Call the Plumber!

Engaging Students With Authentic Engineering Design Practices

BY CHANDAN DASGUPTA, BETH SANZENBACHER, JEREMY SIEGEL, DEANNA MCBEATH, AND TOM MOHER

It is important to start early when helping middle school students become "engineering enabled" (Cunningham 2009; Svihla and Petrosino 2008). Students need to understand the engineering design process in which designers systematically generate, evaluate, and revise designs whose form and function achieve clients' needs while satisfying a specified set of constraints (Dym et al. 2005; Rose 2004). Middle school students need appropriate scaffolding and intuitive resources to help them understand this process and be productive while solving an engineering design challenge. Here, we present a curricular unit that uses a possible solution to a problem, the suboptimal model, to productively scaffold student work and encourage them to creatively solve engineering design challenges.

An *engineering system* consists of many interlinked components that work together to accomplish the function of the system; as such, a system will have multiple levels or layers of complexity. *Systems thinking* means that students have an understanding of these multiple levels and how the components work together. A *suboptimal model* highlights the relationship between all the design parameters in a system and provides a deficient solution for reference. Thus, the suboptimal model represents poor design decisions made while building the system. Students use the suboptimal model for exploring the engineering system by manipulating various design parameters embodied in the model and using the model as a thinking tool (Harrison and Treagust 2000). Conversely, an *optimal*

model is one that fulfills all of the design requirements and is the best possible solution to a problem under the given constraints.

Design context and authentic experience

This unit allows students to experience an authentic design scenario, such as designing the plumbing system of a house. Students build an optimal physical model of the plumbing system while satisfying a given set of constraints and needs. This design context is appropriate for middle school because students use this engineering system daily when they use a sink faucet. The system is not novel, yet students have naïve theories and ideas about how the water flows into the tap. Design elements and engineering design decisions that go into creating an efficient plumbing system are hidden from plain sight behind the walls.

Students work on the design challenge in small groups and have the flexibility to move around the classroom and interact with other groups. Like engineers, they share ideas and conflicting viewpoints about how to design the optimal system. These conflicts provide space for students to negotiate ideas with their peers and learn how to accommodate multiple design perspectives and optimize their design, helping them become better problem-solvers (Solomon and Hall 1996). Plumbing systems offer an authentic design context that students are familiar with but are still complex enough to keep them engaged. This design context also teaches students about pressing social issues such as depletion of water resources due to

CONTENT AREA

Engineering and physics

GRADE LEVEL

5–8

BIG IDEA/UNIT

Students learn how to deconstruct a design challenge, develop systems thinking by reasoning with multiple design parameters and making tradeoffs, weigh multiple solutions, and iterate for design optimization.

ESSENTIAL PRE-EXISTING KNOWLEDGE

None

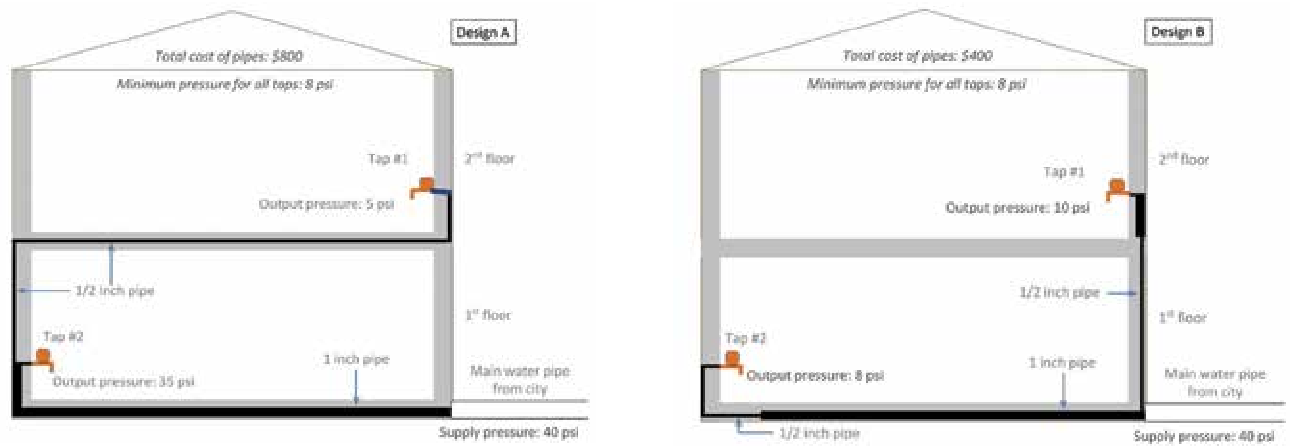
TIME REQUIRED

150–200 minutes

COST

Approximately $30 per class

FIGURE 1: Compare and contrast two plumbing systems



overuse and drought (UNDP 2006). While there are many factors leading to a water crisis, a critical factor is the inefficient use of our existing water resources due to poorly designed plumbing systems, which leads to unreliable water flow and wastage of water. For future citizens to tackle these issues, they need to learn how to make effective trade-offs and make informed design decisions in order to engineer optimal solutions.

Preparation

"Call the Plumber!" uses both virtual and real-world materials to immerse students in the engineering design process. In Call the Plumber!, students are part of a plumbing company and work in small groups of three to five students. Because activities vary from computer simulations, budget computations, discussions, presentations, and the use of tactile design boards, creating mixed-ability groups enables many types of learners to lead, feel successful, and learn from peers. The key to Call the Plumber! and the engineering-design process is the ability to record ideas, questions, information, design specifications, and prototype evaluations. The use of a science notebook is an effective tool for this; students create and add to a "Plumbing Company" notebook section throughout this challenge.

Empathize and define the problem (day 1: 40–60 minutes)

Begin by gauging students' prior knowledge with a brief discussion on plumbing. Ask students to share what they know about plumbing and their own experiences with "good" plumbing, who decides what is "good" plumbing, "bad" plumbing, and what goes wrong in "bad" plumbing. Then engage students in the engineering challenge by introducing the problem: The plumbing in the science lab is broken and you need to fix it. Students will create an optimal plumbing system that does not go over a $3,000 budget and meets minimum pressure requirements. A great way to introduce the problem is for the teacher to make a video about it or act out an emergency plumbing disaster. Then split the class into small groups and explain that they are now plumbing companies. The company with the most optimal design and "best" budget for the client, whose needs are defined by the teacher, will win the science lab contract.

Transition to the first challenge for the plumbing companies: Define an optimal system. Each company will examine two plumbing systems (Figure 1), identify the variables between the two designs, and decide which one is "better." Students should record their observations and ideas in their notebooks. Each company will create a brief presentation to the client (teacher) that includes variables in the system and the reasons for why one design is "better" than the other. These presentations can range from a PowerPoint, poster, or simple speech, depending on student abilities. After the presentations, summarize the variables (pipe length, pipe diameter, pressure, cost), and the concept of design choice, and introduce the terms "suboptimal" and "optimal."

Depending on the ability of your students, the first challenge and presentation can be anywhere from 30–90 minutes. If you have less time, the presentations should be simple speeches with each member of the group contributing one point. If more time is available, the presentations can be more creative, including visual aids such as a poster with each team member adding one or two items or a PowerPoint presentation with each team member making and presenting one or two slides.

Research the problem (day 2: 30–40 minutes)

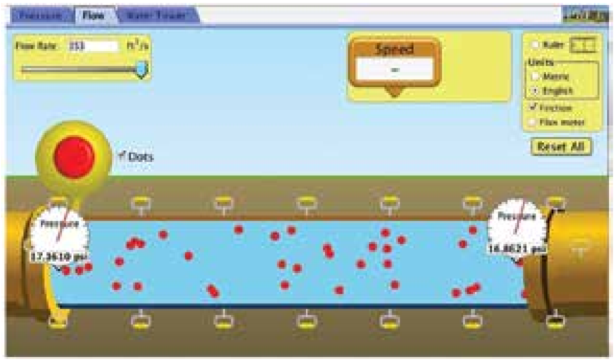
Now that students have an idea of the variables that affect plumbing systems, they will research how the variables are interrelated to make better design choices. Students will use the PhET Fluid Pressure and Flow simulation (Figure 2) to answer the question, "How does pipe length and diameter affect water pressure?" Students should explore the simulation by changing the diameter of the pipe and placing the two pressure gauges at different points along the pipe. Students should make observations and record pressure data in their notebooks. The observations can be recorded in a data table, written or graphic, depending on student abilities. Students should see that as the length of the pipe increases, water pressure is lost. Next, change the simulation as indicated in Figure 2b. Students should see that as the pipe diameter decreases, water pressure is also lost. This loss of water pressure is a result of the force of friction between the water molecules and the pipe. Depending on student abilities, there are several free resources listed on the PhET Fluid Pressure and Flow simulation page that could be used for more in-depth activities on psi, fluid dynamics, contact forces, and

FIGURE 2: PhET interactive simulations

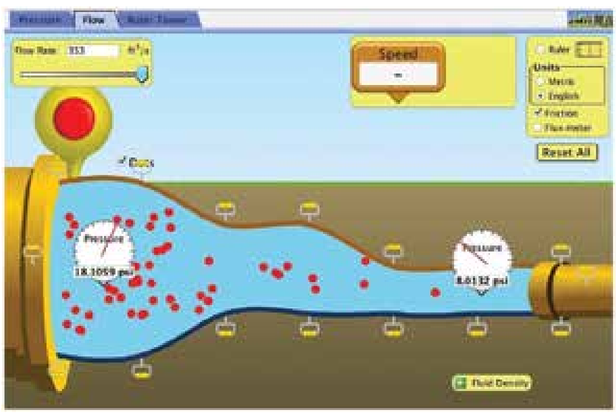
Fluid pressure and flow (*http://phet.colorado.edu*)
All simulations available at http://phet.colorado.edu are open educational resources available under the Creative Commons Attribution license (CC-BY).

Access the simulation at *http://phet.colorado.edu/en/simulation/fluid-pressure-and-flow*. After opening the simulation, select the "Flow" tab at the top, set the units to "English," select "Friction," and move the "Flow Rate" slider all the way to the left.

(a) Set the pipe so that the diameter is the same across its length and place one pressure gauge at the far right and the other at the far left.



(b) Pipe diameter and pressure: Set the diameter of the pipe so that the diameter is the largest at the far left and the smallest at the far right.



Students will explore how pipe length, diameter, cost, and other plumbing variables can influence their design choices.

the Bernoulli principle (see "PhET Fluid Pressure and Flow Simulation" in Resources). After students explore the simulation, engage the class in a discussion. Some example discussion questions around balanced and unbalanced forces and Newton's first law of motion (MS-PS2-2) are: What type of force acts between the water molecules and the pipe? How does an increase in pipe length or a decrease in pipe diameter increase the friction between the pipe and the water molecules? How is pressure related to force? How does a change in the pipe diameter create an unbalanced force that can affect the water pressure?

A formative assessment on these concepts will help solidify student understanding. This assessment should be tailored to the level at which the concepts were explored, and to the needs of students. The assessment can range from an exit ticket asking students how pipe diameter and length affect water pressure, to a homework or mini-quiz (where students predict relative water pressures from photos of different lengths and diameters of pipe), to a more formal test.

Identifying trade-offs (day 3: 40–60 minutes)

Next, students will explore how pipe length, diameter, cost, and other plumbing variables can influence their design choices. Instruct the class that they will use a plumbing simulation (see PlumbingSim in Resources) to see how pipe diameter, length, bends, and branches affect water pressure and cost for the model they will be building (Figure 3a). Assign each company a different pipe diameter (1″, ¾″, ½″) in the plumbing simulation. Some companies will have the same size, which will be important when students share the data they collected to check data accuracy. Students will place segments of pipe along a grid to record pressure drops and cost changes for their pipe diameter in data tables (outlined in Figure 3b). Each company shares the data they recorded, and then, as a class, completes the tables for each of the pipe diameters. Students then create "rules of thumb" for how the variables relate to one another by answering guiding questions as outlined in Figure 3b. (Note: Students will only be using their data tables and rules of thumb to design and build their models and will not be able to use the plumbing simulation again). Conclude with a discussion on what trade-offs are and what students might trade off when designing their plumbing system. Some possible trade-offs include high psi at faucets, with a high budget, or a low budget with lower psi at faucets.

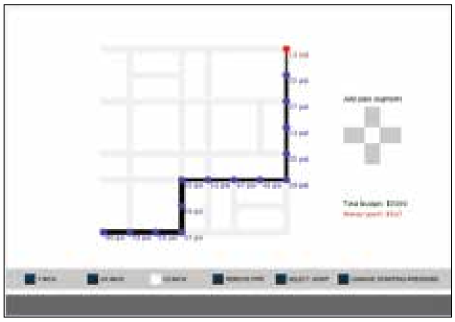
To assist with class management during this activity, divide the tasks (running the computer simulation, recording data in a table, recording the rules of thumb) among the company members based on each student's strengths or abilities. A quick formative assessment on student understanding of the rules of thumb and engineering concepts is helpful at this point. This assessment should be tailored to the needs of students but can be as simple as a three-question quiz asking students: "What are the variables we are taking into consideration with our plumbing designs?", "What is meant by the idea of 'trade-offs' in a design project?", and "What does 'optimal' mean in a design project?"

FIGURE 3: Screenshot of plumbing simulation, sample data tables, and rules of thumb

All simulations available at PlumbingSim (see Resources) are open educational resources available under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License

Instructions for using the simulation:

- Double-click on the software icon to launch the simulation.
- Select a pipe thickness (1", ¾", ½") and press the direction buttons (up, down, left, right) under "Add pipe segment." Switch pipe thickness by selecting the required thickness from the menu at the bottom.
- Place pipes only along the plumbing gray lines.
- Remove pipes by selecting the "Remove Pipe" option and clicking on a segment of the pipe you wish to remove.
- Place pipes from a joint that is not currently highlighted in red, choose "Select Joint" option, and click on the joint where you want to add pipe segments.
- Starting pressure can be changed by selecting the "Change Starting Pressure" and entering the desired pressure. The output pressure will update automatically.



Screenshot of plumbing simuation

Sample data tables and rules of thumb

Pipe diameter	Change in pressure drop	Rule of thumb questions and answers
1" pipe	1 psi	• What is the effect of the length of pipe on water pressure? • The longer the pipe, the lower the pressure. • What is the effect of the diameter of the pipe on water pressure? • The pressure drop increases as the pipe diameter decreases.
¾" pipe	4 psi	
½" pipe	12 psi	

Pipe diameter	Change in cost	Rule of thumb questions and answers
1" pipe	+$45	• What is the effect of length of pipe on cost? • The longer the pipe, the greater the cost. • What is the effect of diameter of pipe on cost? • The greater the diameter, the greater the cost.
¾" pipe	+$33	
½" pipe	+$28	

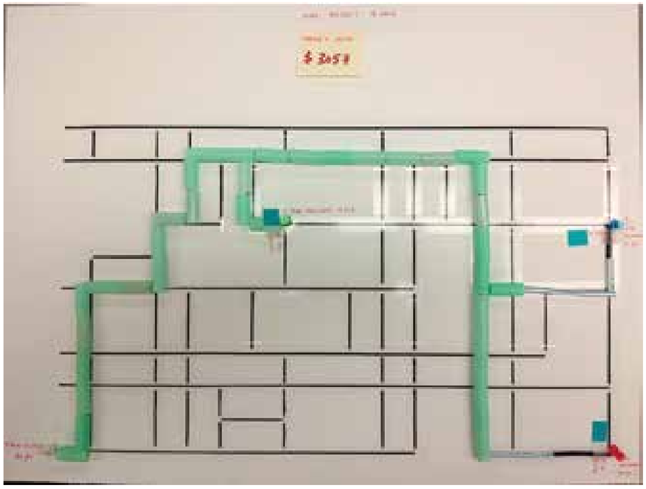
90° pipe bend	Change in pressure	Change in cost	Rule of thumb question and answer
1" pipe	Stayed the same	+$145	• What is the effect of a 90° pipe bend on the water pressure and cost? • A pipe bend does not change the water pressure but adds $100 to the cost. (Note: For simplicity purposes of this activity, it is assumed that pipe bend does not change the pressure.)
¾" pipe	Stayed the same	+$133	
½" pipe	Stayed the same	+$128	

Pipe branching	Change in pressure	Change in cost	Rule of thumb question and answer
1" pipe	Stayed the same	+$190	• What happens to pressure and cost when the pipe branches out? • A pipe branch does not change the water pressure but increases the budget; the greater the diameter, the greater the cost.
¾" pipe	Stayed the same	+$166	
½" pipe	Stayed the same	+$156	

FIGURE 4: Plumbing design board, sample final design, and sample student work

Instruction for making the design board:

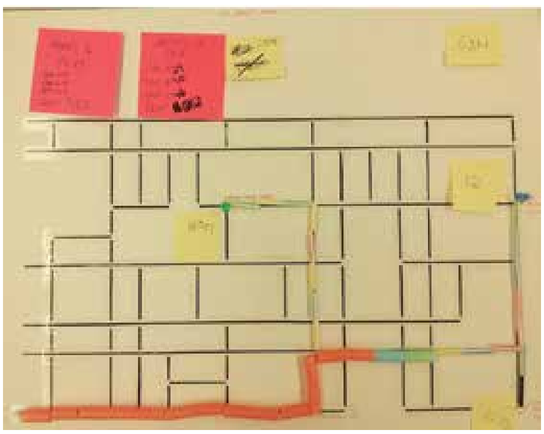
- Print the plumbing line template.
- Paste the template on a 20" × 30" sturdy foam board that won't easily bend. Using a black marker, trace the plumbing lines.
- Put double-sided tape on the template along the black plumbing lines only.
- Get straws of three different diameters (e.g., smoothie straws for 1" pipes, regular straight straws for ¾" pipes, and coffee stirrers for ½" pipes) and cut them into 1" segments.
- Place these pipe segments along the plumbing lines as shown in the suboptimal model example in Figure 4a and write the total cost as $3,057 at the top. Write the suboptimal pressures for Tap A (42 psi), Tap B (5 psi), and Tap C (0 psi).



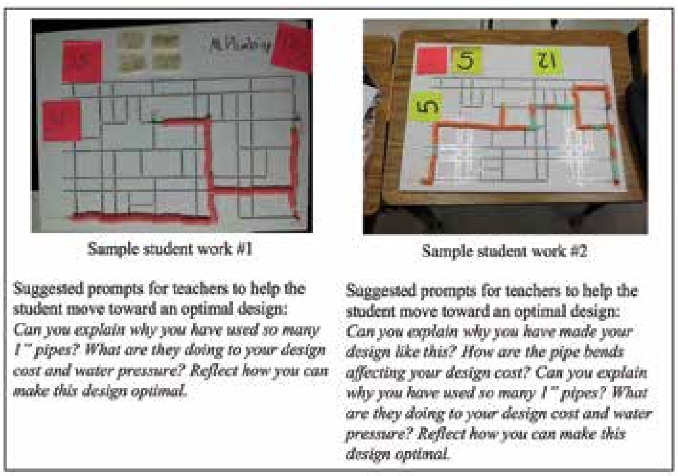
(a) Plumbing design board. Suboptimal example model.

Supply list

- Foam board can be purchased from any office supply store or online retailer. An average cost of a 20" × 30" foam board is approximately $5. This size can be cut in half to create two boards. A class set of six foam boards should cost approximately $15.
- Black markers and double-sided tape can be purchased from any office supply store or online retailer. One marker and one role of doubled-sided tape are required. Double-sided tape is approximately $5 per roll.
- Smoothie straws, regular straight straws, and coffee stirrers can be purchased from any office supply store, grocery store, or online retailer. You will need approximately 50 of each type of straw per class. Cost for a class set of straws should not exceed $8.



(b) Sample final design built by a student group



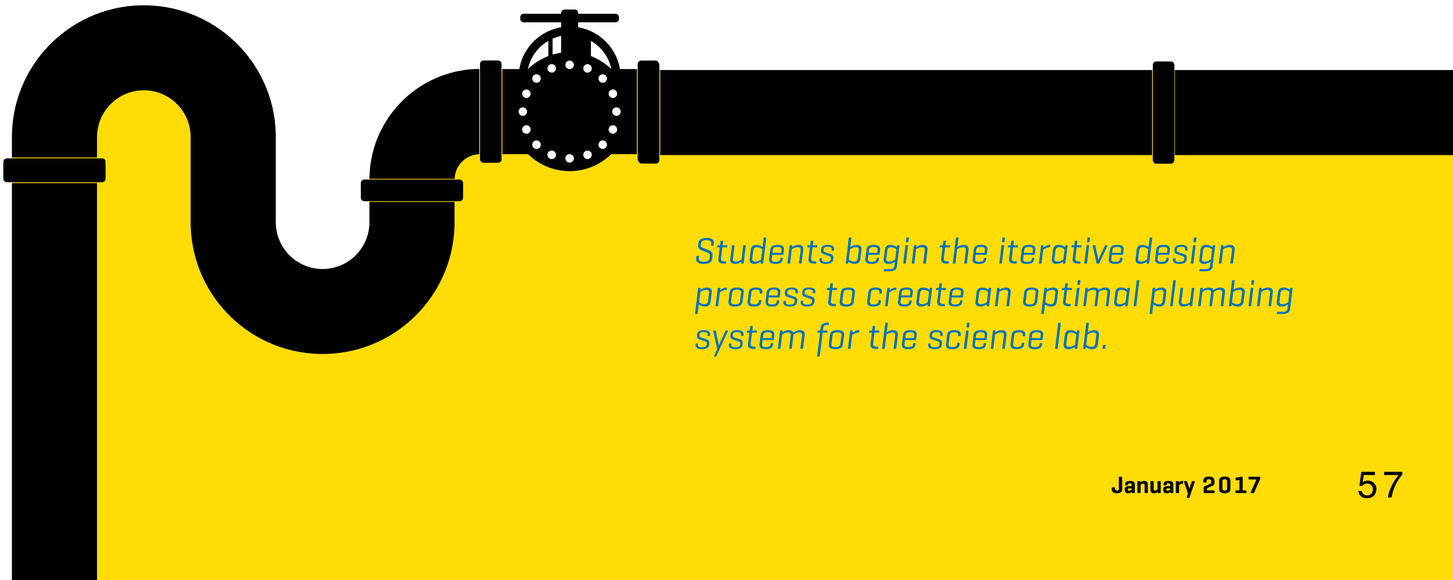
(c) Sample student work and suggested teacher prompts

Iteratively designing, prototyping, and testing the system (days 4 and 5: 60–120 minutes)

Students begin the iterative design process to create an optimal plumbing system for the science lab. *Safety note:* As with any activity, please make sure students follow appropriate safety procedures. Safety goggles must be worn when students are constructing and demonstrating their plumbing model. Students should also be cautious when using the push pins, which can pierce skin. Each company will get a plumbing design board with the plumbing lines, straw pipes, and push pins that represent the taps in a suboptimal layout (downloadable; see Plumbing-Sim in Resources). In the fictional science lab, there is one source and three taps. Each tap must have a minimum of 10 psi and students have to spend less than $3,000. The first step in the design process is for each company to list and record their criteria for their optimal plumbing system, define the "best" plumbing system (e.g., highest pressure, most cost effective), and decide what their trade-offs will be (see Online Supplemental Materials for the downloadable worksheet). Students should record the information in their notebooks. Information can be written or recorded graphically depending on student abilities. The criteria will be different for each company and will depend on what trade-offs students are willing to make and how they define "optimal." For example, some companies may decide that a plumbing system with the lowest budget is optimal, while others might determine that the highest psi at each tap is optimal. Each company will then go through two to four prototype cycles where they test out designs by placing different pieces of straw pipe on the foam board. At the end of each prototype, they should calculate the psi at each tap and the total cost, and answer reflection questions before they move on to the next prototype (see Online Supplemental Materials for a downloadable worksheet). For the final design, students should prepare a short presentation that includes the final psi at each tap, the final cost, an explanation of why their design is optimal, and what trade-offs they made. These presentations can be in the form of anything from a PowerPoint, poster, or simple speech, depending on student abilities.

Communicate and defend design solutions (day 6: 40 minutes)

Each company will use their plumbing boards and presentations from their final designs to communicate their solution to the class. Classmates should be encouraged to ask questions about design decisions and trade-offs so that each company can defend their design choices. The client (teacher) will then award the plumbing contract to the company with the most optimal plumbing system based on the client's needs or predispositions. This is purposefully vague as a way to customize this unit based on community and student needs. For example, drought may be a major concern in the fictional community and water conservation is important in an optimal system, or the client is thrifty so the budget is a major concern. Student notebooks and presentations are useful tools for assessing how they developed in the en-



Students begin the iterative design process to create an optimal plumbing system for the science lab.

The design context helps students connect new knowledge with their prior knowledge and learn how to solve real-world design challenges by taking into consideration the impact of their solutions.

gineering design process and their understandings of optimization and trade-offs. Assess the use of data and observations to evaluate the plumbing system against the defined criteria and its ability to improve successive prototypes when grading the prototype evaluations and final analysis questions (a sample downloadable rubric for assessing student work from iteratively designing, prototyping, testing, and presenting their system is available; see Online Supplemental Materials).

Conclusion

This curricular unit helps middle school students engage with core engineering design practices using physical models. The design context helps students connect new knowledge with their prior knowledge and learn how to solve real-world design challenges by taking into consideration the impact of their solutions. Students productively engage with the iterative design process and learn how to make effective trade-off decisions by generating design heuristics, comparing and evaluating solutions, and analyzing data to create an optimal design. The ability to critically analyze data and make informed design decisions helps inculcate a mindset that is prepared to engineer optimal solutions for present and future social challenges. ●

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RESOURCES

PhET fluid pressure and flow simulation—*https://phet.colorado.edu/en/simulation/fluid-pressure-and-flow*

PlumbingSim—*http://chandandasgupta.com/PlumbingSim.html*

ONLINE SUPPLEMENTAL MATERIALS

Worksheet and rubric—*www.nsta.org/scope1701*

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

MS-PS2-2: Motion and Stability: Forces and Interactions
www.nextgenscience.org/pe/ms-ps2-2-motion-and-stability-forces-and-interactions

Performance Expectations

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.

MS-PS2-2. Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.

DIMENSIONS	CLASSROOM CONNECTIONS
Science and Engineering Practice	
Developing and Using Models	Students use the iterative design process to create an optimal plumbing system for the science lab.
Disciplinary Core Ideas	
ETS1.A: Defining and Delimiting an Engineering Problem • The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that is likely to limit possible solutions.	Students examine an optimal and suboptimal plumbing system, and run simulations to understand how variables (pipe length, diameter, pressure, and cost) affect a plumbing system. Students use simulations to investigate the effect of length of pipe on the water pressure.
PS2.A: Forces and Motion • The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion (MS-PS2-2).	Students use a fluid pressure and flow simulation to investigate how pipe length and diameter affect water pressure. Through observations and class discussions, students understand that a change in pipe diameter or pipe length causes a loss of water pressure, which is the result of the unbalanced contact forces between the water molecules and the pipe (friction).
Crosscutting Concepts	
Cause and Effect Systems and System Models	Students use computer simulations and a physical model to simulate systems and interactions and understand that systems can be designed to cause an increase or decrease in pressure or an increase or decrease in a budget.

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

ELA

CCSS.ELA-LITERACY.SL.8.4: Present claims and findings, emphasizing salient points in a focused, coherent manner with relevant evidence, sound valid reasoning, and well-chosen details.