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The INSPIRES Curriculum

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Students Working on Hemodialysis Module

Image courtesy of Ezana Dawit, Justin Santos, and Gabrielle Salib.

The INSPIRES Curriculum (INcreasing Student Participation Interest and Recruitment in Engineering and Science) is comprised of five standards-based modules for grades 9–12 that focus on integrating all areas of STEM. Our approach uses real-world engineering design challenges and inquiry-based learning strategies to engage students, increase technological and scientific literacy, and develop key practices essential for success in STEM disciplines. The curriculum is flexible and cost effective. Modules are independent of one another, so they can be implemented individually in an existing science or technology education course or together to comprise a full course.

The INSPIRES Curriculum is currently available by contacting the authors at inspires@umbc.edu.

Although the INSPIRES Curriculum was developed prior to the publication of *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), all modules align closely to this vision and the NGSS (NGSS Lead States, 2013) performance expectations related to engineering design. The curriculum modules target all eight Science and Engineering Practices and therefore provide a strong platform for discussion of the relationship between engineering and science. Each of the INSPIRES modules utilizes a different engineering design challenge and therefore targets different science disciplinary core ideas and crosscutting concepts.

Design Principles

Each module follows a common lesson plan structure and is based on the following curriculum design principles:

1. C**ontext.** Real-world, defined problem space that provides intellectual challenge for the learner
2. **Standards Based.** Publications that define the language and methods of the larger community, including the *National Science Education Standards* (NRC, 1996), *Standards for Technological Literacy* (ITEEA, 2000, 2005, 2007), and *Common Core State Standards* (NGA & CCSSO, 2010).
3. **STEM Practices.** As defined by *A Framework for K–12 Science Education*
4. **Collaboration:** Interaction between students, teachers, and community members to share information/designs, negotiate alternatives and build consensus
5. **Public Artifacts:** Public representations of ideas or practices that can be shared, critiqued, and revised to enhance learning
6. **Metacognitive:** Opportunities to explicitly (1) recognize the nature of STEM practices, (2) interpret key STEM concepts individually, and (3) revise designs and reports based on feedback

Principles 1, 2, and 3 are based on the theory of situation cognition—that knowing is inseparable from doing, and that knowledge develops in social, cultural and physical contexts (Linn & Hsi, 2000; Singer, Lotter, Feller, & Gates, 2011). Principles 4, 5, and 6 are based on the theory that making thinking visible by encouraging meaningful dialogue focused on science content will help students not only increase subject matter knowledge but also improve their reasoning abilities (Garet, Porter, Desimone, Birman, & Yoon, 2001; Lotter, Singer, & Godley, 2009; Rushton, Lotter, & Singer, 2011). Each of these principles plays out in the form of specific instructional strategies, as we will describe in two of the curriculum modules.

Where Does INSPIRES Fit in the High School Curriculum?

Each module is approximately six weeks in length (assuming a 45 minute class period) and is structured for students who have Algebra I competency. Modules have been tested for efficacy in various settings, including biology, physics, chemistry, allied health, and technology education classrooms. Table 1.1 suggests course placement for each module. In most cases, a single module is chosen for implementation based on the STEM content fit for the given course. Alternately, the modules can be grouped together to form a complete semester or full-year "Engineering Design" course.

Following are brief descriptions of two of the INSPIRES modules: "Engineering in Healthcare: A Hemodialysis Case Study" and "Engineering Energy Solutions: A Renewable Energy System Case Study." Design principles associated with the various activities are indicated in (**bold**).

Table 1.1 INSPIRES Curriculum Modules

INSPIRES Module	Science Concepts Currently Included	Recommended Course Placement
Engineering in Healthcare: A Hemodialysis Case Study	• Diffusion/Selective diffusion • Equilibrium • Membrane structure • Fluid flow/Flow rates	• Biology • Technology Education • Allied Health
Engineering in Healthcare: A Heart-Lung System Case Study	• Heat transfer • Fluid flow/Flow rate/Pumps • Anatomy and physiology of the heart and lungs	• Physics • Anatomy/Physiology • Technology Education
Engineering Energy Solutions: A Renewable Energy System Case Study	• Work/Power/Energy • Gears/Simple machines • Systems/System efficiency • Renewable resources	• Physics • Technology Education
Engineering and Flight: A Hot Air Balloon Case Study	• Forces/Force balances • Weight/Density • Buoyancy • Heat transfer • Material properties • Properties of an ideal gas	• Physics • General Physical Science • Technology Education
Engineering and the Environment	• Currently under revision to enhance fit in chemistry	• Chemistry • Environmental Science • Technology Education

Engineering in Healthcare: A Hemodialysis Case Study

An introductory video focuses on a teenage girl with kidney failure who undergoes hemodialysis on a regular basis. The video describes her treatment, introduces her doctor, and explains the function of a modern hemodialysis machine (**Context**). Student teams are given the challenge to design, build, test, and refine a system that mimics attributes and functions of a hemodialysis system, including the removal of a minimum of 2.5 mg of "waste" from simulated "blood." Design teams are challenged to maximize efficiency while minimizing system cost. The maximum system cost is set at $50 (**STEM Practices**). After watching the video and receiving the challenge, students use a "Think, Pair, Share" strategy to reach consensus (**Collaboration**) on key ideas as well as the criteria and constraints required to construct a design solution.

Example Classroom Display: Design Target Poster

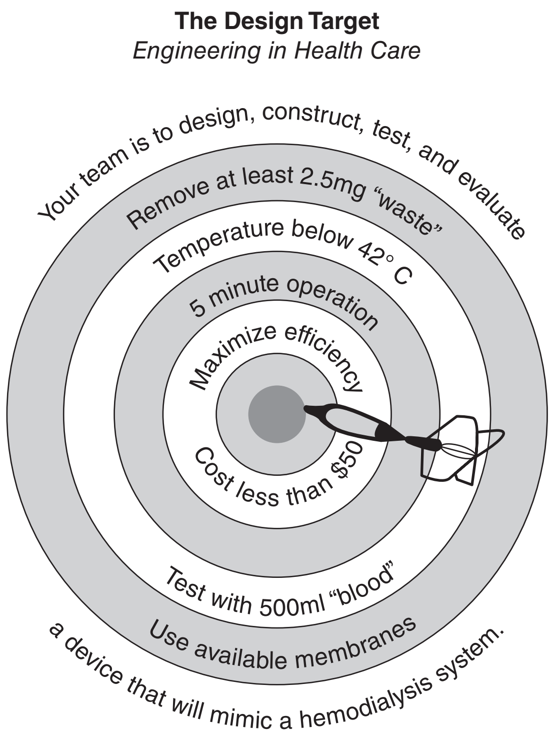


Image courtesy of the University of Maryland.

As students attempt to solve the design challenge, they are introduced to the engineering design process as a rational and methodical cycle of steps (**STEM Practices**). The various steps are explicitly addressed during the lessons to ensure that students understand each process they use (**Metacognition)**. A large classroom poster is used to facilitate these explicit connections (**Public Artifacts**). To understand the various design constraints and criteria as well as make informed design decisions, the students learn relevant scientific principles as well as mathematical equations to quantitatively assess and refine their design (**Standards Based**).

In this module, students learn concepts associated with (1) diffusion/selective diffusion, (2) equilibrium, (3) membrane structure and function, and (4) fluid flow. These science concepts are introduced in the curriculum through a variety of "just in time" phenomena-first activities (**Context**) and inquiry-based investigations (**STEM Practices**). First, student teams are presented with a mini design challenge in which they must design and test an apparatus to separate Rice Krispies® from a complex mixture of breakfast cereals. This hands-on exercise is used to introduce the concept of separating a component from a mixture in a way that is visual to the learner. It is also used to reintroduce the engineering design process (**Context/Standards**). Students must consider the physical properties of the various cereal components as they begin their designs and decide on properties that could be used as a basis for separation. Prior to receiving teacher approval to start device construction and testing, individual group members submit potential design solutions, then engage in small group discussion to build consensus (**Collaboration**) on a prototype design. Most student groups focus on size as the basis for separation, which is consistent with the overall hemodialysis design challenge. Group presentations of designs and design decisions link the exercise to the overarching hemodialysis design challenge.

Students then learn more about the function of the kidneys and how dialysis works. Fundamental concepts such as concentration, concentration gradient, molecular motion, and diffusion are introduced through a serious of hands-on exercises. Students visualize the concept of selective diffusion by observing the movement of a dye across a semipermeable membrane. Students then consider and explore various factors that influence the rate of diffusion and the total amount of mass transfer in a given time period. These factors include the effects of temperature, molecular weight, membrane pore size, and membrane surface area. Finally, students investigate ways to make fluid flow and learn how fluid flow is measured and described quantitatively. This allows design teams to consider how fluid flow may be used in the design of a hemodialysis system.

Following hands-on exploration, students use online models and animations to illustrate the "nonvisible" mechanism(s) driving many of the observed macroscopic events. Concepts of molecular motion and diffusion are stressed, linking the online visualization to the hands-on activities. Computer-based mathematical simulations are utilized prior to the final design and build phase allowing students to alter a variety of design parameters and quantify their impact on system efficiency (**STEM Practices**). Students then plan, build, test, and refine a "hemodialysis system" (**Integrates all principles**). Student teams present their final designs along with an analysis of design decisions in an open forum **(Collaboration/Public Artifacts)**. Concepts and key ideas are reinforced and continuity between lessons is maintained through the use of a design notebook and by having students post artifacts representing their understanding (**Metacognition**) on a classroom artifact board (**Public Artifacts**).

Example Online Animation: Students manipulate parameters on the right and visualize the effect on molecular motion.

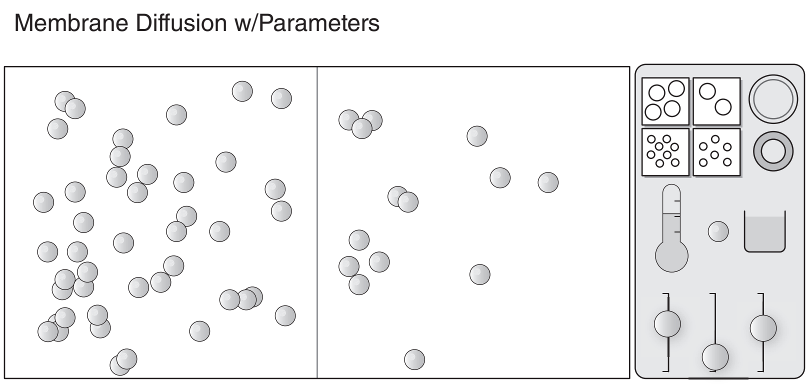


Image courtesy of the University of Maryland.

Engineering Energy Solutions

A Renewable Energy System Design Challenge

An introductory video focuses on how society uses energy, the structure of modern energy systems, current and projected energy challenges, and the need for the development of renewable energy strategies. Students learn that many steps are involved in supplying energy to the consumer, including collection, conversion, storage, and transport (**Context**). Student teams are given the challenge to design, build, test, and refine an energy system that (1) collects energy from a renewable source (hydro, wind, or solar), (2) stores the energy, (3) transports the energy to a testing location, (4) converts the energy to a useful form, and then (5) powers a 0.4 watt light bulb for a minimum of 15 seconds. Design teams are challenged to maximize system performance while minimizing system cost. The maximum system cost is set at $100 (**STEM Practices**). After watching the video and receiving the challenge, students use a Think, Pair, Share strategy to reach consensus (**Collaboration**) on key ideas as well as the criteria and constraints required to construct a design solution.

As students attempt to solve the design challenge, they are introduced to the engineering design process as a rational and methodical cycle of steps (**STEM Practices**). The various steps are explicitly addressed during the lessons to ensure that students understand each process they use (**Metacognition)**. A large classroom poster is used to facilitate these explicit connections (**Public Artifacts**). To understand the various design constraints and criteria as well as make informed design decisions, the students learn relevant scientific principles as well as mathematical equations to quantitatively assess and refine their design (**Standards Based**).

As in the Hemodialysis module, students are introduced to the engineering design process (**STEM Practices**). Through the activities unique to this module, they learn concepts associated with (1) work/power/energy, (2) gears/simple machines, (3) systems/system efficiency, and (4) renewable energy resources. These science concepts are introduced in the curriculum through a variety of just in time phenomena-first activities (**Context**) and inquiry-based investigations (**STEM Practices**). First, student teams are presented with a mini challenge in which they must design a system to use hydropower (2 qt. of water) to raise a weight as quickly as possible. This hands-on exercise introduces the concepts of work and power and reintroduces the engineering design process (**Context/Standards**). Students learn how to measure work in this system and calculate power, exploring the relationship between the two concepts. Prior to receiving teacher approval to start device construction and testing, individual group members submit potential design solutions, then engage in small group discussion to build consensus (**Collaboration**) on a prototype design. Group presentations of designs and design decisions link the exercise to the overarching energy system design challenge. Students next learn about gear systems and how they can be used to increase the work done by a system (mechanical advantage) and transfer motion or power from one moving part to another. Using hands-on activities, teams explore gear function and gear ratios. Design teams are then issued a follow-up mini challenge to incorporate gears into their systems to increase performance.

Students next learn about energy conversion through hands-on activities using a solar cell and windmill. In the first activity, groups use solar power to lift a weight, thereby learning how a solar cell works and how a motor converts electricity into kinetic energy. A second activity focuses on the conversion of kinetic energy from a windmill into electricity using a generator. Students learn how to calculate work, power, and efficiency. Students then learn about how energy is stored, how energy is transported and how each step in an energy system combines to yield the overall system efficiency. Mathematical calculations for efficiency are included.

After hands-on exploration, students use computer-based mathematical simulations to alter a variety of design parameters and quantify their impact on the system efficiency (**STEM Practices**). Students then plan, build, test, and refine a renewable energy system to meet design criteria (**Integrates all principles**). Student teams present their final designs along with an analysis of design decisions in an open forum **(Collaboration/Public Artifacts)**. Concepts and key ideas are reinforced and continuity between lessons is maintained through the use of a design notebook and the classroom artifact board (**Public Artifacts**).

Example of Hands-on Activity

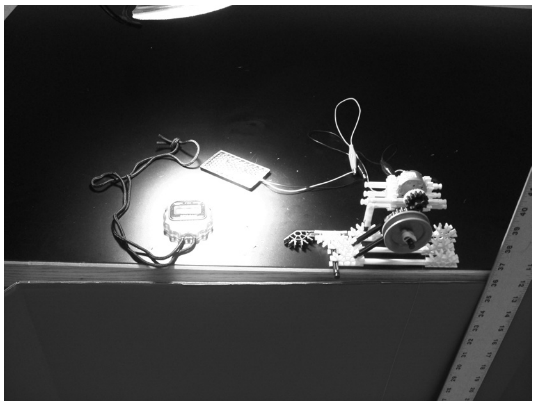


Image courtesy of the University of Maryland.

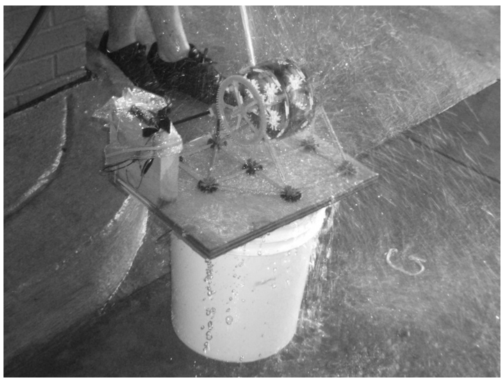
Instructional Materials

Instructional materials for the INSPIRES Curriculum consist of a variety of components for each module as described below.

Design Challenge. Each module includes an overarching open-ended engineering design challenge that focuses on a real-world problem or need. The design challenges are written with quantitative design criteria and constraints and require students to make decisions about trade-offs as they move through the design process. The challenges have enough

Example of Student Energy Collection Devices

a



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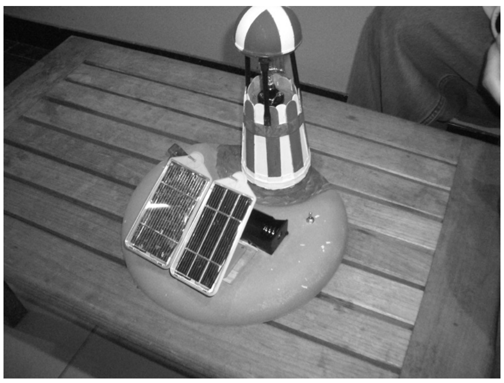

Images courtesy of the University of Maryland.

specificity to allow solution within a week to two weeks of class time but are open-ended enough to allow for significant creativity in the design solution.

Lesson Plans. Complete lesson plans for each module include detailed instructions for presenting content and doing hands-on activities and suggest appropriate pedagogical strategies. Student handouts and worksheets are included to facilitate instruction.

Classroom Display. Electronic files suitable for printing at poster size for classroom display are available, including the "Engineering Design Loop" and a "Design Target" specific to each module.

Video Content. The curriculum uses professionally produced video segments to introduce students to the real-world application and societal need behind each engineering design challenge. Videos also introduce students to career pathways related to the module content.

Online Animations and Mathematical Simulation. All modules include an online mathematical simulation that allows students to vary parameters specific to the design challenge. In doing so, students explore quantitatively how these changes affect system performance. Selected modules also include online animations that allow students to visualize molecular level phenomena responsible for macroscopic behavior.

Assessments. The curriculum includes end-of-module multiple choice tests to assess student learning of engineering and science concepts. These tests can also be given before a module, if evidence of student growth is required. Scoring guides for assessing individual and team performance on engineering design tasks are also included in the curriculum materials.

Laboratory Equipment and Supplies. The INSPIRES Curriculum is designed as a low-cost solution to integrating engineering into the high school classroom. The curriculum does not require the purchase of expensive core equipment and relies heavily on common science lab supplies and materials often found in art rooms or woodshops. Almost all materials needed to complete the modules are available through retailers such as Walmart®, Target®, Radio Shack®, Home Depot® and Lowes®. Recycled and common materials are used as much as possible.

Tips for Maximizing Student Success

From the beginning, INSPIRES was developed as an integrated STEM curriculum that focuses not only on engineering design but also scientific and mathematical concepts and reasoning. The ultimate learning goal associated with the INSPIRES modules is to support students in making explicit connections among design decisions, underpinning STEM concepts and the contextualizing challenge. As a result, this integrated approach aligns very well with the NGSS. However, it also presents challenges for teachers not accustomed to teaching in this manner. To be successful, the classroom teacher needs to consistently keep the integration of Content, Context, and Practice (Design Principles 1–3) visible by employing instructional strategies consistent with Design Principles 4–6.

1. **Make explicit connections to the overarching design challenge during each lesson.** Student learning is maximized with the INSPIRES modules when students are pressed to provide rationales for their design decisions that are grounded in foundational STEM concepts and practices. These foundational concepts are learned throughout the modules using an inquiry-based format. Most science teachers are familiar with inquiry-based strategies such as a predict-observe-explain cycle that provides hands-on common experiences prior to introducing formal definitions. This type of strategy has been the accepted norm of high quality science education for decades. However, in the case of the INSPIRES Curriculum, taking an additional step to facilitate connections between the newly introduced idea and how that concept may be applied in the actual design challenge is key. Making such connections on a routine basis will help students keep focused on the overarching learning goals.

2. **Use simulation results to inform design decisions.** Each of the INSPIRES modules includes computer-based lessons that occur just prior to the final system design, build, and test activities. The computer-based lessons include a tutorial style program that reviews key concepts followed by a set of questions that must be answered correctly before continuing onto the next idea. An incorrect response prompts the student for further review. In addition, a mathematical simulation is included that allows the learner to systematically manipulate one design variable (e.g., flow rate in the Hemodialysis module) while holding the other design variables constant in order to quantitatively predict system performance. A data chart is generated showing the results of the simulation and can be used to make informed design decisions. The combination of computer lessons fulfills the same purpose as the meaning-making sequence required at the conclusion of each inquiry-based activity. The tutorial reviews the fundamental STEM concepts while the simulation applies that information directly to the design challenge. Teacher survey data have indicated that when teachers run short on time it is these two lessons that tend to be skipped. As a result, the design, build, and test phase often takes longer because students do not know what combination of design parameters are likely to lead to a successful design. Therefore, requiring students to justify design decisions based on results of the simulation will lead to less "trial and error" and shorten the time needed to enact the module.

3. **Emphasize planning and rationale for decision making.** When enacting lessons requiring students to plan, build, and test an apparatus, teachers tend to place too much emphasis on the "build" and insufficient emphasis on "plan" and "test." Many students approach design projects with an initial attitude of trial and error. When given a design task such as those described in the section above, students will enthusiastically start putting pieces and parts together to build something. This "rush to build" may also be inadvertently supported by the teacher in response to time pressures or the teacher's own enthusiasm for students' eagerness. As a result, many teachers focus on the actual building process and lose sight of the larger educational goals. This overemphasis on the building phase can also cause groups to become fixated on construction issues and lose sight of the larger purpose of the design challenge. For example, student groups may fixate on trying to repair a small leak in the hemodialysis system, even though the leak does not greatly affect system performance. As a result, students may spend a great deal of

time on activities that are not supporting new or deeper learning of STEM content. It is therefore imperative that the teacher be able to redirect groups and make a determination if the quality of construction is sufficient to collect the required design performance data.

In many ways, the building activity is less important than what should occur immediately before and after. Prior to building, students should be involved in a structured planning phase. In this phase, the teacher should require a plan illustrating and explaining how the design will be constructed as well as criteria that will be used to measure the level of design success. Requiring students to provide a rationale grounded in the understanding of STEM concepts and the results of the mathematical simulation is at the heart of the learning objectives. Similarly, at the conclusion of the building activity the teacher should organize a class discussion that explicitly makes connections to the importance of the systematic approach they used, connecting the approach to the accepted practices of the STEM field (e.g., Design Loop or Scientific Method). After testing, results should be related back to design decisions and STEM understanding.

Connection to the NGSS

In its current form, the INSPIRES Curriculum targets multiple aspects of the NGSS. Each module focuses on distinct scientific content. Therefore, coverage of NGSS performance expectations with respect to science concepts varies from module to module. Similarly, mapping to the NGSS Crosscutting Concepts varies from module to module. However, each INSPIRES module was developed to focus on engineering design and the approach to design is consistent across the curriculum. As a result, each INSPIRES Curriculum module targets all four HS-ETS1 Engineering Design performance expectations as shown in Table 1.2 and all eight NGSS Science and Engineering Practices as shown in Table 1.3.

Table 1.2 Mapping of INSPIRES to Performance Expectations in the NGSS

NGSS Performance Expectation	INSPIRES Curriculum Component
HS-ETS1-1: Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.	Each INSPIRES module includes an overarching real-world engineering design challenge. While criteria and constraints are included in the challenge, students must prioritize criteria, consider trade-offs and include constraints that are specific to their classroom or situation.
HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.	In each module, student teams design and build an apparatus or system to meet performance criteria. Learning is scaffolded to focus on various technical aspects of the design independently prior to performing the overall design and build.

NGSS Performance Expectation	INSPIRES Curriculum Component
HS-ETS1-3: Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible societal, cultural, and environmental impacts.	After the student teams design and build an apparatus or system, they must test and evaluate performance based on design criteria, cost, and safety. Groups must document trade-offs and explain how constraints impact their design. If time permits, redesign is recommended. During final presentations, groups evaluate and discuss the design solutions of other teams in the class.
HS-ETS1-4: Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.	Each module includes an online mathematical simulation in which students vary several design parameters and investigate the effect the changes have on system performance and cost.

Table 1.3 Mapping of INSPIRES to Practices of Science and Engineering in the NGSS

Practice	Science	Engineering
1. Asking questions and defining problems		X
2. Developing and using models	X	X
3. Planning and carrying out investigations	X	X
4. Analyzing and interpreting data	X	X
5. Using mathematics and computational thinking	X	X
6. Constructing explanations and designing solutions		X
7. Engaging in argument from evidence		X
8. Obtaining, evaluating and communicating information	X	X

In addition to targeting specific engineering and science content knowledge, the INSPIRES Curriculum is designed to develop critical thinking skills foundational for student success in STEM fields. Each module focuses on the following skill sets:

- **The ability to effectively work in teams and communicate technical ideas** both orally and in writing.
- **The ability to solve an open-ended problem**. Students using the INSPIRES Curriculum address questions such as: Is the problem under- or overdefined? What do you need to know in order to solve the problem? Are you lacking necessary information? If so, can you get the information? Do you need to make assumptions or approximations to bridge the gap between what you need to know and what you do know? What constraints are there on the solution (i.e., what is the acceptable "solution space")?

- **The ability to synthesize** what is learned in science and mathematics classes **and to apply** the **knowledge** to a real-world open-ended problem. This skill asks students to transfer what they are learning in one environment and to use the information in another way.
- **The ability to describe the natural world using mathematics.** With the INSPIRES Curriculum, students learn how mathematics is *used* to aid in the solution of a complex open-ended problem. Students focus on questions such as the following: What calculation do we need to do? Why is that the appropriate calculation for this problem? What will happen to the solution if I change a certain parameter? How does this information help me solve the engineering design problem?
- **The ability to think creatively** with respect to the solution of an open-ended problem. Student teams are encouraged to develop a solution to the design challenge that is unique.

Conclusion

The INSPIRES Curriculum was developed by engineering and secondary education faculty at the University of Maryland, Baltimore County in collaboration with faculty from the University of Maryland School of Medicine. To date, the curriculum has been used by over 170 science and technology teachers impacting more than 4500 students in the mid-Atlantic region. Our research program has shown that the curriculum enables students to achieve significant learning gains in science and engineering.

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