Design an Energy-Efficient House

Applying Multidisciplinary Knowledge to Solve a Design Challenge

BY MINJUNG RYU AND LUAN SOARES

Designing a solution that solves a real-world problem requires knowledge drawn from multiple disciplines, such as science, mathematics, and engineering (Honey, Pearson, and Schweingruber 2014). The STEM integration unit "Design an Energy-Efficient House" aims to facilitate students' learning and applications of knowledge and skills in these various disciplines to provide a solution for a real-world problem. This unit teaches fundamental ideas of heat transfer (Figure 1) and is based on a problem that many people face: how to keep a house warm during winter while avoiding high energy bills.

Lesson 1: Identify problems

We start this lesson by providing an engaging problem situation. In this problem, Andrea (a fictional character) moved from Mexico to Indiana during the summer. When winter arrived, her family received a much higher electricity bill than they did during the summer months. Andrea decided to write a letter asking for students' help in reducing her family's electricity bill, while still keeping the house warm. After reading the scenario (Figure 2), the teacher should ask students to identify the problem Andrea is facing and what further information could and should be gathered to better understand her problem (the scenario can be revised to make more explicit connections to local contexts and students' backgrounds). The teacher can provide average temperature and weather data of the two regions in summer and winter for students to analyze and compare. (Weather data can be retrieved from weather websites; see Resources.)

To facilitate students' development of global perspectives, the teacher can ask students to research how people in different parts of the world keep their homes warm. If some students were born in or have lived outside of the United States or have family and community members who live or have lived outside of the United States, this is a good opportunity to build on their experience and knowledge. If students conduct online research to answer this question, the teacher can facilitate students' information literacy skills by guiding and monitoring students as they locate information and evaluate the sources of information.

At the conclusion of this lesson, students compose a problem statement, propose several potential solutions to the problem, and share them with the class. Because this lesson will be a stepping stone for thinking about heat and insulation of different materials, the teacher should gauge students' prior knowledge of heat, insulation, and heat-related properties of matter (see the online supplements).

Lesson 2: Heat, thermal energy, and heat transfer

Thermal energy and heat are abstract ideas. At the middle school level, it is important to highlight that *temperature* is a measure of the average

CONTENT AREA

Physical Sciences, Engineering, Technology, and Applications of Science

GRADE LEVEL

6–8

BIG IDEA/UNIT

Energy

ESSENTIAL PRE-EXISTING KNOWLEDGE

Conservation of energy and energy transfer; Matter is made from particles that are moving around or vibrate in position.

TIME REQUIRED

10 days

COST

Less than $50

FIGURE 1: Overview of the unit

Lesson	Objective
Lesson 1 (two days): Identify the problem	• Identify the problem • Conduct research on how people around the world keep their homes warm
Lesson 2 (two days): Thermal energy and heat transfer	• Explain the differences between temperature, heat, and heat transfer • Differentiate three different processes of heat transfer and give examples of each • Explain thermal energy through modeling of small particles' behavior
Lesson 3 (two days): Investigate insulations	• Investigate conductivity and insulation of different materials • Discuss potential explanations of different insulations of materials
Lesson 4 (four days): Design a model house	• Design, build, and test a model house • Justify design solutions • Analyze data and brainstorm for redesigning the house

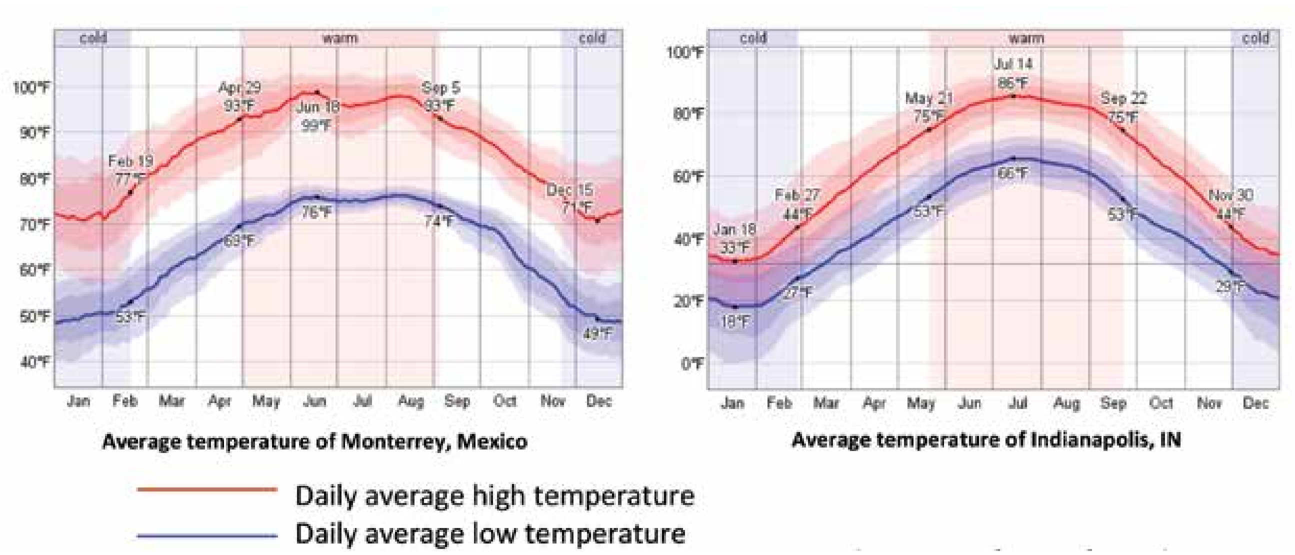
kinetic energy of particles of matter and energy is spontaneously transferred out of hotter regions or objects and into colder ones. In particular, it is important to note how the term "heat" is used more broadly in everyday language to incorporate both thermal energy and energy transfer, whereas in science it refers to only energy transfer (NRC 2012). Additionally, the teacher should introduce the idea that particles of a material at a higher temperature (i.e., thermal energy) move (vibrate, rotate, and translate) faster than those at a lower temperature. Three different processes of heat transfer—conduction, radiation, and convection—should be discussed from the particulate perspective. Emphasis should be placed on how conduction occurs in a solid and how convection occurs in a liquid or gas.

To facilitate students' understanding of these complex ideas, the teacher should use students' ex-

FIGURE 2: The scenario

Andrea recently moved to Indianapolis, Indiana, from Monterey, Mexico, with her parents. She was very excited to live in a new place, but a little worried about the cold weather in Indiana. After the relocation, Andrea had her first winter in Indiana. She realized it was not too bad. Her home had a heating system run by electricity and it kept her home warm. When she went outside, she wore layers. In early December, however, she overheard her parents worrying about their electricity bills. They were charged a very high electricity bill for the first winter month in Indiana. Andrea would like to do something to lower their electricity bills. Can we help Andrea's family? Let's take a look at the two cities on the map. From their location, what can you say about the climate of the two cities?

Here, we have historical temperature data of the two cities:



How are the temperatures of the two cities different?
Is this what you expected? If not, in what ways is this different from your expectation?

FIGURE 3: Lesson 3: Investigate insulation!

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Figure 3a: A testing station set up.

Figure 3b: A cube to fix and test insulation materials. The slit is used to fix it to the light clamp.

Figure 3c: Infrared thermometer used to measure surface temperature.

The "Investigate Insulations!" activity can be done at a testing station built using a light source, such as an incandescent light bulb, a light clamp fixed on a ring stand (Figure 3a), and a cube made with a manila folder (Figure 3b). Alternatively, a testing station can be built using a plastic lamp holder. Please note that we used a light bulb cage to protect materials from being too close to the bulb. Students place each insulation material (e.g., bubble wrap, felt, foam sheet, foam board) inside a wall of the cube using paper clips or tape and measure the temperature of the wall outside. The temperature of each wall can be measured with an infrared thermometer (Figure 3c). It is important to ensure that students discuss and understand that the light source should be set at equidistance from the walls and that one wall should be tested without insulation as a control.

periences of thermal energy, various visual representations of particles, and modeling. For instance, students can act as particles of a material and represent particles of a solid (they stay stationary in a fixed position while vibrating), a liquid (they move past each other and stay relatively close), and a gas (they move around freely and bump into each other). The teacher asks students to change temperature in one state. For instance, if the temperature increases in a solid state, students vibrate more vigorously and expand the distance between them while staying stationary. The class can also represent conduction, in which the faster motion of a particle is passed to an adjacent particle without translational motion of particles, whereas convection can be represented by fluid particles' translational motion.

Lesson 3: Investigate insulation

In this lesson, students learn that different materials conduct thermal energy at different rates; thus, materials that conduct thermal energy slowly can be used for thermal energy insulation. The teacher can start with a simple demonstration using cups made with several different materials, such as plastic beverage cups, foam cups, porcelain cups, wood cups, and metal cups. (Teachers can use what are available to them. All of these cups can also be purchased online.) Each group of four students receives a set of cups made from different materials and puts a small ice cube in each cup. Before placing an ice cube, students are asked to predict in which cup the ice would melt fastest or slowest, explain their predictions, and support the prediction with what they have learned in previous lessons about heat transfer. After about 10 minutes, students observe the result. The teacher should encourage students to observe the cups carefully and note the condensation of water inside and outside of the cups and explain the differences between the two. (In porcelain cups and cups of other less conductive materials, the condensation is formed only in the lower area of the cup, whereas in metal cups, the condensation is usually found across the entire surface.) The teacher guides students' reasoning by asking why ice melts, where the thermal energy to

FIGURE 4: Design an energy-efficient house

Your goal

To design and build a model house within the design constraints, using your knowledge about thermal energy transfer and insulation.

Things to keep in mind

- thermal energy transfer and insulation
- size of house
- placement of windows
- price of the insulation materials used
- Be creative!

Design constraints

- floor size ≥ 645 cm^2 (100 $in.^2$)
- roof height ≥ 30.5 cm (12 in.)
- window size ≥ 194 cm^2 (30 $in.^2$)
- a small hole in the roof to install a thermometer and a narrow slit on one side of a wall to place the light bulb clamp on the house

Insulating materials

ALL MATERIALS ARE 30.5 × 30.5 CM (12 × 12 IN.)	PRICE
BUBBLE WRAP	$0.20
FELT	$1.00
FOAM SHEET	$1.50
FOAM BOARD	$2.50

melt the ice comes from, which process of heat transfer can explain their observation, and why ice melts at different rates.

After understanding that materials have different heat conductivities, students test heat conductivity and insulation of common craft and household items. In groups of four, students build a simple model house out of a manila folder (see Figure 3 and Activity 1, p. 44), choose two or three different materials they want to test, and attach those materials to the walls of the model house. In the testing station (see Figure 3a), students turn on the light bulb and measure the temperature of each wall (one of the walls without any material is used as a control) every minute for 10 minutes. If time allows, the teacher can guide students to make multiple measurements in order to (a) test multiple materials, (b) test different conditions (e.g., multiple layers of a material), and (c) ensure test reliability by making multiple measurements of each material. The teacher asks students to record the measurements, graph the data, and discuss why these materials have different conductivities and insulations, and guides them to decide which materials would be best for insulating a house.

Lesson 4: Design an energy-efficient house

In the same groups as in lesson 3, students design, build, and test a model house that stays warm on the inside. To complete this design challenge, students have to make decisions about the structure of the house and insulation materials to use (Figure 4), drawing on science knowledge learned in previous lessons, mathematics ideas, and engineering decision-making principles such as constraints and trade-offs. Design constraints are given in terms of the size of the house—area of the floor, height of the house, and size of the windows—to encourage students to draw on their geometry knowledge. Students are asked: Which three-dimensional shape would minimize its surface area? To make a certain three-dimensional shape (e.g., cylinder), what two-dimensional shapes are to be cut? What is the length of each side, or diameter, to make the given surface area of the floor?

Students also consider the costs and benefits of using insulation materials. For instance, students will know from the previous lesson that bubble wrap is not as efficient as other materials but notice that it is much cheaper, which will lead them to consider both the price and efficiency of the materials in their design. Additionally, if students decide to use a small piece of expensive foam board, they need to consider how to maximize the effect of it: Should it be used for the floor, ceiling, or on one side of the walls?

To help students reflect on the decision-making and argue in favor of their decision, the teacher can ask students to design three houses initially within a small group of three or four students, choose one out

FIGURE 5: Assessment rubric

Criteria	0	1	2	Score
Drawing on scientific knowledge in the design brief	No scientific justification is made.	Students partially explain their selection and arrangement of materials based on scientific knowledge about heat transfer.	Students thoroughly articulate their selection and arrangement of materials based on scientific knowledge about heat transfer.	
Drawing on engineering design principles in the design brief	No engineering justification is made.	Students partially refer to engineering principles.	Students adequately refer to engineering principles (e.g., trade-offs, constraints).	
Drawing on geometric principles in the design brief	No geometric justification is made.	Students partially draw on geometric knowledge in determining the structure and shape of the house.	Students thoroughly draw on geometric knowledge in determining the structure and shape of the house.	
Size dimension of the house	No constraint is met.	One or more constraints are met.	All size constraints are successfully met.	
Cost for materials	The group's prototype is in the lowest 30th percentile.	The group's prototype is in the second lowest 30%.	The group's prototype is in the lowest 40%.	
Performance of the prototype (final temperature)	The group's prototype is in the lowest 30th percentile.	The group's prototype is in the second best-performing 30%	The group's prototype is in the best-performing 40%.	

Note: Depending on the relative importance of each item determined by individual teachers, the total possible points can be adjusted for each criterion.

of the three, and justify their choice either verbally or in writing. After this design briefing, students build their house and test it in the testing station used in lesson 3. A testing station, which contains a light bulb and a socket and a thermometer installed on a ring stand, can be set up at the corner of a lab bench where the teacher can constantly monitor. If there are more than five students groups, two to three testing stations are recommended. Students measure the temperature inside the house with the light turned on for 10 minutes and then turn off the light and measure for 10 more minutes to check whether the house maintains the temperature. A one-minute measurement interval is recommended. Students graph the collected data and discuss whether their expectations were met and why or why not. To conclude, the class can compare each group's design and results and analyze which design worked better. Students brainstorm changes they would like to make in their house design to improve its performance and cost-effectiveness.

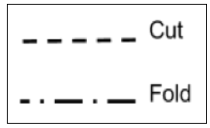
Assessment

To design and implement a successful assessment, the teacher should consider multiple aspects of the design challenge and what skills and competencies should be assessed. One aspect is the performance of the designed house and cost of the house building: Does the house stay warm? How much did it cost to build the house? The teacher can also assess students' reasoning

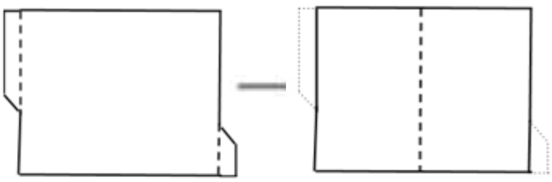
ACTIVITY 1

Building a model house for an insulation material test

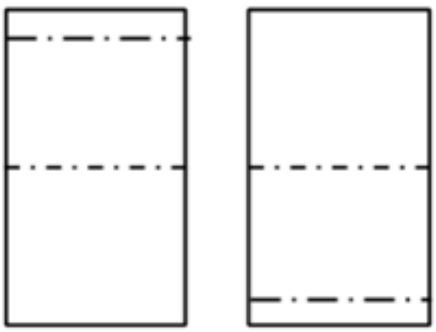
Note: Teachers can create a model house with different sizes based on their needs and availability of materials. Consider this procedure as a sample.



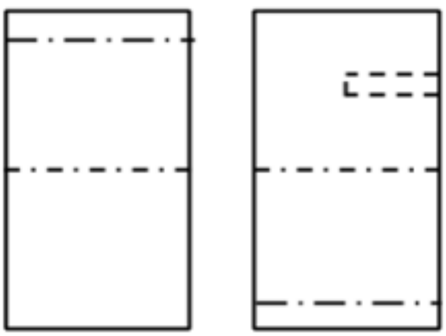
1. Cut out edges of a manila folder to make a rectangle and cut the rectangle in half. This is to make the walls of your house.



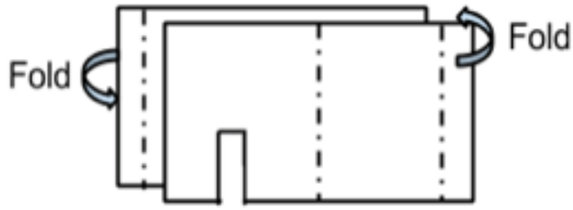
2. Fold the two small rectangles in half. Measure 1.3 cm (0.5 in.) from one of the shorter sides of the rectangle, draw a line, and fold along the line.



3. In one of the rectangles, using the side that doesn't have the line you drew, cut a 7.6 × 1.3 cm (3 × 1/2 in.) strip in the middle.

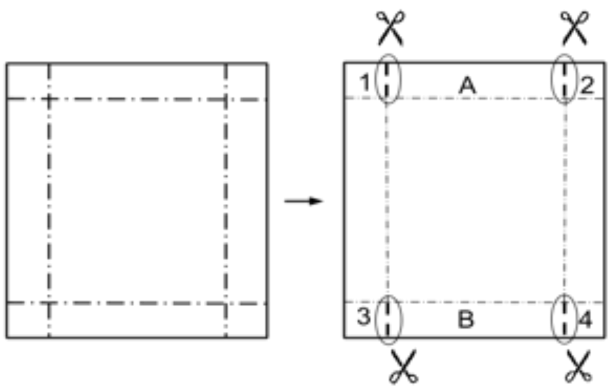


4. Place one rectangle on top of the other, aligning with the lines you drew. Attach them using tape. Open it, making four walls of the model house.



5. Use the second manila folder to make a roof for your model house. On one side of the folder, draw and cut a rectangle measuring 23 × 21.6 cm (9 × 8.5 in.).

6. Measure 3.8 cm (1.5 in.) from each edge, make lines with your pencil, and fold along the lines. Cut four corners as shown in the picture.



7. Tape folded edges as follows: A-1, A-2, B-3, and B-4. This will become the box-shaped roof of your model house

Measurement 1

1. Choose two insulating materials from the available materials.
2. Use tape or paper clips to fix them on two sides of your box.
    a. Don't use the side that has a cut.
    b. Write down which side has which material.
    c. Leave one side with no material as your control.
3. Using the cutout on one side of the model house, place your box over the lamp on the ring stand. Put the roof on.
4. Using the infrared thermometer, measure the initial temperature of each wall and record in a data table (Table 1). Then, turn on the lamp and start the stopwatch. Measure the temperature of the walls every two minutes until you reach 10 minutes.
5. Be careful; the box will get hot. Turn off your lamp and wait for your box to cool to take it apart.

Data record and analysis 1

1. Write down a title for your data table.

Table 1:

Wall:	A	B	C
Description of insulation			
Time (min)	Temperature (°C)		
0			
2			
4			
6			
8			
10			

2. On graph paper, plot your data. Label your graph properly.
3. Discuss in your group what you found out about the insulation of different materials.

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013)

- The chart below makes one set of connections between the instruction outlined in this article and the *NGSS*. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities.
- The materials, lessons, and activities outlined in the article are just one step toward reaching the performance expectations listed below.

Standards

MS-PS3: Energy
www.nextgenscience.org/dci-arrangement/ms-ps3-energy

MS-ETS1: Engineering Design
www.nextgenscience.org/dci-arrangement/ms-ets1-engineering-design

Performance Expectations

MS-PS3-3. Apply scientific principles to design, construct, and test a device that either minimizes or maximizes thermal energy transfer.

MS-ETS1-1. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

DIMENSIONS	CLASSROOM CONNECTIONS
Science and Engineering Practice	
Planning and Carrying Out Investigations	Students test heat conductivity and insulation of common craft and household materials.
Disciplinary Core Ideas	
PS3.A: Definitions of Energy • Temperature is a measure of the average kinetic energy of particles of matter. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter present.	Students model particles of a material at different temperatures.
ETS1.B: Developing Possible Solutions	Students design, build, and test a model house. Students analyze the collected data and propose ideas to improve their design.
Crosscutting Concept	
Energy and Matter	Students observe the melting of ice contained in various materials and are asked to explain heat transfer and why ice melts at different rates.

Connections to the *Common Core State Standards* (NGAC and CCSSO 2010)

Mathematics

CCSS.MATH.CONTENT.6.G.A.1. Find the area of right triangles, other triangles, special quadrilaterals, and polygons by composing into rectangles or decomposing into triangles and other shapes; apply these techniques in the context of solving real-world and mathematical problems.

in the process of designing. For instance, the teacher could assess whether and how students draw on science knowledge (e.g., thermal energy, heat transfer) in the design and consider the geometric relationship between the shape of a structure and its surface area. This can be assessed when students explain their design decision or informally gauge throughout the process of house designing by interacting with students and asking questions. Finally, creativity and aesthetics of the design, communication skills, and teamwork are other important aspects to assess. See the sample rubric (Figure 5); teachers can modify it based on their specific objectives.

Safety

There is a possibility that the materials can burn when they are placed close to a light bulb. A light bulb guard should be used to keep it safe (see Figure 3). Alternatively, the light bulb can be covered with aluminum foil (The Concord Consortium 2012). Warn students not to touch the light bulb or place any materials in a close proximity (no closer than 13 cm [5 in.]). Light bulbs with lower wattage (e.g., 40 W) are recommended. Other safety tips: Make sure cords of light bulbs are not in an area where people can trip. When using an infrared thermometer, do not point the laser at eyes. When testing insulation, students should not use insulating materials such as fiberglass due to the possibility of inhaling small particles. Students need to wear safety goggles at all times. Testing stations should be close to the teacher's area so that teachers can easily monitor and access them.

Conclusion

While STEM integration is getting more attention as an innovative approach to teaching science, teachers often feel insecure and do not know how to use this new method in the classroom. In this unit, students build knowledge of key ideas about heat, practice using mathematical knowledge in real-world contexts, learn key engineering concepts, and engage in science and engineering practices. Our hope is that this activity provides teachers with a starting point and helps them build more confidence as they experience this new way of teaching. ●

REFERENCES

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National Research Council (NRC). 2012. *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards*.

The Concord Consortium. 2012. Building and test a model solar house. *http://concord.org/stem-resources/model-solar-house*.

RESOURCES

Weather data:

WeatherSpark—*https://weatherspark.com*

Weather Underground—*www.wunderground.com*

Various home heating and cooling systems:

Radiant heating—*http://wiki.kidzsearch.com/wiki/Radiant_heating*

Passive solar—*http://encyclopedia.kids.net.au/page/pa/Passive_solar_heating*

Worldwide methods for heating/cooling of a home—*www.filters-now.com/news/worldwide-methods-for-heatingcooling-a-home*

Modeling of heat transfer:

Heat, temperature, and conduction—*www.middleschoolchemistry.com/lessonplans/chapter2/lesson1*

Using the interactive whiteboard to resource continuity and support multimodal teaching in a primary science classroom—*http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2729.2007.00269.x/full*

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