gym meetings and that has constructed parallel circuit lightbulbs and wondered why they are brighter than series lightbulbs, they may even suggest this analogy. My Grade 11 class did, and Mark Cosgrove's (1995) Grade 9 students also constructed a similar analogy. Don't underestimate student imagination.

The School Gymnasium Analogy for Parallel Circuits			
Focus	**Concept**	Parallel electric circuits function as independent circuits. Two lightbulbs connected in parallel glow equally bright; each globe receives the battery's full voltage and they divide the current between them.	
	Students	After a school meeting, students can exit the gym twice as fast if two doors are open than if one is open; open three doors and they exit three times as fast.	
	Analog	This is sometimes called the teeming crowd analogy: the rate students leave a school gym depends on the number of doors open—this is like a circuit with lightbulbs connected in parallel.	
Action	**Likes—Mapping the Analog to the Target**		
	Analog—Students leaving a school gym after a meeting	**Target—Parallel circuit lightbulbs receiving the full voltage and dividing the current**	
	Gym full of students for a meeting	Fully charged battery	
	Students exiting through 1 open door	One globe in the circuit	
	Students exiting through 2 open doors	Two lightbulbs connected in parallel	
	Speed of exit through each door the same	Each globe receives same voltage and current	
	2 doors open hall empties twice as fast	2 lightbulbs in parallel, battery runs flat twice as fast	
	Unlikes—Where the Analogy Breaks Down		
	• Two lightbulbs often do not draw as much current as two separate circuits of 1 globe plus 1 battery. • Depending on the number of exits, the emptying rate may be like or not like the circuit. • People stop, talk and jostle each other as they leave a gym; electron flow is regular.		

The School Gymnasium Analogy for Parallel Circuits (Continued)		
Reflection	**Conclusion**	Did the students link the rate of flow from a gym with the flow of electrons in an electric circuit? Do I need another explanation or a supporting analogy next lesson?
	Improvements	Do we need to simulate this in our classroom (if it has two doors)? Can I customize this analogy to our school gym next time I teach parallel circuits?
Science Content Standard B, Physical Science, Grades 5–8: "Energy is transferred" (NAS. 1996, p. 155); "energy is an important property of substances and . . . most change involves energy transfer" (NAS, 1996, p. 154). The School Gymnasium Analogy shows the rates at which electric current flows in series and parallel circuits. Physical Science, Grades 9–12, benefit from this analogy when it is used to explain Ohm's Law and "moving electric charges" (p. 180).		
Suggested teaching strategies	Role-play is an excellent way to establish this analogy's ideas; should I lead the role-play or let the students organize it (class age is a factor here)? Could an older or more able class derive this analogy from their own experiences with circuits and school life?	
Resources	Recent experience with a school meeting; ability to simulate this in the classroom. Overhead transparency diagram of two or three gym setups. Can this be modeled on a recent disaster where people had to escape from a dangerous building (older students only)?	
Applications	Works well with middle school and high school students	

The Continuous Train Analogy for Current Conservation in a Series Circuit

The idea that electric current is used up in an electric circuit is a common belief. After all, batteries go flat or die and flashlights gradually grow dim, and the current decreases with time. The current reduces, say students, because the current returning to the battery is less than the current going to the bulb: hence, current is gradually used up. Tasker and Osborne (1985) found this conception in up to 40% of 10- to 16-year-olds.

Various analogies and models have been used to help students understand that the current out equals current back and that current is never used up in a lightbulb or motor. It is energy that is used up, or better, transferred from the battery to the lightbulb or motor.

A useful analogy to address this intuitive idea is that of the continuous train; however, it is contrived because continuous trains do not exist except as toys. The version that Dupin and Johsua (1989) used is shown in Figure 8.13 and has workers pushing the train cars (representing the battery) and an obstruction on the tracks slows it down (representing the lightbulb).

Another version of The Continuous Train Analogy is shown in Figure 8.14, and this one shows people boarding the train at one station (battery) and alighting from the train at the other station (lightbulb). In this model, the train carriages represent the current and the people represent the energy.

Figure 8.13 Continuous Train Pushed by Workers (Bottom Box) Slowed Down by Sand Obstruction (Top Box)

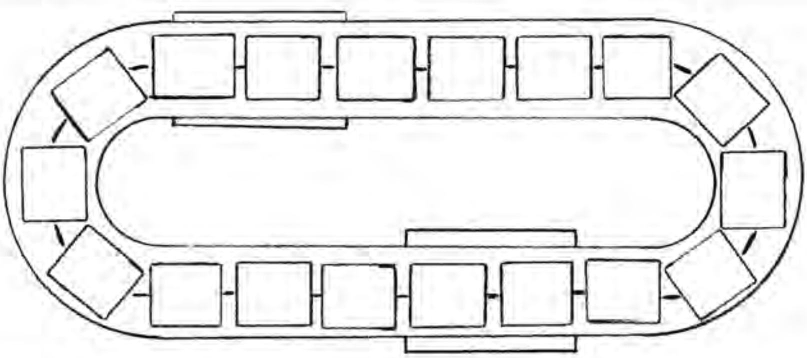
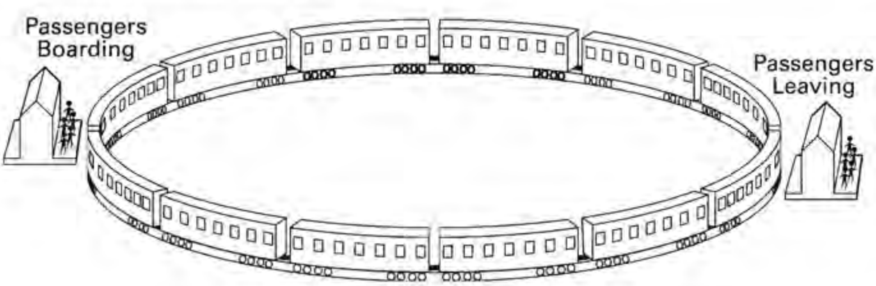


Figure 8.14 Continuous Train With People Boarding at One Station (Battery) and Alighting at the Other (Lightbulb)



When using either analogy, discuss the artificial nature of the analogy with the students. If students are unsure of the analog or feel it is too artificial, then abandon the analogy. Aubusson and Fogwill (2006), however, show that even flawed analogies yield effective learning outcomes if the discussion is critical and comprehensive. The moral is, don't attempt an analogy you don't fully understand. Alternative current conservation–energy transfer models include The Escalator Analogy, The Bicycle Chain Analogy, and The Conveyer Belt Analogy (see Chapter 4). These three analogies use moving steps, chains, or belts to representing electric current, and they use people, work, and coal to represent energy transfer. These correspondences are drawn more fully in the following table.

Analogy or Model	*Electric Current Represented by*	*Electrical Energy Represented by*	*Battery Represented by*	*Lightbulb Represented by*
Continuous Train with People Analogy	Train carriages	People riding on the train	Station where people board	Station where people alight
Escalator Analogy	Moving steps in escalator	People riding escalator	Where people step onto escalator	Where people step off escalator
Bicycle Chain Analogy	The bicycle chain	Energy going from pedals to back wheel	Feet driving the pedals	Rotation of rear wheel
Conveyer Belt Analogy	Rubber conveyer belt	Coal, sand, rock	Mine rock face	Loading a train

The Continuous Train Analogy for Current Conservation in a Series Circuit		
Focus	**Concept**	Electricity only flows in closed circuits; energy is consumed (or more accurately, transformed) in electric circuits, but current is conserved. Remember, energy is hard to model.
	Students	Students think that current is consumed because batteries go flat and flashlights go dim. Some believe that the current

<table>
<tr><th colspan="5">The Continuous Train Analogy for
Current Conservation in a Series Circuit (Continued)</th></tr>
<tr><td rowspan="2"></td><td colspan="2"></td><td colspan="2">going from the battery to the bulb exceeds the current going from the bulb to battery. They are familiar with toy trains and escalators.</td></tr>
<tr><td colspan="2">Analog</td><td colspan="2">A continuous train carrying people (energy) from one station to another. The train is not used up.</td></tr>
<tr><td rowspan="10">Action</td><td colspan="4">Likes—Mapping the Analog to the Target</td></tr>
<tr><td colspan="2">Analog—Continuous train</td><td colspan="2">Target—Current in a series circuit</td></tr>
<tr><td colspan="2">Train carriages</td><td colspan="2">Charge carriers or electrons</td></tr>
<tr><td colspan="2">Carriages moving</td><td colspan="2">Electric current flowing</td></tr>
<tr><td colspan="2">Train track</td><td colspan="2">Complete or closed circuit</td></tr>
<tr><td colspan="2">Passengers</td><td colspan="2">Energy</td></tr>
<tr><td colspan="2">Station where passengers board train</td><td colspan="2">Battery</td></tr>
<tr><td colspan="2">Station where passengers leave train</td><td colspan="2">Lightbulb</td></tr>
<tr><td colspan="4">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="4">• People or cargo are used to represent energy, but energy is not a substance.
• When one teacher used this analogy, her class concluded that the train slowed down as it passed through the "obstacle" representing the resistance. Current does not slow down when it passes through a resistance.
• This analogy only works for simple series circuits.</td></tr>
<tr><td rowspan="2">Reflection</td><td colspan="2">Conclusion</td><td colspan="2">Were my formative assessments of analog-target mappings appropriate? Should I recapitulate the analogy or use a further analogy next class?</td></tr>
<tr><td colspan="2">Improvements</td><td colspan="2">If the continuous train caused problems, is the bicycle chain, escalator, or aquarium water circuit a better choice? Should I use a suite of complementary analogies next time?</td></tr>
</table>

The Continuous Train Analogy for Current Conservation in a Series Circuit (Continued)	
Science Content Standard B, Physical Science, Grades 5–8: "Energy is transferred" (NAS, 1996, p. 155); "electrical circuits provide a means of transferring electrical energy" (p. 155). The Continuous Train Analogy shows that current is always conserved in a circuit and energy is transferred from its source to devices that convert the electrical energy into heat, motion, or light.	
Suggested teaching strategies	As with all current conservation analogies, the problem should be grounded in experiences with simple series and parallels circuits. Use of the Tasker and Osborne (1985) quizzes is recommended. The analogy should only be introduced when students claim that current is used up or when they cannot explain circuit problems. Where possible, ask students to map the analogy and critique it. Once they understand The Continuous Train Analogy, can they construct another (e.g., Bicycle Chain Analogy, Escalator Analogy)?
Resources	Toy continuous train or, if not available, overhead transparency. Young classes can "play trains" (have a look at the M&M's analogy). Bicycle, picture of escalator, or real one, if easily available.
Applications	Suitable for middle and high school students—the mapping expected of students should increase with their ages.

The M&M's Circle Analogy for Electric Current

This model helps children make sense of the difference between energy that is consumed in an electric circuit and the current that is conserved. It's designed as a role-play so students can act out the circuit processes.

Clear away the desks and chairs and mark a large circle on the floor (use colored rope or ribbon). Place one colored piece of cardboard (labeled "Battery") on one side of the circle and opposite it another piece of colored cardboard called "Lightbulb." Note: this analogy is not perfect and the flaws are good opportunities to discuss the analogy's meaning.

Ask the students, "What do you think of when I say *energy*?" A popular answer is "food." Go on to say something like this: "Now electric circuits need energy to work, so we're going to pretend that each person is a little piece of electricity and these M&M's are the electrical energy. All these pieces of electricity (you students in the circuit) can move around, but you need something to make you move—that's what the M&M's are for." Students might even suggest this if you ask them.

Have the students stand on the marked circle (see Figure 8.15), ready to move. The circle moves in a direction decided by the students. Why does the circle move? It moves because the teacher or student standing at the Battery card gives students a small push as each passes the card. The Battery person also gives each student two M&M's. Continue your directions: "You can eat one of the M&M's to give you energy to move, and when you reach the Lightbulb card, you give the other one to Kerry, the Lightbulb person. When Kerry receives your M&M, she waves her hands over her head. What do you think this represents?" We sincerely hope the students will reply, "The lightbulb glowing." Another way to simulate the idea of the lightbulb glowing with energy is to put a box on the Lightbulb card. Students have to step onto the box and down again as they eat the second M&M (this model is more hygienic).

Two revolutions of the circle are enough for the students to get the idea. It's important to rehearse the analogy and discuss it again afterward. It's also essential to map out where this analogy works and where it breaks down. It's not perfect, and most electric circuit analogies are imperfect. This is an excellent discussion point for models and explanations.

In the discussion, pose questions like these: What do the Battery and Lightbulb people represent? Why did we draw a circle? Would it help if we linked arms? What do the two M&M's represent? (Is there a problem here? Yes, the M&M's do different things.) How can we improve the drama? Will the drama continue indefinitely? No. Why? (The hoped-for answer would be, "When we run out of M&M's, the battery's flat!")

Figure 8.15 The M&M's Circle Analogy for Electric Current

NOTE: The candy circle role-play is shown. For the M&M's Analogy, replace each lollipop with two M&M's per person.

<table>
<tr><th colspan="3">The M&M's Circle Analogy for Electric Current</th></tr>
<tr><td rowspan="3">Focus</td><td>Concept</td><td>Electricity only flows in complete circuits; energy is consumed (or transformed) in electric circuits but current is conserved. Energy is hard to model.</td></tr>
<tr><td>Students</td><td>Students readily associate energy with food, and M&M's are well known and liked (and they're high energy food).</td></tr>
<tr><td>Analog</td><td>Students in a circle receive two M&M's from the designated battery; one is used to make the electricity move and the other to make the bulb glow when they get to it.</td></tr>
<tr><td rowspan="13">Action</td><td colspan="2">Likes—Mapping the Analog to the Target</td></tr>
<tr><td>Analog—Students moving in a circle eating M&M's</td><td>Target—Circuit with one battery and one bulb transferring energy</td></tr>
<tr><td>Students in a circle</td><td>Electrons in a wire</td></tr>
<tr><td>Student or teacher pushing circle</td><td>Electrons moving around a simple circuit</td></tr>
<tr><td>M&M's</td><td>Energy</td></tr>
<tr><td>Person giving out M&M's</td><td>Battery</td></tr>
<tr><td>Student eating first M&M</td><td>Energy used to make electrons move</td></tr>
<tr><td>Giving M&M to Lightbulb person</td><td>Electrical energy making the bulb glow</td></tr>
<tr><td>Stepping onto box and eating M&M</td><td>Conversion of electrical energy into light</td></tr>
<tr><td>Lightbulb person eats M&M</td><td>Lightbulb glows, producing heat and light</td></tr>
<tr><td colspan="2">Unlikes—Where the Analogy Breaks Down</td></tr>
<tr><td colspan="2">• Circuit wires rarely consume as much energy as a lightbulb, but both representatives get an M&M
• M&M's are not really energy (though they release energy), but electricity is energy.
• Electricity is depicted as moving objects, whereas electricity is an interactive effect, not a substance.</td></tr>
</table>

<table>
<tr><th colspan="3">The M&M's Circle Analogy for Electric Current (Continued)</th></tr>
<tr><td rowspan="2">Reflection</td><td>Conclusion</td><td>Did the role-play enable the students to differentiate between energy consumption (M&M's) and current conservation (students remaining intact)? If the students' ideas remain tenuous, will a parallel analogy like The Continuous Train Analogy help clarify the concepts?</td></tr>
<tr><td>Improvements</td><td>If the role-play was teacher led, is it time to move toward a more student-designed drama?</td></tr>
<tr><td colspan="3">Science Content Standard B, Physical Science, Grades 5–8: "Energy is transferred" (NAS, 1996, p. 155); "electrical circuits provide a means of transferring electrical energy" (p. 155). The M&M's Role-Play shows that current is conserved in a circuit and energy is transferred from its source to devices that convert the electrical energy into other energy forms.</td></tr>
<tr><td>Suggested teaching strategies</td><td colspan="2">Role-play engages students at many levels: from telling them the scenario through to allowing them to discuss circuit concepts and design the analogy. Role-play works best when students make circuits, identify the explanatory problems, discuss the conditions for an active circuit, and identify what they need to know.</td></tr>
<tr><td>Resources</td><td colspan="2">Batteries, light globes, and wires; M&M's, colored rope or ribbon, cardboard markers for Battery and Lightbulb, box or step stool (optional).</td></tr>
<tr><td>Applications</td><td colspan="2">Grades 5–8; for younger grades, teachers should lead the role-play, older grades can enact it as a project.</td></tr>
</table>

NOTE: Ken Appleton is thanked for his rendition of this analogy. Ken acknowledges the input of the Children's Learning in Science group at Waikato University in New Zealand.

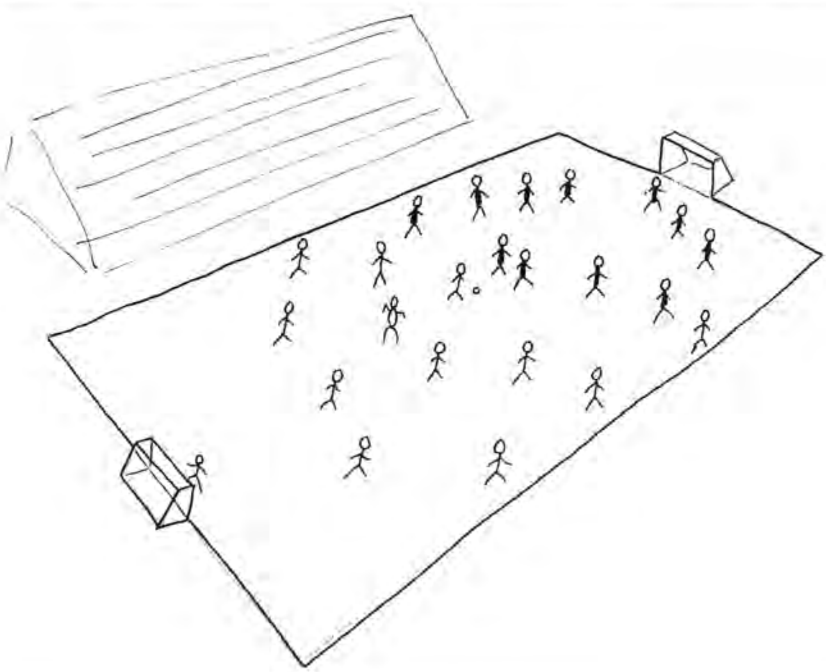
The Field Analogy for Electric Circuits

Gravity, magnetism, and electricity are forces that act at a distance. These forces spread throughout the space in which they operate, and we call this space a *field*. But just what is a gravitational, magnetic, or electric field? Where does the field metaphor come from? Michael Faraday invented field ideas to describe the sphere of influence of a magnet or electric charge. The problem in using this metaphor with students is that field concepts are rarely fully explained. Teachers assume students know when they really don't.

Fields take their name from specific areas that are used for agriculture, war, or sport. A soccer game is played on a field and the teams interact within this space and nothing of consequence to the game happens outside the field. The contest uses a ball, skills, and team players and is controlled by rules. Whether a team wins or loses is determined by the interaction of all the players. If you remove or restore a star player to the soccer team, that player usually affects every other player on both teams on the field. The field metaphor also applies to agriculture—the soil, plants, rain, fertilizer, and animals (if it is a grazing field) all interact to determine the farmer's profit or loss. The field concept is as an interaction, and the field's parts affect all other parts, or we can borrow from John Donne and say, "no *part* is an island, entire of itself."

Fields are used to explain force at a distance. It is an abstract idea, and lines of force is an analogy. The direction of a magnet's field is shown by the direction of its lines of force. The strength of the magnetic field is described by the closeness of the lines of force. But here's a problem: In weak fields, the lines of force are far apart. The diagram shown in Figure 8.16 implies that there is no force in the space between the lines, but there is. The analogy is often misinterpreted.

Figure 8.16 A Soccer Field Is Like a Complex Electric Circuit



Most of the difficulties with teaching electric circuits occur because teachers try to explain circuit properties in terms of their parts rather than their interactions. Think about an electric circuit with three or more lightbulbs connected in series and parallels. Expert teachers tell students, "Look at the overall circuit; don't concentrate on the parts, because it's the interactive whole that helps you work out currents and voltages."

The Field Analogy is a useful way to explain electric circuits when properly developed. Just like a magnet, batteries have lines of electric field joining the positive and negative terminals (Hewitt, 1999, p. 541). In a complete circuit, the conducting wires provide an excellent pathway for the lines of electric force to join the positive and negative terminals. Most of the electric field is confined to the conducting path. The battery, wires, filaments, and coils interact with each other to determine the field's strength and direction. The circuit functions as a unit. It is as if the field knows where every part of the circuit is, how they connect to and affect each other, and what they do. This is like a football team that interacts and plays together. No member of the team can do anything without affecting the other members.

The field concept explains how one bulb in a mixed series and parallel circuit seems to know that there is another bulb some distance along the wire that needs to share the electrical energy. The electric field takes the easiest path through the circuit, and the electrons flow best where the electric field is strongest.

The Field Analogy for Electric Circuits		
Focus	**Concept**	Electric and magnetic forces act at a distance, and their spheres of influence are described as fields. They exert their effect throughout the field, diminishing with distance from the source. Electric fields can be used to explain the flow of electricity in both simple and complex circuits.
	Students	Students know about playing fields and the team games that are played on fields (e.g., football, soccer). They know that a team succeeds if it functions as a whole and not as separate parts.
	Analog	In a football team, all the players function as a unit; in like manner an electric circuit functions as a whole and acts as if each part knows what every other part in the field is doing.

The Field Analogy for Electric Circuits (Continued)		
Action	**Likes—Mapping the Analog to the Target**	
	Analog—A football team playing on a field	**Target—Complex electric circuits acting as a unit in an electric field**
	Playing field	Electric field
	Team members	Circuit components
	Game limited to the field of play	Electric circuit limited to conducting parts
	Rules of the game	Laws determining electric interactions
	Rules constraining player interactions	Laws constraining electric interactions
	All players affecting all others	Interaction of all parts together
	Players knowing what is happening everywhere on the field	Circuit parts functioning in accordance with the properties of all other parts
	Players taking the easiest route to the goal	Electrons flowing easiest where the field is strongest in the circuit
	Unlikes—Where the Analogy Breaks Down	
	• Team members know what each other person is doing and can communicate; circuit parts cannot: Interactions are governed by the electric field intensity at each point in the circuit. • Sport is totally confined to the field of play; electric fields are mostly confined to the circuit but weakly extend beyond the conductor.	
Reflection	**Conclusion**	Was the field metaphor well understood? Could average students explain The Field Analogy rules in their own words? Were they able to see the application to electric circuits?
	Improvements	Perhaps this concept should be revisited next period. Ask students to retell the analogy. Would a short video of a team sport or a discussion of a recent game help introduce the idea?

The Field Analogy for Electric Circuits (Continued)	
Science Content Standard B, Physical Science, Grades 9–12: "Interactions of energy and matter" (NAS, 1996, p.180). The Field Analogy explains how an electric field (in a conductor) applies motive force to the charge carriers, which flow easily and create an electric current.	
Suggested teaching strategies	Introduce this metaphor when students are having trouble with a series or complex circuit. The sports field analogies work best when the students realize they can't explain a phenomenon (e.g., how does the first bulb "detect" that there are others in the circuit? Discuss a recent popular big game to introduce the field concept.
Resources	Lightbulbs, batteries, and wires, newspaper or video accounts of a recent game. Demonstrate a magnetic field or have an OHT (remember that a magnetic field is an analogy for the electric field).
Applications	Grades 9–12. This is a powerful analogy, but be sure you can work it through. This analogy is best used as a culminating explanation for electric circuits. The analogy emphasizes the fact that electric circuits are rule-based interactions—a circuit is an interactive process, not bits acting on their own.