Save the penguins: Teaching the science of heat transfer through engineering design

by Christine Schnittka, Randy Bell, and Larry Richards



any scientists agree that the Earth is warming, and that human activities have exacerbated the problem (NRC 2001; 2002). Engineers, scientists, and environmental groups around the globe are hard at work finding solutions to mitigate or halt global warming. One major goal of the curriculum described here, Save the Penguins, is to help students recognize that what we do at home can affect how penguins fare in the Southern Hemisphere. The energy we use to heat and cool our houses comes from power plants, most of which use fossil fuels. The burning of fossil fuels has been linked to increased levels of carbon dioxide in the atmosphere, which in turn has been linked to increases in global temperature. This change in temperature has widespread effects on Earth, including effects on the

life of penguins. If homes were better insulated, they would require less energy for heating and cooling, reducing fossil fuel use and carbon dioxide emissions. This is the problem presented to students in the beginning of the Save the Penguins curriculum.

In the Save the Penguins curriculum, students learn how engineers are addressing global warming by designing energy-efficient building materials. Students learn the science of heat transfer, design experiments to test materials, and then assume the role of engineer to design, create, and test their own energy-efficient dwellings.

Penguins

Penguins are in peril. As the Earth warms, the oceans warm, pack ice melts, and penguins lose habitat. They

FIGURE 1 The cans demonstration



FIGURE 2

Plastic and silver-plate trays



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also lose food sources such as krill, which rely on the protection of pack ice and feed on the algae that grow underneath the ice (Gross 2005). The emperor penguins in Antarctica are in severe decline due to climate change (Jenouvrier et al. 2008). South African penguins are actually leaving their nests to cool off in the water, placing their eggs at risk to attacks by gulls. Park rangers at Boulders Beach in Cape Town, South Africa, have created little semi-enclosed "huts" for penguins to nest in, which keep them cooler and protect their eggs from predation (Nullis 2009). Several short videos found on YouTube help engage students in this issue and address the impacts of global warming (see Resources). If your school blocks access to YouTube, download and save the videos at home using an online tool such as the one provided free at Downloader9.com (www.downloader9.com), then save them to a disk or flash drive for use at school.

Setting the stage for engineering design

The problem presented to students in this curriculum is an analogy with symbolic meaning—to build dwellings that protect penguin-shaped ice cubes from increasingly warming temperatures. Through their work on the project, students learn about thermal energy transfer by radiation, convection, and conduction. Students test materials for their ability to slow thermal energy transfer in order to keep the ice penguins cool. After testing materials, students build their penguin homes, and then see how well the dwellings keep the penguinshaped ice cubes from melting in a test oven.

Students' alternative conceptions

Involving students in a series of discrepant-event demonstrations helps them form more scientific understandings of heat transfer. The five demonstrations that follow can be used to target common student misconceptions. Other demonstrations are possible, but the following were used in research and empirically shown to be effective (Schnittka 2009).

The cans: Understanding insulation and conduction *Materials*

- six cans of soda refrigerated overnight
- paper towel
- aluminum foil
- plastic wrap
- wool sock
- cotton sock
- six thermometers

If you ask students what they would wrap around a can of soda to keep it cold on a field trip, most will suggest wrapping it in aluminum foil. They might explain that aluminum foil "keeps the cold in." They would not dream of wrapping the can in a wooly sock, due to the prevalent conception that wool makes things warm. Demonstrate this fallacy by wrapping cold cans in different materials and taking their internal temperatures several hours later. Be sure to include a control (no wrapping) for fair comparison (see Figure 1). Have students make predictions about which can is the coldest. They are usually quite surprised to find that the wool sock keeps the soda coldest. Use this

FIGURE 3

Taking the temperature of the trays



demonstration to help your students understand what insulators and conductors are. This demonstration and the interpretive discussion that follows usually take 20 minutes.

The trays and the spoons: Understanding why metals feel cold *Materials*

- plastic tray
- silver (or silver-plate) tray
- thermometer strips
- silver (or silver-plate) spoons
- plastic spoons
- penguin-shaped ice cubes

To prepare for the following demonstrations, borrow or bring from home two trays—one metal and one plastic (see Figure 2). Tape an aquarium thermometer strip to the underside of each tray. Each thermometer should display room temperature (see Figure 3). Flat LCD thermometers in a large, easy-to-read size can be purchased from PetSmart (*www.petsmart.com*). Alternatively, Ideal brand #61-310 multimeters with thermocouple probes can be used. They can be purchased from a number of online sources.

For the first part of the demonstration, walk around with the trays and allow students to touch them and describe which tray feels colder. While both trays are at room temperature, students will insist the silver tray is colder. After the demonstration with spoons (description follows), reveal the actual temperatures of



the trays to students. Students should understand that both of the trays are the same temperature, but that heat transfers faster from a warm hand to the silver tray than it does from a warm hand to the plastic tray.

The second part of this demonstration involves spoons and penguin-shaped ice cubes. Lékué brand penguin ice cube trays (model # 39004) can be purchased online from a number of sources (see Figure 4). Give each student group a plastic and a silver spoon to hold. Silver plate or stainless steel will suffice, but silver is a better conductor of heat. Students may comment that the silver spoon feels colder and infer that metals are naturally colder than plastics, just as they may have done with the two trays. Have students predict which spoon works best to keep an ice cube from melting. Most students predict the silver spoon because it feels colder, as did the silver tray. Place penguin-shaped ice cubes on the spoons and have students take turns holding the spoons (see Figure 5). Ask students to explain why the penguin in the plastic spoon does not

FIGURE 5

Silver and plastic spoons with penguin-shaped ice cubes



melt significantly, while the penguin in the silver spoon quickly turns to water.

Through group and class discussions, bring students to an understanding that heat transfers from where the temperature is higher to where the temperature is lower, and that heat transfers faster through the silver spoon than the plastic spoon because silver is a better conductor than plastic. The silver spoon feels colder because the hand, which is warmer, is losing thermal energy in the heat transfer. While students may try and insist that cold transfers because they feel their hands get cold, remind students that there is no such thing as cold transfer; only thermal energy, or heat, can transfer. The feeling that the hand is cold when touching the metal is evidence that the hand is a very good detector of rapid heat loss.

Next, reveal the equal temperatures of the silver and plastic trays. This discrepant event promotes a lively discussion and helps students come to a deeper conceptual understanding about the conduction of heat.

The house: Understanding convection in air and radiation from light *Materials*

- cardboard house made from a box
- digital thermometers or thermocouple probes
- stopwatch or watch with second hand
- computer with spreadsheet software (optional)

The following demonstrations help students understand that convection occurs when less dense fluids

FIGURE 6 Data and graph from house demonstration				
	Time (sec.)	Attic temperature (°C)	First-floor temperature (°C)	
	5	37	22	
	10	36	23	
	15	35	24	
	20	34	25	
	25	33	26	
	30	32	27	
	35	31	28	
	40	30	29	
	45	29	28	
	50	28	27	
	55	27	26	
	60	26	25	

rise and more dense fluids fall. It can also be used to demonstrate how black surfaces absorb radiation and become quite hot, while reflective surfaces do not. These demonstrations and the interpretive discussions that follow usually take 20 to 30 minutes.

Make a hollow cardboard house and paint the roof black with acrylic paint. Shine a shop light onto the house, and place temperature probes in the attic and the first floor. The attic gets quite hot inside, approaching 38° C (100.4°F). (Safety note: The cardboard black roof gets very hot and can start to smoke if the shop light is placed too closely. Be sure to monitor this, and have a fire extinguisher nearby just in case.)

After you turn off the light, ask students why the attic remains hotter than the first floor. The likely answer is "Heat rises!" The scientifically correct explanation would be that cooler air falls because it is more dense (particles are closer together), and this forces hot air, which is less dense, to rise. There are several popular demonstrations of convection involving water and food coloring that can be used, but this demonstration helps students understand that convection is the movement of all warmer and cooler fluids (liquids and gases), not just water.

After the light has been off for a moment, flip the house upside down. The air masses change places

FIGURE 7 Mylar on a hot black roof



due to density differences, and the thermometers or temperature probes reveal this change. Have students record the temperature of the attic and first floor as the air masses change places. They can graph the data by hand or enter the data into a spreadsheet to graph the changes over time. Without access to computerbased probes, we usually have one pair of volunteers, wearing safety goggles, call out the temperatures while one volunteer calls out the "time" every five seconds and another pair of volunteers record the temperatures. See Figure 6 for sample data collected from a demonstration.

Make sure students come to understand that the air masses are changing places as cooler, more dense air falls and warmer, less dense air rises. You might also want to repeat the demonstration with several layers of aluminized Mylar film protecting the house, as seen in Figure 7, in order to demonstrate the difference between a black roof and a reflective roof (optional).

FIGURE 8

Samples of materials



The shiny Mylar: Understanding radiation and how to reflect it *Materials*

- shop lights (one per group with 150W lightbulb)
- ring stands (one per group)
- several sheets of aluminized Mylar (per group)

The following demonstration helps students understand that light can be reflected, preventing heat transfer from radiation. This demonstration and the interpretive discussion that follows usually take 15 minutes.

Mylar is a polyester film that can be coated with aluminum to be very shiny. It is usually thin and can be somewhat translucent, but when layered, it is excellent at reflecting light and preventing heat transfer. It is commonly used in snack-food packaging, helium-filled balloons, and emergency blankets. We have found that the easiest and least expensive way to purchase aluminized Mylar is at a craft or stationary store as metallic tissue wrapping paper.

Have students feel the radiation from the lights with their hands. (Safety note: Make sure students keep a safe distance from the shop light. To do this safely, have the shop light mounted on a ring stand at a safe distance pointing toward the counter.) Have students working in groups take turns placing their hands on the counter under the lamp as their partners slip the shiny Mylar layers in between the light and their hands. Students will immediately feel the reduction of heat transfer, especially with multiple layers. Use this demonstration

to help students understand that radiation is a type of heat transfer that occurs nearly instantaneously, at the speed of light, and that the light is easily reflected by shiny materials. Students are amazed at how suddenly the heat transfer is blocked the moment the Mylar is placed between their hands and the light.

Creating a dwelling for ice cube penguins Testing building materials

After students have a good, basic understanding of how heat transfers, introduce the challenge: to build a dwelling for a penguin-shaped ice cube in order to keep the penguin from melting. First, students must decide which materials to build with.

Students engage in scientific inquiry as they test materials and eventually design and test dwellings. Student groups are given materials such as felt, foam, cotton balls, paper, shiny Mylar, and aluminum foil to test for their effectiveness at preventing some form of heat transfer (Figure 8). It is best for the teacher to prepare all of the samples ahead of time. We find that cutting the fabrics, foils, papers, and foams into 7.6×7.6 cm $(3" \times 3")$ squares with a 7.6 × 45.7 cm $(3" \times 18")$ clear acrylic quilting ruler on a cutting mat with a rotary cutter works best. These items can be purchased from sewing stores. (Safety note: All safety protocols need to be followed with building and cutting-students should wear safety glasses.) Decide as a class which materials or combinations of materials can be compared and tested, then divide the work up among the different lab groups. It is reasonable for each group to run three or four tests. For example, one group might compare aluminum foil to shiny Mylar, while another group compares white felt to white foam. Some groups could test bubble wrap with different colored papers on top. Students can compare materials under a shop light mounted to a ring stand shining on a black surface such as a black countertop or black plastic tray. Give students access to thermometers and timers to fairly test samples under the light or on the hot black surface. As students explore the materials, they begin to formulate ideas about how to build a dwelling for a penguin-shaped ice cube so that the least amount of ice is melted. Allow students to procure additional materials after they decide which ones are better building materials. We usually price the materials and give each student group a budget to work with (see the Sumrall



and Mott article on page 45 of this issue for additional pricing information).

Encourage open inquiry and allow students to come up with their own testing ideas. Be sure student groups share the results of their experiments so that the knowledge gained is communal, encouraging a more collaborative and less competitive environment. During sharing time, it is helpful to encourage students to explain to each other why they tested certain materials, what their results were, and why they think the results turned out as they did. This is the perfect opportunity to help students understand heat transfer as it applies to each experiment performed. Expect students to spend at least one class period testing materials and half of a class period sharing their results with each other.

Building the dwelling

After students have tested different building materials and shared their results with the class, they will be eager to start using the materials to build little houses to keep the penguin-shaped ice cubes from melting. Students will finally be able to apply what they have learned from the demonstrations, discussions, and materials testing. As students take on the role of "engineer" to keep ice from melting, remind them that engineers are designing innovative materials for houses, schools, and other buildings to prevent heat transfer. Preventing heat transfer is energy effi-

FIGURE 10 Little dwellings in the oven



cient, and efficient buildings use less energy. The less energy needed to heat and cool a building, the less negative impact it has on the environment.

Provide students with tape and glue, and scissors to cut paper and fabrics. Most students will use the materials as given, but some will want to modify them by cutting, folding, crumpling, or layering. Students need to be sure to create an opening so that the penguin can be easily placed in the dwelling and easily removed after testing. As the designs evolve, students may need to conduct further testing, discuss results with other groups, and receive support for their ideas from the teacher. A class period should be sufficient for this phase of the curriculum. Engineers work with constraints of time, space, and money, so give your students a time deadline, too.

Testing the design

Eventually, students are ready to evaluate their dwellings in the oven. The oven can be a large plastic storage bin lined with aluminum foil on four sides and spray-painted black on the bottom, with three 150W shop lights shining inside so that all three forms of heat transfer can occur. If you use a black plastic storage bin, simply line the sides with foil and attach the shop lights. See Figure 9 for a suggested test-oven design. Houses placed in this preheated oven experience conduction with and radiation from the black floor, radiation from all sides, and convection as hot air rises off the black bottom.

Fill the ice-cube trays the night before with 10 mL of water for each penguin. We use a medical syringe to

be accurate. The carefully created and frozen 10-gram ice penguins are simultaneously placed inside the dwellings and then placed in the oven and subjected to 20 minutes of intense heat. See Figure 10 to see how dwellings are placed in the oven. The oven can accommodate more dwellings depending on its size, but students need to be told about the space limitation. Typically, we have eight teams in each class, so we tell students that their dwelling cannot be larger than oneeighth of the floor space in the oven.

During the 20-minute wait, we sometimes show students a slide show on energy-efficient building materials such as smart windows, aerogels, radiant barriers, and solar-panel roofing tiles. Sometimes we show an excerpt from the movie March of the Penguins or an excerpt from An Inconvenient Truth to spark discussion. After 20 minutes, the dwellings are finally removed and the remaining solid portions of the ice penguins are placed in little plastic cups for mass measuring. (Determine the mass of the plastic cups ahead of time and write the mass on the cups.) Students always enjoy the thrill of rescuing their dwelling from the oven and seeing how much penguin they were able to save. After the solid penguin remains are placed in plastic cups, it will not matter if some melting occurs prior to measuring the mass because the water stays in the cups. This provides a teachable moment to discuss melting and the conservation of mass. It usually takes a few minutes for each group to take a turn determining the mass of their cup and penguin on a digital mass scale, then subtracting the mass of the cup. (Safety note: Mount the test-oven shop lights on ring stands so that they can be turned off and moved away when students place their penguin dwellings in the oven or retrieve them.)

The results are shared and discussed after all penguin-ice-cube masses are measured. Some student groups are able to save at least half their penguin, but some usually only have a few grams remaining.

It is always interesting to discuss which design features were best at preventing conduction with the black oven bottom. Which design features were best at preventing radiation from the heat lamp from penetrating the dwellings? Which design features were best at preventing the convection of hot air moving? Students discuss and decide. They analyze the results, and then, if time is available, it is back to the drawing board to make revisions and improvements for a second round of testing.

When time is available, students are able to use their shared results and ideas to make revisions that help save even more ice penguins. This step helps to mitigate competition, because each group of students is a winner if their revised design is better than their first one. The process mimics how engineers continually work together in an iterative process to make things better. It usually takes students an entire class period to redesign their dwellings, bake them in the oven, measure the mass of the penguins, and discuss the final results.

See Figure 11 for an initial and revised design after students were able to learn from their first experience and share results with each other. Notice that stu-

dents decided to plug up the door to prevent convection and add insulation in the "tube" to prevent the ice from directly contacting the metal. Many students decide to put their dwelling up on stilts of some sort, and many provide extra protection from radiation on all sides.

When the second trial is conducted, or when results are compared among classes, make sure the ice is at the same starting temperature each time. Ice will be the temperature of the freezer when it is removed, and it warms until it becomes 0°C (32°F) and melts. The standard freezer temperature is -17°C (1.4°F), but each freezer can vary. Therefore, the results will be the most accurate if penguins are removed from the same freezer each time they are used, and used right away.

Conclusion

This unique engineering, design-based approach to learning science in a context relevant to students' lives has been shown to be effective in (1) improving students' conceptual understandings about science; (2) increasing their knowledge about and attitudes toward engineering; and (3) increasing their motivation to learn science (Schnittka 2009; Schnittka et al. 2010). Research using the Save the Penguins curriculum has shown that with scaffolding, students can connect the heating and cooling of their homes to the burning of fossil fuels for energy production, global warming, melting sea ice, and penguins in peril. In the meantime, students are sharpening their inquiry and process skills, working in teams, and thinking

FIGURE 11 Initial and revised designs



creatively. Students learn the science best and engineer better dwellings when the demonstrations are used early on to target their alternative conceptions about heat. Engineering design activities can be used effectively in science classrooms, but careful attention should be paid to pedagogically sound science teaching. Students' alternative conceptions must be acknowledged, addressed, and targeted in science lessons. Otherwise, there is no expectation that students will implicitly learn scientific concepts just because they participate in an engineering activity. The engineering design activity gives students a tangible application for their science conceptions, insight into the world of engineering, and practice with 21st-century skills: innovation, problem solving, critical thinking, communication, and collaboration.

The complete Save the Penguins curriculum with daily lesson plans is available online at *www.uky. edu/~csc222/ETK/SaveThePenguinsETK.pdf*.

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Resources

- Climate Change Likely to Devastate Emperor Penguin Populations in Antarctica—www.youtube.com/ watch?v=RqNJ6B1CSss
- Penguin in a Pickle—www.youtube.com/watch?v=Jz-5Y7WgVEE
- Penguins Are Melting—www.youtube.com/ watch?v=rqUvf9Rxxj4

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