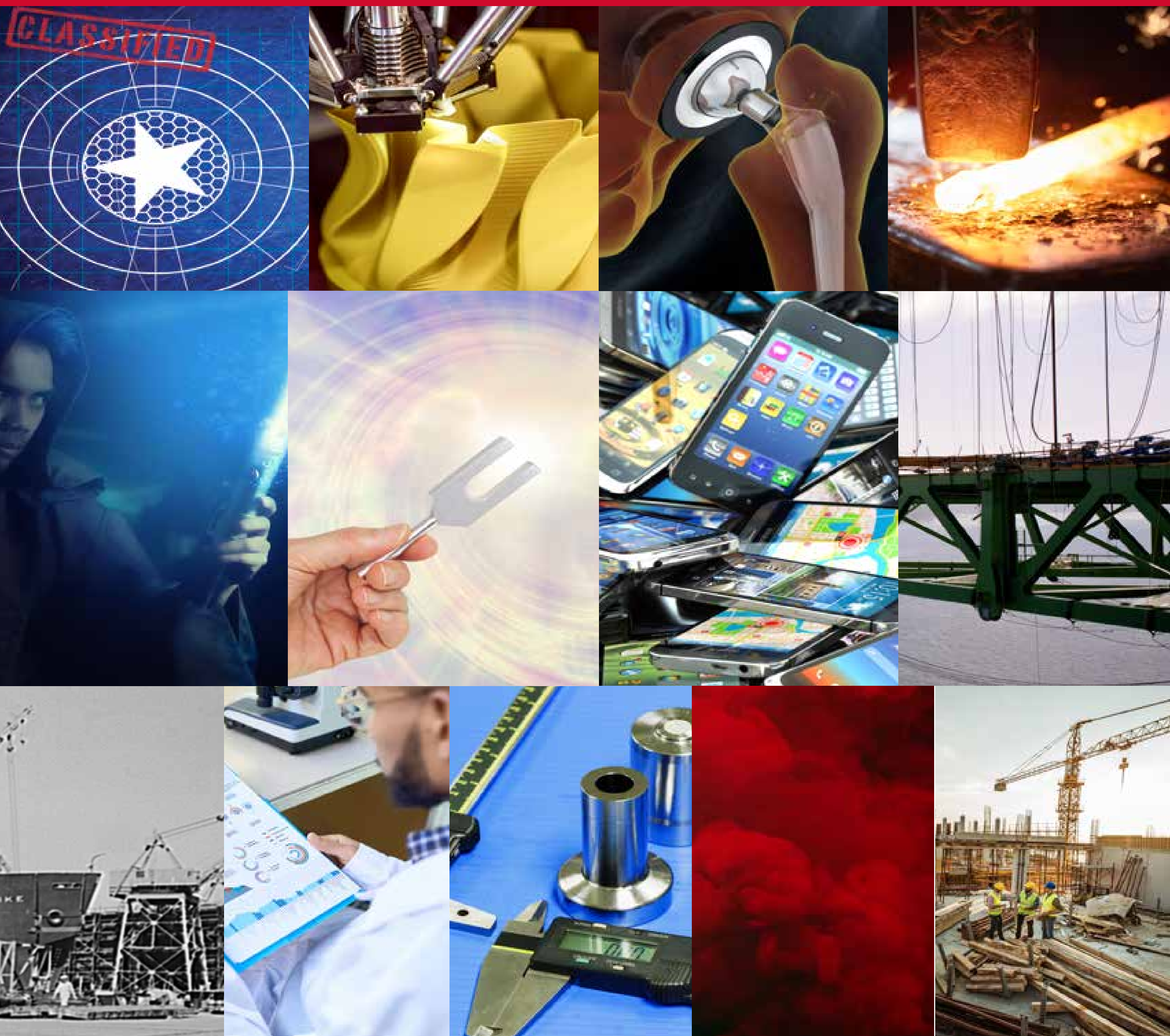
MATERIALS™ EXPLORERS

# *MATERIALS EXPLORERS*™: TEACHERS GUIDE



MATERIALS™ EXPLORERS

# ADDITIVE MANUFACTURING

**Additive manufacturing is transforming design and production across a variety of industries and, with access to 3D printers becoming even more common, additive manufacturing may also change the way consumers access custom items or bring their own ideas to life. Learn more about this revolutionary technology in this chapter.**

**In this module students will be able to:**

- Describe the difference between subtractive processes, forming processes, and additive manufacturing
- Identify various forms of additive manufacturing
- Identify applications of additive manufacturing
- Create and evaluate a prototype
- Explain some potential benefits and limits of additive manufacturing

## Class Activity

### TEAM DESIGN CHALLENGE

**Background:**
What do you think of when you hear the term 3D printing? Did you know 3D printers are being used to create beautiful works of art? Or that NASA is looking into 3D printing shelter for future astronauts on Mars?

Over the last few years, access to 3D printers has exploded, and they can now be found in many schools, office supply stores, and even homes. You can also design your own products and have them printed for you through online vendors. In industry, 3D printing is referred to as **additive manufacturing**, a relatively new process which literally adds materials layer by layer until the desired object is fabricated.

While much of 3D printing uses plastic as the material for fabrication, additive manufacturing for many industrial applications uses metal powder with the layers joined together, or sintered, using a laser. This process is known as Selective Laser Melting. The process begins with the use of 3D modeling software to create a **Computer Aided Design (CAD)** file. The software allows for mathematically precise designs that can take into account exactly how the part will be used and the potential stresses it will need to manage in order to work effectively. The additive manufacturing machine reads this digital file and slices it into virtual layers that serve as the blueprints for the product. Each of these layers defines the path the laser point of light follows as it moves rapidly along the surface of the metal powder to sinter the powder into a solid layer of metal. This process is repeated one layer at a time, with material being added until the three-dimensional part is ready.

To understand what makes additive manufacturing so groundbreaking, it is helpful to first understand more traditional manufacturing processes. **Subtractive manufacturing** dates as far back as prehistoric society. Ancient hunter-gatherers produced survival tools such as spears or arrows by chipping away at wooden sticks until a sharp point was formed. Similarly, they learned to create sharp stone arrowheads by using even harder stones to chip away at the material until it obtained the desired shape. Today, such processes are carried out much more quickly and with greater precision using automated machines, and on more durable materials, such as the metals and alloys used throughout industry. However, the basic principle of creating a product by subtracting from a larger block of material remains the same.

As the ability to generate higher temperatures by fire was attained, the Iron Age and Bronze Age saw the development of **forming processes** such as casting liquid metal and hammering heated metal.

## Class Activity

This provided the ability to make more varied and useful shapes, as well as elaborate artwork. In modern industry, these processes are highly automated and are the backbone, along with machining (subtractive processes), of mass production, which makes many of the products that we enjoy today possible

So where does additive manufacturing come in? Additive manufacturing is the next chapter in the ongoing progression of manufacturing toward improved products. Unlike subtractive and forming processes which produce wasted material which must be recycled or discarded, additive manufacturing saves on cost and materials by producing no waste.

Initially, the focus of additive manufacturing was to create models or prototypes before they were produced on a large scale. However, the purpose of additive manufacturing has shifted to fabricating final products that require customization or exacting precision for use in biomedical applications, transportation, and even fashion. In addition to deciding what material is best for an application, scientists and engineers also think about the particle size, or **voxel**, being used. This activity will ask you to consider the challenges of working with different sized particles.

### Problem

You and a classmate have entered a gameshow and your challenge is to use an additive manufacturing process to create two identical prototypes using sugar and glue.

**Task:**
You and your partner are tasked with creating two identical shapes using glue and sugar. The shapes can be either a heart, diamond or triangle but your designs must match one another's. One prototype will be created by gluing together layers of sugar cubes, while the second prototype will be created by gluing layers of sugar granules.

**Requirements:**
1. The prototypes must clearly resemble the intended shape.
2. The prototypes should be sturdy enough that they can be picked up without falling apart.
3. Both prototypes must have the same shape and dimensions (width, length, and height).

## Class Activity

### Questions

1. **List one advantage and one disadvantage of each material used (sugar cubes and sugar granules).**

2. **The engineering design process entails identifying a problem, brainstorming solutions to the problem, creating solutions to the problem, evaluating the solutions, and refining the solutions. After evaluating your prototypes how would you change your process in the following scenarios?**
   - **i.** You are only given 5 minutes to construct the same prototype. Which method would you select and why?
   - **ii.** You have unlimited time but are asked to create an accurate copy of any given shape. Which method would you select and why?

3. **While there are many benefits to additive manufacturing, it is not always the best process for the job.**
   - **i.** Research subtractive, forming, and additive manufacturing processes and briefly describe each process.
   - **ii.** For each of the processes above, identify one application where it is the preferred production process and explain why that may be.

4. **How would this experiment differ if you had to replicate the subtractive method of manufacturing by chipping away at a block of sugar to create your shape? What challenges would you expect?**

5. **A wide range of materials are being used for additive manufacturing, with new materials being frequently added.**
   - **i.** List 3 types of materials that can be used for additive manufacturing.
   - **ii.** For any one material listed in part i., identify one product it is currently being used to create and discuss why that material was chosen.

### Definitions

**Additive Manufacturing (AM)**
A technology used to build 3D objects by adding layer by layer of material.

**Computer Aided Design (CAD)**
A technology used to create, modify, or analyze a design.

**Forming Processes**
Manufacturing processes that use stresses such as tension, to cause deformation of materials and produce desired shapes.

**Subtractive Manufacturing**
A process used to construct 3D objects by cutting away material from a solid block of material.

**Voxel**
A point in three-dimensional space.

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-ETSI-2 | HS-ETSI-3 |
|---|---|---|---|

**Notes:**
N.B. This activity can be modified to take less time by having students work in larger groups.

1. Materials needed:
   - Sugar cubes
   - Bags of granulated sugar
   - Glue
   - Scoopula or Spoon
   - Toothpicks
   - Cardboard
2. Remind students that they must agree on a shape with their partner and that both prototypes must have the same width, length, and height.
3. Before beginning the process, students should be provided with a piece of cardboard on which they can build their structure.
4. Students can be left to plan their own procedure but teachers may also wish to advise them that it is helpful to outline their shape on the cardboard first and to use very little glue so that the prototype does not become runny.
5. Students should be encouraged to view the results of other teams and discuss how different processes yielded different results.

1. **List one advantage and one disadvantage of each material used (sugar cubes and sugar granules).**

   Cubes – Advantages: Faster/More efficient; Easier to control or manipulate
   Cubes – Disadvantages: Cannot obtain as accurate a shape
   Granules – Advantages: More precise (can get a better defined shape)
   Granules – Disadvantages: Time consuming; needs very precise equipment

2. **The engineering design process entails identifying a problem, brainstorming solutions to the problem, creating solutions to the problem, evaluating the solutions, and refining the solutions. After evaluating your prototypes how would you change your process in the following scenarios?**
   i. ***You are only given 5 minutes to construct the same prototype. Which method would you select and why?***
   Using the cubes (larger pieces) means that you can assemble a shape more quickly.
   ii. ***You have unlimited time but are asked to create an accurate copy of any given shape. Which method would you select and why?***
   Using finer grains means that you can create a very accurate shape.

## Teacher Resources & Answer Key

3. **While there are many benefits to additive manufacturing, it is not always the best process for the job.**
   i. ***Research subtractive, forming, and additive manufacturing processes and briefly describe each process.***
   Subtractive processes are when a material is cut or carved away until a desired shape is reached. This method often produces a lot of waste and can be time consuming.
   Forming processes involve using stresses to deform materials in a controlled way until the desired shape is obtained. While not as much material is wasted through this process as subtractive manufacturing, forming processes often require further machining to obtain a final product.
   Additive manufacturing is when material is added layer by layer until a desired shape is fabricated. Additive manufacturing minimizes waste by building in layers as opposed to removing excess.

   ii. ***For each of the processes above, identify one application where it is the preferred production process and explain why that may be.***
   Answers will vary but examples include: Creating wooden boards or working with stones such as marble still require subtractive manufacturing as a final product is obtained by removing excess material from a larger block. Forming processes are essential for rolling out sheet metal or forging high strength parts. Additive manufacturing is ideal in applications where precision is required or where lightweight components need to be produced as the layer by layer process allows the easy formation of hollow pieces.

4. **How would this experiment differ if you had to replicate the subtractive method of manufacturing by chipping away at a block of sugar to create your shape? What challenges would you expect?**
   Answers will vary but may include that it would be difficult to chip away at the sugar block without breaking off more than expected, that accidentally breaking the block would mean starting over again, or that students would need specialized tools for cutting away with precision.

5. **A wide range of materials are being used for additive manufacturing, with new materials being frequently added.**
   i. ***List 3 types of materials that can be used for additive manufacturing.***
   Student answers will vary. Answers include polymers such as nylon, skin, or epoxy resin; metals such as titanium alloys or aluminum; ceramics such as silica or porcelain; other possible answers also exist.

   ii. ***For any one material listed in part i, identify one product it is currently being used to create and discuss why that material was chosen.***
   Student answers will vary.

## Extension Activity

# LAYERS OF COMPLEXITY: MAKING THE PROMISES POSSIBLE FOR ADDITIVE MANUFACTURING OF METALS

It is a vending machine like no other, dispensing the physical embodiment of ideas and imagination at the touch of a button. Powered by four Makerbot 3D printers, the DreamVendor beckons Virginia Tech students from its vantage point in a busy lobby to design and create everything from prototypes for classroom projects, to chess pieces, to smartphone stands.

Christopher Williams, Director of the Virginia Tech Design, Research, and Education for Additive Manufacturing Systems (DREAMS) Laboratory stresses that he and his team developed the DreamVendor 3D printing station to reach individuals who never thought to step into an engineering laboratory. "The vending machine interface is very important. It lowers the barrier to the technology and engages students in public making," said Dr. Williams. "No longer are these machines behind a laboratory's locked doors. No permission is needed for students to design and build. Countless students from across the university have used the machine to build parts and some have reported learning Computer Aided Design (CAD) just to use the DreamVendor."

*Similar to inserting coins to buy a snack, Virginia Polytechnic Institute and State University (Virginia Tech) students like Amy Elliot (above) insert an SD card with their design into DreamVendor, and the machine fabricates and dispenses a finished part. Amy is researching additive manufacturing of copper for her Ph.D. work in the Virginia Tech DREAMS Laboratory. (Photo courtesy of Virginia Tech.)*

DreamVendor's intent to empower anyone to design and produce anything at any time is also the beating heart of what has become known as the Maker Movement. Using 3D printing techniques and computer-aided tools, a rapidly growing community of independent inventors, called makers, is rewriting the rule book on how, where, and when products are manufactured.

## Great Potential in Need of a Workforce

The excitement seen in community makerspaces— shared workshops that provide affordable access to fabrication tools—is evident in many advanced industrial settings as well. Rather than the 3D printers typically used by makers, these companies are adopting many similar technologies, collectively known as additive manufacturing (AM), for large-scale fabrication of parts.

Simply stated, additive manufacturing works by joining materials, layer by layer, to build components according to 3D

## Extension Activity

modeling data. This helps design drive the manufacturing process, rather than the other way around. From a production standpoint, AM techniques can eliminate the time, equipment, and waste of proving out a mold, milling a piece from solid block, and other subtractive machining methods. The parts also tend to be lighter weight and lower maintenance since they can be produced in one piece, reducing the need for welding and joining. The potential cost and time savings in effectively adopting this new approach to manufacturing could be enormous, while the ability to render one-piece, complex components opens design possibilities that were never possible with conventional manufacturing methods.

**A Lighter Way to Fly:**
*GE Aviation used additive manufacturing technology to design and fabricate fuel nozzles for its LEAP-56 engines. Fuel nozzles that had been traditionally manufactured consisted of 20 separate components joined together. The additively manufactured fuel nozzle is one, continuous piece that is "grown," layer by layer. The weight savings of the new fuel nozzle over the previous model is estimated at around 25 percent. Among expected benefits of using the additive approach for fabricating it is a decrease in fuel burn due to weight reductions and design improvements resulting from the elimination of so many points of joining. (Photo courtesy of GE Aviation)*

Interest in harnessing the possibilities offered by additive manufacturing has skyrocketed over the last few years. However, there is concern that a shortage of appropriately prepared workers may be a barrier to fully adopting the technology. "In order to further the application of AM, we must educate the workforce on when, why, and how to make use of this powerful technology," said Dr. Williams. "The need for AM education spans many levels. This ranges from training technicians for machine operation, maintenance, and repair, to educating Ph.D.s to advance the core science and technology that will drive improvements in machine precision, as well as material quality and selection."

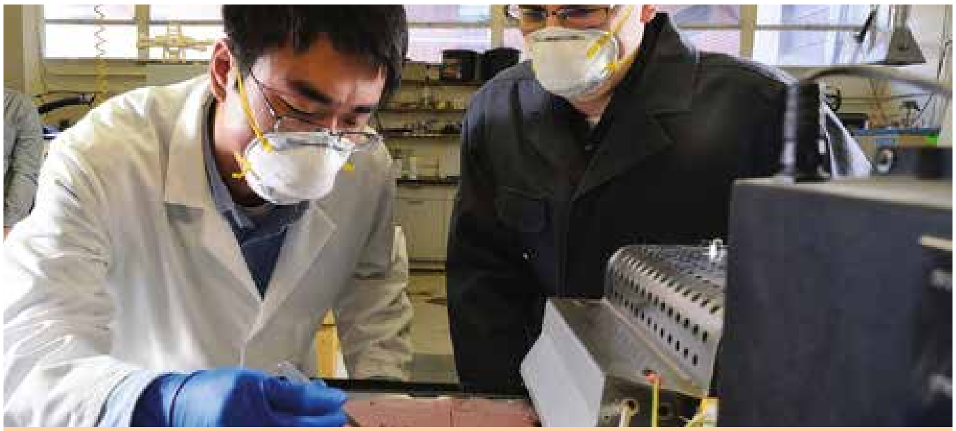
With metal AM still very much in its infancy, the challenges of understanding the science, perfecting the engineering, and addressing related policy and educational issues are just now coming into focus. Even so, there is great optimism that metal AM can transform how many manufactured goods are produced.

### The Right Tool for the Job

For the aerospace sector, the current primary applications for structural AM are tooling, fixtures, form-fit models, and prototyping. AM can significantly reduce lead

*Mary Kinsella demonstrates the use of a desktop 3D printer. A focus of Air Force research is 3D printing and additive manufacturing technology for prototyping, tooling, fixtures, and some noncritical parts.*
*(U.S. Air Force photo by Lori Hughes [88ABW-2013-3348])*

## Extension Activity



*To accelerate the rate of adoption, we need to train future engineers on when to use AM, which technologies/materials they should select, and how to design," said Christopher Williams, Virginia Tech University. (Photo courtesy of Virginia Tech)*

times for all of these applications and, in some cases, enhance capability through more complex geometries, such as for **casting tooling**. There are also some non-critical part and **niche applications** in which component life requirements are reduced or otherwise limited.

"In the future, we plan to apply AM for new design, enabling multi-material and multi-functional components and location-specific properties," said Mary E. Kinsella, Additive Manufacturing IPT Leader and Senior Manufacturing Research Engineer, U.S. Air Force Research Laboratory (AFRL). "This is down the road, though, and we have much work to do."

More than a decade ago, the AFRL was the first to qualify and fly a metallic part on a military aircraft—a pylon rib for the F-15. "We had a situation where a replacement part was needed, but lead time for tooling was excessive. Also, the part was already intended to be redesigned for a different material—from an aluminum forging to titanium—to solve corrosion fatigue problems," said Dr. Kinsella. "This niche application provided an opportunity to try out a process called laser additive manufacturing. It was difficult and expensive, but necessary to meet mission requirements. We learned a great deal about the challenges of using AM technologies for aerospace applications."

A key takeaway from this and subsequent experiences is that AM is not suitable for all applications, noted Dr. Kinsella. "It is a new tool to place in the manufacturing toolbox and to use only as appropriate," she said. "If you are trying to replace an existing part, it is important to remember that the original part was designed with a different manufacturing process in mind, and you need to respect the original design intent. For new designs, materials and manufacturing approaches can be optimized for AM to meet part requirements. But it will be some time before we can take full advantage of AM's unique benefits for critical aerospace structures."

*This article was excerpted from "Layers of Complexity: Making the Promises Possible for Additive Manufacturing of Metals" by Lynne Robinson and Justin Scott, published in* JOM, *November 2014, Volume 66, Issue 11, pp 2194-2207.*

*In addition to making new items, additive manufacturing can be used to extend product life and repair damaged components. (Photo courtesy of Optomec)*

## Extension Activity

### Questions

1. **Describe the process of fabricating a component, such as the LEAP fuel nozzle, using additive manufacturing technologies.**

2. **Military laboratories are not the only places using additive manufacturing. Research mills, plants, universities, or laboratories close to your school that utilize additive manufacturing techniques. What parts do they produce and what are the parts utilized for?**

3. **Why is additive manufacturing not always suitable for all applications?**

4. **Think about a product problem you encounter in everyday life. What is the problem and how could additive manufacturing help you solve the problem?**

### Definitions

**Casting Tooling**
Casting tooling involves the molds and cores used to produce castings. Casting involves pouring molten metal into the mold and allowing it to solidify, forming a part that has the shape of the cavity inside the mold.

**Niche Application**
Applies to the very specific wants and needs of a small group of people.

## Extension Activity Answer Key

1. **Describe the process of fabricating a component, such as the LEAP fuel nozzle, using additive manufacturing technologies.**
   A component that is fabricated by additive manufacturing is designed first with 3D modeling software to create a Computer Aided Design (CAD) file. This instructs the computer on how to direct the placement of super-thin layers of metal in a powdered form. A laser melts the powder together by raising the temperature of the powder to just above its melting point which allows the powder particles to form a melt pool and then solidify. The 3D printer continues to spread out one layer of powder at a time, repeating the process until the entire part is fabricated.

2. **Military laboratories are not the only places using additive manufacturing. Research mills, plants, universities, or laboratories close to your school that utilize additive manufacturing techniques. What parts do they produce and what are the parts utilized for?**
   Students answers may vary. Examples include General Electric's use of additive manufacturing to print fuel nozzle interiors for jet engines or Schroeder Industries' 3-D prints filters used for cleaning hydraulic fluids and diesel fuels or the research taking place at numerous labs into 3D printed medical devices or tissue repair and organ printing.

3. **Why is additive manufacturing not always suitable for all applications?**
   Additive manufacturing needs to be used appropriately. Not all parts that need to be repaired were created using additive manufacturing so the original process needs to be accounted for during repair. Additive manufacturing is an expensive process and many parts can be produced more cheaply using conventional processes. Additive manufacturing is used in four situations: 1) when a product is needed quickly and the manufacturer is willing to accept the higher cost rather than wait for forming or machining; 2) when a only one or a small number of parts are needed; 3) when several parts can be combined into one by using additive manufacturing to reduce weigh and/or enhance performance (as is the case with the GE fuel injection nozzle); 4) when the part cannot be made by any conventional processes. The latter point has led to revolutionary ways to design parts that are more effective and lower cost than conventional parts, but can only be made by additive manufacturing.

4. **Think about a product problem you encounter in everyday life. What is the problem and how could additive manufacturing help you solve the problem?**
   Student answers will vary. One example includes custom printing prosthetics such as a new foot, bird's beak, or turtle's shell that were malformed during birth or damaged during life.

MATERIALS™ EXPLORERS

# BIOMEDICAL MATERIALS

**From hip implants to bone cement, medical devices can enhance patients' health and quality of life, but have you ever thought about the materials these devices are made of? In this chapter, you will learn about some of the important qualities that make biomedical materials safe and useful when placed in the body.**

**In this module students will be able to:**

- Describe the properties of viscoelastic materials
- Compare and contrast solids and liquids
- Define biomedical materials and identify applications
- Classify and balance the reaction that occurs when magnesium is absorbed by the body
- Define polymers and identify an example of a polymer

## Class Activity

### Practical Prosthetics

**Background:**

Humanity has a long history of introducing materials into our bodies to replace broken parts or to help aid the body with its natural healing process. The ancient Egyptians used surgical sutures or "stiches" made from animal or plant components, and dental implants made of animal teeth and gold wire were used in Europe more than one thousand years ago. The materials used in these processes are known as **biomedical materials**. What is a biomedical material? Broadly speaking, it is any material being introduced into a biological system for a medical purpose.

Today, medical experts developing biomedical devices have a much wider selection of materials than their historical predecessors. This is thanks to the biomedical researchers who study materials to determine if their properties are suitable for use in a medical device.

One set of materials that are of interest to many biomedical researchers are **viscoelastic** materials, or those that exhibit both **viscosity** and **elasticity**. Many of the materials we encounter on a daily basis are viscoelastic. One example is skin. When skin is pinched, it takes a few moments before the skin returns to its original flat position. Another example of a viscoelastic material is a **polymer**. Polymers, or long chains of molecules, can exhibit properties of both solids and liquids and have a wide variety of uses. Biomedical engineers are currently experimenting with polymers and other viscoelastic materials to create artificial skin that can make prosthetics look, feel, and even function more like real skin.

**Problem**

A group of materials scientists suspect that a highly elastic polymer has potential to be used in certain types of prosthetics. Before conducting further research on using the polymer as a biomedical material, the scientists have asked your class to investigate the properties of a viscoelastic putty that mimics the characteristics of their polymer. Your team will write an evidence-based conclusion explaining your findings and the feasibility of using a material with similar properties in prosthetics.

**Task:**

Your task is to create a polymer material using common household items that would mimic the characteristics of one being developed for use with prosthetics. You will test what happens when your polymer material is stretched, pulled apart, and rolled into a ball. Because the electrostatic forces that hold viscoelastic materials together can change depending on temperature, you must also test how temperature affects your polymer.

## Class Activity

**Requirements:**
Create a polymer material using equal parts of the following ingredients: water, white glue, and borax. A few drops of food coloring may also be added. The polymer material should be kneaded until smooth and must be able to be easily stretched, pulled apart, and rolled. To determine whether the polymer would be effective in cold temperatures, record your observations of its behavior after being stored in the refrigerator for an hour.

*Measure and mix equal parts of water, white glue, and borax.*


*Knead until smooth and easily stretched, pulled apart, and rolled.*

### Questions

1. **Record observations for the following scenarios at room temperature and after the polymer material has been chilled:**
   **i.** What happens when it is stretched?
   **ii.** What happens when it is pulled apart?
   **iii.** What happens when it is rolled into a ball?
2. **Create a Venn diagram comparing the properties of solids and liquids.**
3. **Would you classify the polymer material as a solid, liquid or both? Why?**
4. **Define cross-linking and explain how it pertains to your polymer material.**
5. **Compose an evidence-based conclusion consisting of your observations and the feasibility of using a polymer with similar characteristics for creating prosthetic skin.**

### Definitions

**Biomedical material**
Any substance that has been modified or developed to be introduced into a biological system for a medical purpose.

**Viscoelastic**
Pertains to a substance that exhibits properties of both solids and liquids.

**Viscosity**
A measure of a fluid's resistance to flow. The less viscous a fluid, the more easily it flows.

**Elasticity**
The ability to return to its normal shape after being deformed

**Polymer**
A large molecule, or "macromolecule," composed of many repeated smaller units, or "monomers," bonded together.

# MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

| | | | |
|---|---|---|---|
| Standards: | NGSS | HS-PS1-3 | HS-PS2-6 |

**Notes:**

1. Students will need access to the following materials:
    - **a.** Small mixing bowl
    - **b.** White glue (non-washable)
    - **c.** Borax
    - **d.** Measuring Spoons
    - **e.** Water
    - **f.** Resealable plastic bags
    - **g.** Food coloring (optional)
2. Two tablespoons each of borax, white glue, and water per student should be sufficient.
3. Any liquid remaining in the bowl after the polymer material is formed can be disposed of down the sink.
4. Whether or not students are permitted to take the polymer material outside of the classroom is up to teacher discretion.

**1. Record observations for the following scenarios at room temperature and after the polymer material has cooled:**

***i. What happens when it is stretched?***

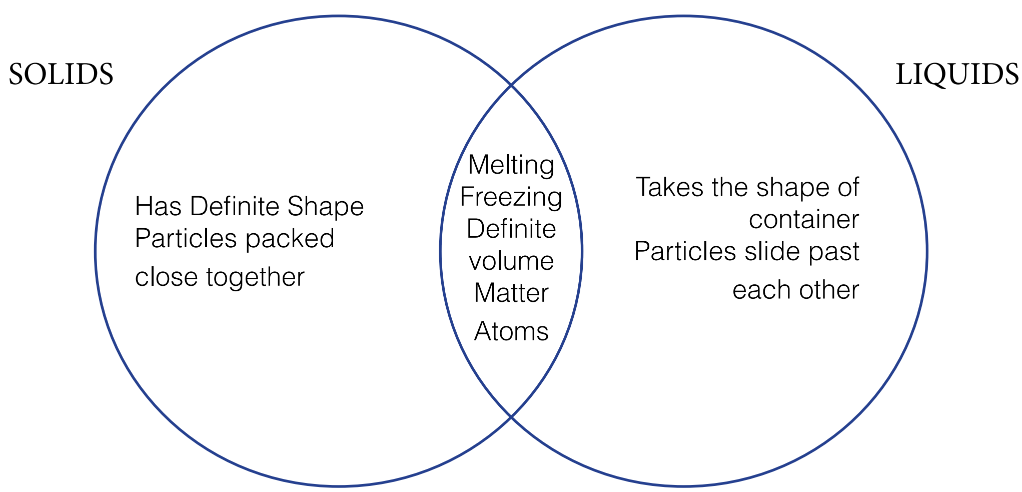
***ii. What happens when it is pulled apart?***

***iii. What happens when it is rolled into a ball?***

Student answers will vary.

**2. Create a Venn diagram comparing the properties of solids and liquids.**

*Figure 1.*



## Teacher Resources & Answer Key

3. **Would you classify the polymer material as a solid, liquid, or both? Why?**
   The polymer material created by the students is a semisolid. It has properties of both liquids and solids; it primarily acts as a viscous liquid, yet has the properties of an elastic solid. It flows slowly, but can also be returned to its original shape and size.

4. **Define cross-linking and explain how it pertains to your polymer material.**
   Cross-linking refers to a bond that links one polymer chain to another, often resulting in molecules that can no longer freely slide past one another. Cross-linking in the polymer material occurs between the protein molecules from the glue and the borate ions from the borax solution.

5. **Compose an evidence based conclusion consisting of your observations and the feasibility of using a polymer with similar characteristics for creating prosthetic skin.**
   Student answers will vary.

### Activity Grading Rubric

| **Component** | **Level** | | |
|---|---|---|---|
| | 2 | 1 | 0 |
| **Claim –** *A conclusion that answers the original question.* | Makes an accurate and complete claim. | Makes an accurate, but incomplete claim. | Does not make a claim, or makes an inaccurate claim. |
| **Evidence –** *Scientific data that supports the claim. The data needs to be appropriate and sufficient to support the claim* | Provides appropriate and sufficient evidence to support claim. | Provides appropriate, but insufficient evidence to support claim. May include some inappropriate evidence. | Does not provide evidence, or only provides inappropriate evidence (Evidence that does not support claim). |
| **Reasoning –** *A justification that links the claim and evidence. It shows why the data counts as evidence by using appropriate and sufficient scientific principles.* | Provides reasoning that links evidence to claim. Includes appropriate and sufficient scientific principles. | Provides reasoning that links the claim and evidence. Repeats the evidence and/or includes some scientific principles, but not sufficient. | Does not provide reasoning, or only provides reasoning that does not link evidence to claim. |

## Extension Activity

### MAGNESIUM, MEDICINE, AND MATERIALS ENGINEERING*

You may not see them working in a hospital or doctor's office, but materials scientists and engineers play a big part in helping people recover from illnesses and injuries to enjoy a better quality of life.

Contact lenses, dental implants, pacemakers, and surgical sutures all fall under the category known as biomedical materials. A biomedical material is any substance that has been modified or developed to be introduced into a biological system for a medical purpose. Some of these applications include replacing diseased or damaged body parts, enhancing appearance through cosmetic implants or assisting the natural healing process.

Many biomedical materials are designed to permanently stay in the patient's body, but sometimes implants are only needed temporarily. An example of this would be pins used to keep bones in place while they heal. When the pins are made of traditional materials such as stainless steel, cobalt-chromium, or a titanium alloy, the patient often needs to undergo an additional surgery after healing in order to remove the implants. Because further operations create additional expense and risks for patients, materials scientists and engineers have recently researched and developed new biomedical materials that are safely absorbed into the body after the healing process is complete.

The most commonly used biodegradable and bioabsorbable implant materials are the polymers, poly-glycolic acid (PGA), poly-lactic acid (PLA), and poly-dioxanone (PDS). However, these materials have limitations. Their low **specific strength** means that they aren't suitable for load bearing andtissue supporting roles and their **radiolucency** makes it difficult to accurately place implants that are made of these materials.

Metals, on the other hand, have many of the desirable qualities these polymers lack, such as high strength and fracture toughness. However, most metals are either non-absorbable for the body or can produce toxins as they corrode. One notable exception to this is magnesium (Mg); and it has received a lot of attention among biomedical researchers.

Magnesium has a high specific strength and an **elastic modulus** that is closest to the human bone when compared with traditional metallic implant materials. Studies have also confirmed that magnesium has the ability to stimulate bone growth and healing, and that its degradation leads to harmless corrosion products which are excreted through the urine.

However, magnesium has its own limitation as an implant material. It reacts with water to produce a mildly protective film of magnesium hydroxide. Although this film slows corrosion in a moist environment, it reacts with water present in the human body to produce magnesium by-products and hydrogen gas. This reaction accelerates corrosion and absorption into the body, which can undermine the mechanical integrity of the implant before the bone or tissue has sufficiently healed. Magnesium's tendency to produce hydrogen gas and form gas bubbles that accumulate around the implant can also delay the healing of the tissue.

In order to make magnesium effective for use in **bioabsorbable** temporary implants, materials scientists and engineers need to find a way to keep it from degrading before the patient's bones or tissue have healed enough to support themselves. Efforts to control the corrosion rate of magnesium have used various processing methods such as purification, alloying, anodizing, and surface coating.

Studies have shown that purification of magnesium reduces the corrosion rate considerably. However, due to the low **yield strength** of pure magnesium, its application in orthopedics and other load bearing applications is limited. Alloying elements can be added to increase the strength of pure magnesium, but they must be selected carefully to maintain the magnesium's biocompatibility. Creating a magnesium alloy with elements such as iron, nickel, copper, and cobalt actually increases the corrosion rate of the magnesium. Aluminum and zirconium are not bio-compatible and instead may have long term effects, including dementia and cancer, respectively. Rare earth elements such as cerium, lutetium, and praseodymium are generally considered toxic for the human body.

## Extension Activity

So what materials can be safely used? Scientists propose choosing materials that are already essential to the human body to serve as alloying elements. Calcium and zinc are two examples. They are essential elements found in most vitamins that also provide mechanical strengthening in magnesium-based alloys. In simulated body fluid, calcium has been reported to improve the corrosion resistance of magnesium-based alloys. Meanwhile, zinc additions increase the strength of magnesium-based alloys through precipitation strengthening.

Despite the challenges that magnesium and its alloys present, teams of chemists, materials scientists, and physicians are determined to unlock this element's full potential as a biomedical material. The impact that fully biocompatible and biodegradable magnesium alloy implants could make on the lives and healing of so many people is well worth the effort.

**This article is excerpted from "Magnesium as a Biodegradable and Bioabsorbable Material for Medical Implants" by Harpreet S. Brar, Manu O. Platt, Malisa Sarntinoranont, Peter I. Martin, and Michele V. Manuel, published in* JOM, *September 2009, Volume 61, Issue 9, pp 31-34.*

### Questions

1. **Write out the reaction for magnesium and water.**
2. **Balance and classify the type of reaction that occurs between magnesium hydroxide and water.**
3. **What is precipitation strengthening?**
4. **Scientists are looking towards elements such as magnesium, calcium and zinc because they are already used in the body. How does your body use each of these elements in its day to day functioning?**
5. **Materials are all around us and even in us. Advancements in biomedical engineering have led to the creation of a variety of implants. There are many challenges that must be overcome to create an implant. Depending on the implant, those challenges can include difficulties with bioabsorption, resistance to corrosion, and durability.**
   **Select one of the following implant categories and research the materials that compose the implants and the challenges that accompany them: dental, cardiovascular, brain, spine, and orthopedic.**

### Definitions

**Specific Strength:**
A measure of a material's strength relative to its density. It is also known as the strength to weight ratio.

**Radiolucency:**
Radiolucent materials allow radiant energy such as X-rays to pass through them. They therefore appear as dark spots on an X-ray image.

**Elastic Modulus:**
Also known as Young's modulus, the elastic modulus is a measure of the elasticity of a material. The higher the elastic modulus of a material, the more the material will resist stretching. It can be calculated by dividing stress by strain.

**Bioabsorbable:**
Capable of being broken down or dissolved within the body.

**Yield Strength:**
The stress at which a material begins to deform plastically. That is, the point at which enough stress is applied that the material does not return to its original shape after the stress is removed.

## Extension Activity Answer Key

1. **Write out the reaction for magnesium and water.**

   $Mg + H_2O \longrightarrow Mg(OH)_2 + H_2$

2. **Balance and classify the type of reaction that occurs between magnesium hydroxide and water.**

   $Mg + 2\ H_2O \longrightarrow Mg(OH)_2 + H_2$ Single Replacement

3. **What is precipitation strengthening?**

   A heat treatment process used to increase the strength of malleable materials.

4. **Scientists are looking towards elements such as magnesium, calcium and zinc because they are already used in the body. How does your body use each of these elements in its day to day functioning?**

   Magnesium is necessary for hundreds of reactions in the body. Some possible answers include that it is needed to maintain a healthy immune system, support nerve and muscle function, and produce energy. Calcium combines with phosphorus to form bones and teeth, aids in blood clotting, and supports nerve and muscle function among other potential answers. Zinc supports the body's immune system, cell growth and the healing of wounds. Other answers may also apply.

5. **Materials are all around us and even in us. Advancements in biomedical engineering have led to the creation of a variety of implants. There are many challenges that must be overcome to create an implant. Depending on the implant those challenges can include bioabsorption, resistance to corrosion, and durability. Select one of the following implant categories and research the materials that compose the implants and the challenges that accompany them: dental, cardiovascular, brain, spine, and orthopedic.**

   Student answers will vary.

# MATERIALS™ EXPLORERS

# BLADESMITHING

**From ancient literature to modern movies, hand forged metal weapons have long captured the imagination. View some of the blades created for the TMS Bladesmithing Competition and design a blade of your own in this chapter that delves into the science behind bladesmithing.**

**In this module students will be able to:**

- Compare and contrast alloys and pure metals
- Identify advantages and disadvantages of various metals when used in bladesmithing
- Calculate the ultimate tensile strength of various metals and alloys
- Apply knowledge of specific strength to discuss applications in other fields
- Distinguish between casting, hot forging, and cold forging

## Class Activity

# BLADESMITHING BATTLE

**Background:**
More than 75% of the elements on the periodic table are metals. Metals tend to be solid at room temperature, have high melting and boiling points, and high densities. Metals are also lustrous, malleable, ductile, and are good conductors of heat and electricity. When a metal is combined with another element, the resulting **alloy** often has more desirable properties than a pure metal. For example, pure iron is too soft to make a blade but adding carbon to it creates steel, a metal alloy which is strong enough to be sharpened. If chromium is also added, the alloy becomes resistant to corrosion. This is how stainless steel is made.

Bladesmithing, a practice that spans many cultures and millennia, is the art of making blades using equipment such as a forge, hammer, and anvil. Blacksmiths carefully select their materials, often metal alloys, based on the properties they will give the final blade. Most of the alloys used to make blades are forms of carbon steel. Carbon is necessary to make the metal hard, but too much carbon makes the blade less flexible and brittle, increasing the likelihood of breaking in battle. The chart below displays some common alloy additions to steel and the advantages and disadvantages of using each:

| Metal | Advantages | Disadvantages |
|---|---|---|
| Chromium | Helps with hardening | Can cause steel to crack during forging |
| Tungsten | Makes a sharp, long-lasting edge | Difficult to forge |
| Manganese | Adds strength during heat-treatment | May be difficult to cast |
| Molbydenum | Helps steel remain hard at high temperatures | Very challenging to forge if present in high quantities |
| Nickel | Adds strength | Does not increase hardness |

One way to quantify the performance of a blade is by calculating the **specific strength** of the material used to create it. Specific strength is a measure of a material's strength relative to its density. In other words, it is a measure of its strength to weight ratio—an important quality to consider when trying to create a strong but lightweight blade.

To calculate specific strength, a material's **ultimate tensile strength (UTS)** is divided by its density. Ultimate tensile strength refers to the maximum amount of **stress** a material can sustain before fracturing.

MATERIALS™ EXPLORERS

## Class Activity

### Problem

Dragons are attacking your kingdom and your homeland is not equipped with the right weapons to fight them. You realize that this is because local blacksmiths are not using the best metals or alloys to create their weapons. Using your extensive scientific knowledge, you set out to determine which materials would be best for forging new weapons. You decide to test the specific strengths of various metals and alloys to determine which material is best suited to create a dragon-slaying sword that is both strong and lightweight.

**Task:**

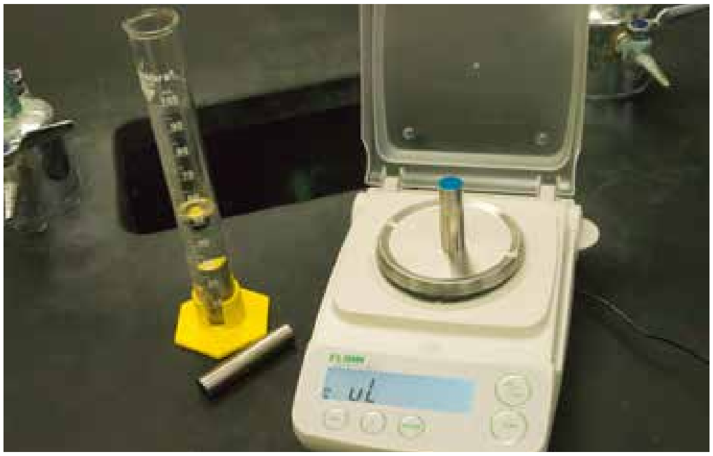
Your task is to determine the specific strengths of various metals and alloys and compose a letter addressed to the king, persuading him to use the material you think best suited to making a sword capable of slaying the dragons and protecting the kingdom.

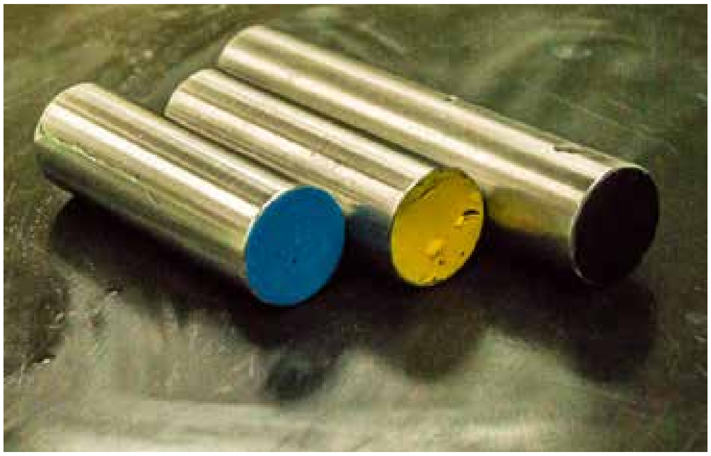
**Requirements:**

1. Your letter must use the results of your tests to justify which material you recommend.
2. Data should be collected in the table provided below.
3. The UTS for each sample will be provided by your teacher.
4. Calculate the specific strength of each sample using the following equation:

$$\textit{specific strength} = \frac{\textit{UTS}}{\textit{Density}}$$

| Sample Name | Mass (g) | Volume (cm3) | Density (kg/m3) | Ultimate Tensile Strength | Specific Strength |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |





MATERIALS™ EXPLORERS

## Class Activity

### Questions

1. **What is an alloy?**
2. **When making a blade, why would you use alloys instead of pure metals?**
3. **Compare the atomic arrangement in a pure metal to that of an alloy.**
4. **In what other fields would the specific strength of a material be taken into consideration and why?**
5. **While alloys often work best in bladesmithing, there are other applications where it is better to use a metal in its pure form. Identify one such application and explain why the pure form of the metal is preferable.**

### Definitions

**Alloy**
A mixture of two or more metals, or a metal and other elements.

**Specific Strength**
A measure of a material's strength relative to its density. It is also known as the strength to weight ratio.

**Ultimate Tensile Strength (UTS)**
The maximum stress a material can withstand while being stretched or pulled before breaking.

**Stress**
A measurement of the force applied to the object per unit area. It can be calculated by dividing the force applied to the material by its cross-sectional area.

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS1-1 | HS-PS1-3 |
|---|---|---|---|

**Notes:**

1. If samples of alloys and metals are not readily available, inexpensive specific gravity metal specimen sets that contain copper, brass, aluminum, and steel are available online and can be substituted for this activity.
2. Students will need access to the following materials:
   - Balance
   - Graduated Cylinder or Calipers
   - Distilled water if using a graduated cylinder to measure volume
3. Ultimate tensile strengths should be provided for the students and will depend upon the metals and alloys provided.
4. Videos of weapons being forged by teams competing in the TMS Bladesmithing Competition are available online through the *Materials Explorers™* website at **www.materials-explorers.org.**

1. **What is an alloy?**
   An alloy is a mixture of two elements, with at least one being a metal.

2. **When making a blade, why would you use alloys instead of pure metals?**
   Alloys are more beneficial because they are stronger than a pure metal.

3. **Compare the atomic arrangement in a pure metal to that of an alloy.**
   Atoms in a pure metal are packed as closely together as possible. Atoms stack on top of each other in layers. The atoms in the second layer move into the gaps between atoms in the first layer. Atoms of different sizes make up alloys, making it more difficult for the layers of atoms to slide over each other.

4. **In what other fields would the specific strength of a material be taken into consideration and why?**
   Student answers will vary. Examples include the field of transportation where reducing the weight of the vehicle is an important factor in reducing fuel consumption or in construction where materials must carry heavy loads. In both cases, engineers look at specific strength to select materials that are lightweight, afforadable, but also strong.

5. **While alloys often work best in bladesmithing, there are other applications where it is better to use a metal in its pure form. Identify one such application and explain why the pure form of the metal is preferable.**
   Copper is commonly used in its pure form for electrical wiring and hot water pipes because it is the most efficient conductor. Aluminum is also commonly used in its pure form for high voltage cables and soda cans due to its low density, high conductivity, and ability to easily be molded.

## Teacher Resources & Answer Key

### Activity Grading Rubric

| | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| **Opening Statement** | Strongly and clearly states a personal opinion. Clearly identifies the issue. | Clearly states a personal opinion. Some references to the issue. | Personal opinion is not clearly stated. Little or no references to the issue. | Personal opinion is not easily understood with no reference to the issue. |
| **Supporting Details** | Provides more than 2 pieces of data, reasons and/or examples in support of the opinion. | Provides 2 pieces of data, reasons and/or examples in support of the opinion. | Provides at least 1 piece of data, reason and/or example in support of the opinion. | Provides little or no support of the opinion. |
| **Format/ Organization** | Sentences and paragraphs are complete, well written and varied. | Sentence and paragraph structure is generally correct. | Sentence and paragraph structure is inconsistent. | Little or no evidence of sentence or paragraph structure. |
| **Concluding Statement** | Summarizes personal opinion in a strong concluding statement. | Summarizes personal opinion in a concluding statement. | Concluding statement is a weak summary of personal opinion. | Concluding statement makes no reference to personal opinion. |
| **Mechanics and Grammar** | Contains few, if any punctuation, spelling or grammatical errors. | Contains several punctuation, spelling or grammar errors that do not interfere with meaning. | Contains many punctuation, spelling and/or grammatical errors that interfere with meaning. | Contains many punctuation, spelling and/or grammatical errors that make the piece illegible. |

## Extension Activity

### WHAT DOES IT TAKE TO FORGE A BLADE?

**Forging a blade is no simple task.**

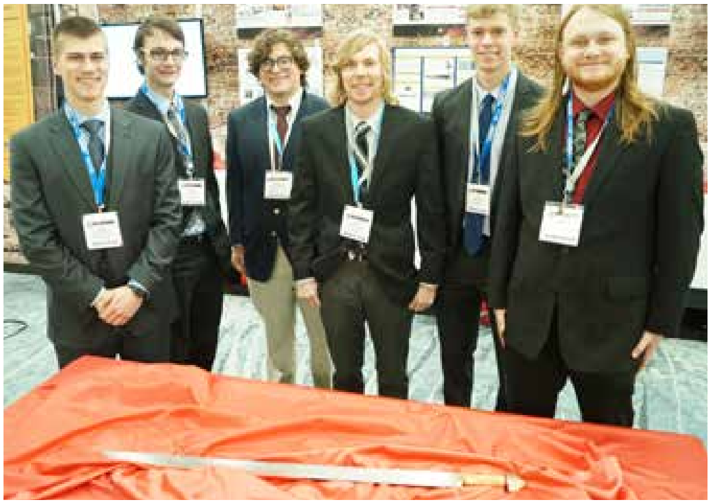
It takes creativity. The first step in creating any blade is to establish a vision and design. These designs are often only created after hours of research into traditional weapons and ancient cultures.

It takes dedication and endurance. With countless hours spent laboring over a hot forge, a blacksmith must hammer, grind, and test the blade until certain it meets his or her demands.

It also takes science. While movies are fond of showing red-hot swords being pulled from the forge and sparks flying as metal strikes metal, they rarely showcase the metallurgy behind the process. In order to create a powerful blade, blackmiths must first understand the properties of the metals and alloys available to determine which materials they should use. They need to understand a material's strengths and its limitations if they want an end product that is strong, durable, and useful.

University students from around the world learn this when they participate in the TMS Bladesmithing Competition. Every other year, teams are challenged to delve into the world of traditional metallurgy by using their theoretical knowledge to produce a real-life blade.  Showcased here are just a few of the many incredible student pieces entered into the competition.

**Norwegian Langseax**
by Jackson Ade, Daniel Funk, Ryan Grant, Frederic Neiderer, Kevin Noto, Luke Shearer and Ryan Stevens of South Dakota School of Mines and Technology.
2017 TMS Wadsworth-Sherby Grand Prize recipients.



The winning team of the 2017 TMS Bladesmithing Competition set out to recreate history in the form of a 10th century Viking sword discovered in a Norwegian burial mound. The team also brought in some history of their own by including wrought iron taken from the site of a historic smelter on their university's campus. Adding this wrought iron to the layers of steel used in the sword's spine resulted in a more flexible blade that would be less prone to breaking.

The team also used a traditional Damascus steel design. Damascus steel is famed for being simultaneously harder and more flexible than other blades of its time and the distinctive ripple-like patterns that form on its blade make it iconic in the world of bladesmithing. Despite centuries of trying to recreate the traditional process for forging Damascus steel, it remains shrouded in mystery. This no doubt, is made even more difficult by the many legends that surround the process, such as quenching the blade in "dragon's blood."

MATERIALS™ EXPLORERS

## Extension Activity

**Bowie Knife**
by Cody Fast, Casey Husk, Hunter Lottsfeldt, Lucas Teeter, Marco Teeter, Oregon State University.

A good forge is the heart of any foundry – so what happens if you don't have one? The team of students from Oregon State University can tell you. They didn't have access to a forge, so they made their own by repurposing a 20 pound propane tank and lining it with high temperature ceramic fiber insulation, refractory mortar, and bubble alumina.

Out of this forge, they created a billet of forge-welded Damascus steel which consisted of 24 alternating layers of two types of steel alloys. They then fashioned this billet into a blade modeled off the historical design of the Bowie knife.

**Kukri**
by Allison Loecke, Ryan Peck, Grant Bishop, Hunter Sceats, Kyle Heser, Connor Campbell, Colorado School of Mines.

The 2015 competition's third place recipients found their inspiration in South Asia. The kukri is the traditional knife of Nepal where it has been used for centuries by warriors and farmers alike who have relied on its front-heavy design for sharp, chopping blows. While most commonly used as an everyday tool for domestic and agricultural needs, the kukri is famous for its military use by the Nepalese army and Gurkha troops around the world.

Because the kukri design can vary widely in curvature, length, and construction across the various regions of Nepal, the team from Colorado School of Mines chose to add their own unique design and style variations to the recreated knife. They worked with local craftsmen to ensure the authenticity of their replica by matching their forging processes and materials to those used by Nepalese knife makers today.

**Damascas Steel Khanjar**
by Remigiusz Błoniarz, Estera Macho, AGH University of Science and Technology, Poland.

Imitation isn't just the sincerest form of flattery—it's a great way to learn. The team from AGH University of Science went to the National Museum in Cracow, Poland to study an 18th/19th century oriental Damascus steel blade in an attempt to recreate it using traditional blacksmithing techniques. Unlike pattern-welded Damascus steel where layers are forged welded together and folded, wootz is formed

## Extension Activity

from re-melted steel in clay crucibles. The team created their own wootz ingot which was then formed into the blade through 85 cycles of forging and heating. The hard work ultimately paid off as the team's testing revealed that the microstructure of their blade matched their museum wootz blade sample.

**Berkelium**
by R. Connick, H. Vo, D. Frazer, W. Connick, R. Traylor, N. Bailey, J. Bickel, J. Austin, P. Hosemann, University of California, Berkeley.

The 2015 team from University of California, Berkeley won special recognition for their historical reproduction of authentic Saxon sword manufacturing techniques. Just as the Saxons would have originally searched for iron ore deposits, the team of students began by collecting magnetite, an iron ore, from a local California beach at low tide. The collected sand was spread thinly over a large area and magnets were carefully passed over the sand to extract the magnetite. The team then smelted the extracted ore to produce the steel that would become their blade.

**Reproduction of the T19391 Sword from the Late Norwegian Iron Age**
by David Brennhaugen, Espen Undheim, Raghed Saadieh, Rune Hagberg Stana, and Vincent Canaguier of Norwegian University of Science and Technology.

The Norwegian University of Science and Technology (NTNU) University Museum is home to the T19391 blade—a late Norwegian Iron Age sword originally discovered in the same county as NTNU. The sword is a prime example of the blades produced during a conflict-heavy period of Norwegian history and it shows the need for mass production in its simple design and lack of ornamentation. The team from NTNU set out to recreate the blade by first studying and measuring the original before selecting a high carbon steel which was flattened into a bar and then manually hammered into the shape of the T19391 blade.

**Dragonslayer: A Modern Myth**
by Jacob Hullings, Emily Feng, and Emma McDonnell of Northwestern University, and Ric Furrer of Door County Forgeworks.

The team from Northwestern University found their

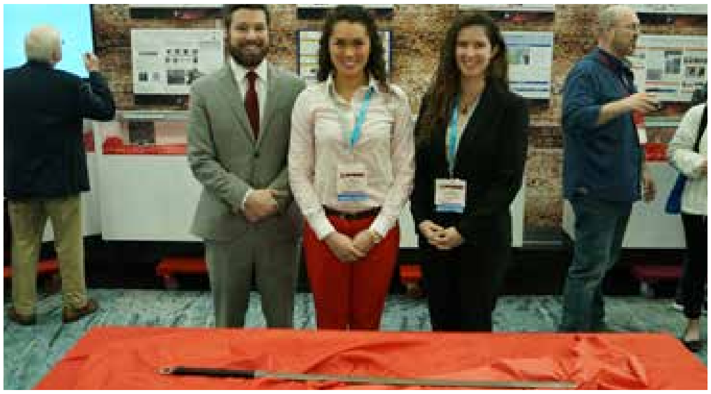
## Extension Activity

inspiration in the Old English poem, *Beowulf*. Despite a life of legendary victories, the tale's eponymous hero is mortally wounded during a fight against a dragon when his seax, a single-edged knife, shatters on the dragon's hide leaving him open to attack. The bladesmithing team set out to recreate a historically accurate seax with one notable exception— their blade would be forged using ultrahigh performance steels, Ferrium® C61™ and C64®, to ensure that it was strong enough to avoid the critical failure of Beowulf's weapon.

**A Rapier Eclectic**
by Dylan Fitz-Gerald, Kyle Rosenow, Cam Atwood, Josh Ledgerwood, and Justin Boothe of California Polytechnic State University, San Luis Obispo.

Eclectic is certainly an apt description for the blade produced by the team from California Polytechnic State University. They set out to experiment with a wide variety of bladesmithing techniques in order to improve their own skills. As a result, each component of the blade presented new challenges ranging from fabricating custom tools for forming the bevels, to Computer Numerical Control (CNC) plasma cutting the ivy leaf pattern, to using a CNC lathe for forming the sword's pommel. The team's rapier is a testament to the many skills utilized in producing a quality blade and, of course, to the talent of the students who produced it.

**Meteoritic Iron Han Dynasty Dao**
by Emily Bautista, Cameron Crowell, Dale Morse, Andrew Pfaff, and Olivia Wilson of Virginia Polytechnic Institute and State University.



All the teams who enter the TMS Bladesmithing Competition "shoot for the stars" when designing and forging their blades, but one team took that mantra more literally than the others. They decided to use meteorite as the basis for their sword, a technique which goes back to 7000 BC in the Chinese sword making tradition. After sourcing an 8 pound meteorite, the team had to cast it into blanks which were then used to forge a traditional Han dynasty (206 BC – 220 AD) Dao, one of the four traditional Chinese weapons. Using the meteorite introduced nickel, phosphorous, and cobalt into the blade, each of which would ultimately influence the sword's characteristics.

## Extension Activity

### Questions

1. What is the difference between casting and forging?

2. What are the advantages of forging?

3. During the forging process recrystallization occurs. What is recrystallization and why is this process vital to forging?

4. Describe the difference between hot forging and cold forging.

5. Many of the teams above designed swords based on historical weapons but a bladesmith can make anything from kitchen knives to throwing stars to a battle axe. What type of blade would you make? Create a poster that includes:
   i. an example of a blade that fascinates you, the history behind the blade and a discussion of the materials and processes used to make it.
   ii. a design or drawing for your own blade, inspired by your example.
   iii. a plan for producing your own blade which notes any changes to the materials or process you would recommend.

MATERIALS™ EXPLORERS

## Extension Activity Answer Key

1. **What is the difference between casting and forging?**
Casting requires heating metal until molten then pouring molten metal into a mold to create a desired shape. Forging requires heating metal to a desired temperature while remaining solid before pressing, pounding, or squeezing the metal under high pressure to create a desired shape.

2. **What are the advantages of forging?**
An advantage of forging is that the metal being forged retains its strength because the grain flow remains unbroken. A second advantage of forging is that it is often more cost efficient than casting or forming.

3. **During the forging process recrystallization occurs. What is recrystallization and why is this process vital to forging?**
Recrystallization is when the deformed grains in the metal become displaced by newly-formed grains, ultimately consuming and replacing the deformed ones. Recrystallization is vital to forging because the process allows the metal to reduce in strength and hardness so that it can be shaped and molded.

4. **Describe the difference between hot forging and cold forging.**
Hot forging occurs above a metal's recrystallization point and prevents materials from strain hardening at high temperatures resulting in optimum yield strength, low hardness, and high ductility. Cold forging occurs below a metal's recrystallization point and increases the strength of a metal through strain hardening at room temperature.

5. **Many of the teams above designed swords based on historical weapons but a bladesmith can make anything from kitchen knives to throwing stars to a battle axe. What type of blade would you make? Create a poster that includes:**
   i. ***an example of a blade that fascinates you, the history behind the blade and a discussion of the materials and processes used to make it.***
   ii. ***a design or drawing for your own blade, inspired by your example.***
   iii. ***a plan for producing your own blade which notes any changes to the materials or process you would recommend.***

   Students can also draw on fictional examples of blades (such as elven swords) but should be able to discuss the theoretical materials and processing used in the novel or film and, in part iii, discuss the real-life materials and production techniques that could be used to forge a similar blade.

MATERIALS™ EXPLORERS

# THE LIGHT ENERGY BEHIND LIGHTSABERS

**How realistic is one of the most iconic fictional weapons of all time? This chapter explores some of the scientific concepts that relate to making a real life lightsaber and asks whether it will ever be possible to replicate it.**

**In this module students will be able to:**

- Discuss the duality of light
- Explain how different colors of light are emitted by different elements
- Define plasma
- Develop a procedure for identifying unknown salts based on the color of light they emit
- Explain the relationship between energy, wavelength, and frequency
- Investigate how lasers are created and their uses in industry

# MATERIALS™ EXPLORERS

## Class Activity

### THE COLOR OF A LIGHTSABER

**Background:**

Imagine if all the neon lights of Las Vegas were the same color. It wouldn't be very interesting, but it would be the reality if they were all truly made of neon. Different elements emit different colors, so the lights that you see are actually made up of any number of different substances.

The **electromagnetic spectrum** consists of all the forms of electromagnetic radiation arranged according to frequency and wavelength. From the electromagnetic spectrum, it can be inferred that energy is directly related to frequency while frequency is inversely related to wavelength.

In the early 1900s scientists conducted two experiments involving interactions of light and matter that could not be explained by the prevailing view of light as a wave: the photoelectric effect and the emission spectrum of hydrogen. Einstein explained the results of these two experiments through what he termed "the duality of light." Einstein proposed that light behaves like a wave when traveling through space and it acts like a stream of particles called **photons** when it interacts with matter.

Elements emit light when there is a continuous and sufficient source of energy. The atoms of the element absorb the energy and the electrons are excited to a higher energy. The electron will emit energy in the form of light called a photon as it returns to a lower energy level or its ground state. The energy of the photon is equal to the energy difference between the atom's excited state and lower energy state and corresponds to a specific color of light. Electrons can be excited through various forms of energy such as electrical or heat. When enough energy is applied to a gas, some electrons can break free from atoms, creating **plasma**.

Light energy, its colors, and its power have made the lightsaber of the *Star Wars*™ universe one of science fiction's most iconic weapons.  Lightsabers can cut through virtually anything and can only be blocked by a material that conducts energy, some rare metals, or another lightsaber. Lightsabers employ many of the concepts mentioned above, although they are described as having plasma blades powered by fictional kyber crystals.

## Class Activity

Could lightsabers ever cross the line from science fiction to science reality? Crystals really do influence the color of light emitted and plasma really can cut through anything. However, light and plasma simply can't stop one another the way two lightsabers can when they clash. Similarly, the very idea of a blade of plasma just isn't physically possible without some kind of containment. Given this, it seems that the creation of real lightsabers is still far, far away.

### Problem

Although lightsabers owe their iconic colors to the kyber crystals that power them, the crystals appear colorless until first discovered by their destined Jedi. The Jedi Council wants to know if it is possible to predict the color of a crystal before it is obtained by a Jedi youngling, using small powdered samples of different crystals to test that colors they emit.

**Task:**
You must create a procedure to distinguish the various kyber powders based on their color. The following materials are at your disposal:

- Bunsen burner
- Striker
- Wooden splints
- Distilled water
- Stirring rod
- Beakers
- Powdered samples A through F
- Petri dishes

**Requirements:**

1. Safety goggles and an apron must be worn at all times.
2. Long hair must be pulled back.
3. Closed toe shoes must be worn.
4. Procedures must be approved by the teacher before beginning.

MATERIALS™ EXPLORERS

## Class Activity

### Questions

1. Create a data table including the columns “Unknown Sample,” “Color Emitted,” “Chemical Identified”, and “Character(s)” based on the information below:

| Lightsaber Color | Character(s) |
| --- | --- |
| Blue/Green | Luke Skywalker, Qui-Gon Jinn, Rey, and Yoda |
| Red | Darth Vader, Darth Maul, Darth Sidious, Count Dooku, Inquisitors, and Kylo Ren |
| Violet/White | Mace Windu and Siths-turned-Jedi |
| Yellow | Jedi Temple Guard |
| Orange | Jedi Temple Guard |

2. List the colors observed in the lab in the following orders:
   - **i.** From highest energy to lowest energy
   - **ii.** From highest frequency to lowest frequency
   - **iii.** From shortest wavelength to longest wavelength
3. What is the relationship between energy, frequency, and wavelength?
4. Given that the Sith are associated with red and the Jedi are associated with blue or green, would you theorize that the Jedi or Sith lightsabers are more powerful? Justify your response using your answer to Question 2 above.
5. What does it mean to “excite” electrons? How were electrons “excited” in this experiment?
6. Explain why different chemicals emit different colors of light using the Bohr model of the atom.
7. While lightsabers are fictional, where have you encountered colorful light emissions? Provide two examples.

### Definitions

**Electromagnetic Spectrum**
The electromagnetic spectrum includes all of the forms of electromagnetic radiation. All forms of electromagnetic radiation are arranged according to frequency and wavelength on the spectrum.

**Photon**
A photon is a light particle.

**Plasma**
A state of matter created when enough energy is applied to a gas causing some electrons to break free from atoms.

MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS4-3 | HS-PS4-4 |
|---|---|---|---|

**Notes:**

1. Teachers must approve student procedures before they begin. An appropriate procedure would be as follows:
   i. Soak wooden splints in distilled water.
   ii. Dip a wooden splint in an unknown sample. Remind students that only a little powder is needed. If too much powder is on the wooden splint it may fall into the burner, skewing further results.
   iii. Set up Bunsen burner so that an inner blue cone appears.
   iv. Hold wooden splint at the tip of the inner blue cone and observe the color.
   v. Repeat until all unknowns have been tested.
   vi. NOTE: For best results turn off lights and close classroom blinds.
2. Students should follow all safety procedures at all times including wearing goggles and aprons, pulling long hair back, no baggy articles of clothing or dangling jewelry.
3. The easiest method for students to access the unknowns is to pour a small amount into a petri dish.
4. The suggested unknowns are: **Sample A:** copper (II) chloride, **Sample B:** lithium chloride, **Sample C:** potassium chloride, **Sample D:** sodium chloride, **Sample E:** strontium chloride, and **Sample F:** calcium chloride.
5. Used wooden splints can be disposed of in garbage cans. Any remaining unknowns can be added to water to create a solution and be disposed of down the drain if the school drains are connected to a sanitary sewer system.

### Answer Key

| Unknown Sample | Color Emitted | Chemical Identified | Character(s) |
|---|---|---|---|
| A | Blue/Green | CuCl2 | Luke Skywalker, Qui-Gon Jinn, Rey, and Yoda |
| B | Red | LiCl | Darth Vader, Darth Maul, Darth Sidious, Count Dooku, Inquisitors, and Kylo Ren |
| C | Violet/White | KCl | Mace Windu and Siths-turned-Jedi |
| D | Yellow | NaCl | Jedi Temple Guard |
| E | Red | SrCl2 | Darth Vader, Darth Maul, Darth Sidious, Count Dooku, Inquisitors, and Kylo Ren |
| F | Orange | CaCl2 | Jedi Temple Guard |

## Teacher Resources & Answer Key

1. **List the colors observed in the lab in the following orders:**
    a. **From highest energy to lowest energy**
    b. **From highest frequency to lowest frequency**
    c. **From shortest wavelength to longest wavelength**

    For all three, the order is Violet, Green, Yellow, Orange, Red.

2. **What is the relationship between energy, frequency, and wavelength?**

    The shorter the wavelength, the higher the frequency, and the higher the energy.

3. **Given that the Sith are associated with red and the Jedi are associated with blue or green, would you theorize that the Jedi or Sith lightsabers are more powerful? Justify your response using your answer to Question 2 above.**

    In theory, the Jedi's lightsabers would be more powerful than those of the Sith because the colors of their lightsabers are associated with high energy while those of the Sith are associated with low energy.

4. **What does it mean to "excite" electrons? How were electrons "excited" in this experiment?**

    Exciting electrons means that electrons are absorbing energy. Electrons were "excited" in this experiment through the heat energy supplied by the flame of the Bunsen burner.

5. **Explain why different chemicals emit different colors of light using the Bohr model of the atom.**

    The distances between energy levels are different for different types of atoms. The color of light emitted depends on the distance the electron "falls" between energy levels.

6. **While lightsabers are fictional, where have you encountered colorful light emissions? Provide two examples.**

    Student answers will vary but may include neon signs, fireworks, rainbows, etc.

## Extension Activity

### BUILDING A BETTER (OR AT LEAST REALISTIC) LIGHTSABER

In the *Star Wars*™ universe, the lightsaber is the symbolic embodiment of The Force and the strength and character of the Jedi (or Sith) who wields it. In *The Force Awakens*, Rey is able to defeat the highly trained Kylo Ren in lightsaber combat once she has accepted and submitted to her considerable Force-sensitive abilities. The lightsaber she uses is actually the one that Luke Skywalker famously lost in *The Empire Strikes Back* when Darth Vader cuts off his right hand, sending it and the lightsaber tumbling down an air shaft in Cloud City. And, Vader should know a thing or two about the power of that particular lightsaber, since it's the same one that Obi-Wan Kenobi takes from Anakin Skywalker as he leaves him to die on Mustafar in *Revenge of the Sith*—and then 20 years later gives it to an inexperienced Luke in *A New Hope*.

While the movies don't give much detail about how a lightsaber is actually made, the expanded *Star Wars* universe has fleshed out a fairly rich mythology as to how this weapon is forged, so to speak. According to the *StarWars.com* databank, a Jedi lightsaber is powered from a Kyber crystal mined from the ice caves of Ilum and then attuned and connected to the Force sensitivity of a particular Jedi knight. The business end of the weapon is a shaft of pure energy that can cut through anything except another light saber or a material that conducts energy.

Mystical crystals aside, could a light saber actually be built in the world as we know it, or are its origins purely the domain of exciting, but improbable, science?

In her book, *The Science of Star Wars*, Jeanne Cavelos, an astrophysicist who worked in the astronaut-training division of NASA's Johnson Space Center, tried to imagine what kind of energy would be contained in such a weapon. It could not be a laser for several reasons. For example, a laser beam would only be visible in air dense with dust, and the beam would travel in a straight line until it was absorbed, reflected, bent, or scattered by some obstruction. Her alternative is plasma—a gas that has been heated to extremely high temperatures. Plasma can be powerful, but containing it to a particular shape, such as the confines of the lightsaber shaft, would pose some hurdles science has not yet overcome. The high-powered plasma would also burn the hands holding the weapon, Cavelos learned in her research.

"In that case, perhaps Luke would prefer to . . . activate it by remote control," she wrote.

These hard science facts might suggest that building a light saber for real would be out of reach for mere mortals who do not channel The Force. When that question was put to a few materials scientists and engineers, they met the challenge with some creative ideas of their own for somewhat bending the laws of physics to build a light saber that could, at least theoretically, work. Read on to see what they proposed and decide for yourself if in some world not too far, far away, the science of *Star Wars* could actually exist.

### A New Element for a New Weapon

*Joseph F. AuBuchon, Applied Materials, and Joel Hollingsworth, Lam Research, recognized that the right element to make their lightsaber simply doesn't exist. So, they tackled the lightsaber challenge by inventing a fictional element of their own that had the properties they needed to make the blade work.*

Master Obi-Wan Kenobi described

## Extension Activity

a lightsaber as “an elegant weapon for a more civilized age.” Contrary to what the name might imply to the uninitiated, the deadly blade of a lightsaber is not actually made up of pure light. By consulting with official records, we see that a lightsaber blade performs feats that no mere beam of light is capable of: parrying similar blades, casting shadows, and stopping in mid-air a short distance from its source (Figure A).

Lightsaber blades actually have solid metal cores. This central part of the formidable weapon is made of a single element, metachlorium (Me), number 138 on the periodic table, whose discovery shattered all materials records for melting point and cohesive energy. An energy cell powers three pumping lasers that are focused onto a coupling crystal at the base of the blade core, allowing a unique electromagnetic frequency to travel along the blade core as surface plasmons. Waste heat causes the blade core to rapidly expand by a factor of four or more, until it reaches its full size.

Magnetic suspension (which produces the weapon’s characteristic hum) physically isolates the Me rod, containing the intense surface oscillations safely on the blade exterior. Some electromagnetic energy escapes as light in a color corresponding to coupling frequency, but the core contains almost all of it until coupled to another object, at which time plasmon energy and blade heat enables it to slice through steel like a knife through butter.

### Don’t Forget Proper Disposal

*Wayne Reitz, Talbott Associates, Inc., sought inspiration for his lightsaber design in a plasma based blade which relied on a nuclear power source.*

Model this new design from a flashlight, except the light beam would be a high-energy plasma that operates in air and is contained by a magnetic field. All components operate from within the hilt of the saber.

The plasma has the ability to degrade the structure and mechanical properties of any material it contacts. The power source would be nuclear, albeit a small reactor; the by-products of the nuclear reaction is the plasma source. Obviously, proper disposal is required. Otherwise, the garbage could become “mixed waste.”

### Too Hot to Handle

*Iver E. Anderson, Ames Laboratory, drew on his experience with lasers to design his lightsaber.*

From my own experience with lasers, the more powerful ones are also much bigger.

A key question is how much laser power is needed? Also, what laser wavelength would be preferred to allow maximum coupling to body parts and assorted weapons that are anticipated?

After knowing the power and wavelength, an optimum laser system (crystal or ionized gas) must be identified. A decision must be made between continuous wave or pulsed operation mode. A pulsed mode would allow higher operation power with a lower cooling requirement. This would also help in portability.

If the invention of a new laser system is required to achieve the optimum wavelength,for example, a long research period may be needed to select and optimize the output power.

If an existing laser system could be used, the packaging of the system for optimum portability will be the next huge challenge. The key is to reduce the weight of the power supply or to figure out how to transmit the power without an umbilical from a base supply to the battlefield. This may be done by microwaves. Also, the high

## Extension Activity

power level would probably need a large cooling capacity, probably needing a gas-turbine-powered cooling fan.

In the end the toughest thing might be to get a volunteer to hold the saber that has a red hot handle and a small jet engine attached to the end; all the while keeping a microwave receiver dish pointed to the power supply that is sending a megawatt beam at him or her.

Any takers?

*Parts excerpted from "The (Mostly Improbable) Materials Science and Engineering of the Star Wars Universe" by Maureen Byko, published in* JOM, *May 2005, Volume 57, Issue 5, pp 12-18.*

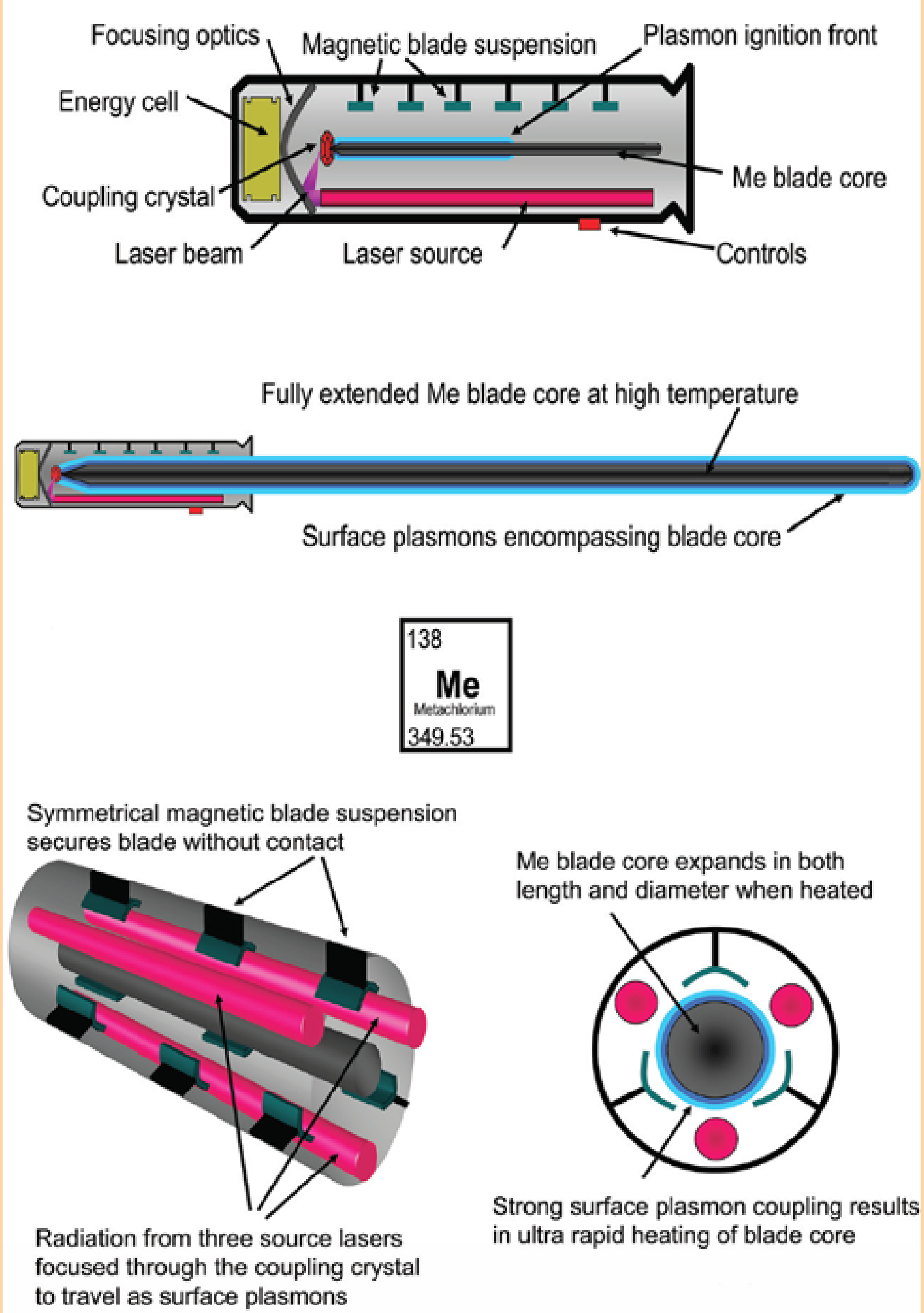



*Figure A (a) A schematic drawing of a lightsaber during the plasmon-initiation process. (b) A schematic of the fully extended lightsaber. (c) Element 138 on the periodic table (filled5g shell). (d) A three-dimensional schematic of lightsaber interior when weapon is off. (e) A schematic of the lightsaber cross section.*

## Extension Activity

### Questions

1. What is plasma?
2. What does laser stand for?
3. How is a laser created?
4. What are lasers used for in industry?
5. Figure A illustrates a metachlorium blade core. While metachlorium is a fictitious element, what properties might it need in order to work as the core of a lightsaber?
6. Based on the commentaries provided, how would you construct a lightsaber?

## Extension Activity Answer Key

1. **What is plasma?**

   A state of matter created when enough energy is applied to a gas causing some electrons to break free from atoms.

2. **What does laser stand for?**

   Laser stands for light amplification by stimulated emission of radiation.

3. **How is a laser created?**

   A laser is created when billions of atoms produce trillions of photons at once and the photons line up to form a concentrated light beam.

4. **What are lasers used for in industry?**

   Student answers will vary but some examples include repairing detached retinas, reading product codes on groceries, recording and playing CDs and DVDs, cutting materials, transmitting phone calls and data, surveying roads, identifying molecules or viruses, measuring airplane velocity, cleaning diamonds and art relics, and guiding missiles

5. **Figure A. illustrates a metachlorium blade core. While metachlorium is a fictitious element, what properties might it need in order to work as the core of a lightsaber?**

   Metachlorium would need to be solid at room temperature with a high melting and boiling point, and would need to be a good conductor of heat and electricity.

6. **Based on the commentaries provided, how would you construct a lightsaber?**

   Student answers will vary.

# MATERIALS™ EXPLORERS

## SCIENCE OF SOUND

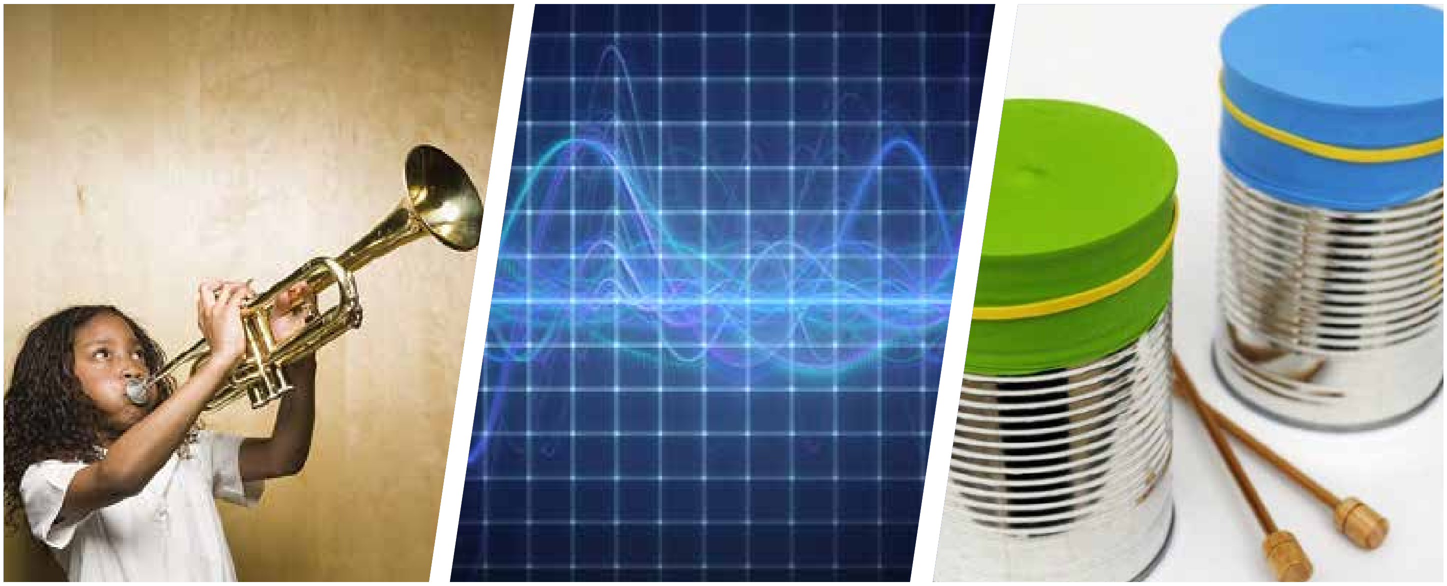
**Ever wonder how music is made? In this chapter, you'll learn about the connection between waves and music by exploring how musical instruments produce sound. You'll also learn more about how musical instruments can be affected by the materials they are made from.**

**In this module students will be able to:**

- Explain how pitch and amplitude can be adjusted for string and wind instruments
- Construct a prototype of an instrument which can be adjusted for pitch and amplitude
- Demonstrate the prototype and discuss challenges encountered
- Explore how various materials are used in the manufacturing of musical instruments
- Interpret graphs displaying sound waves, comparing pitch and loudness

## Class Activity

# ACOUSTIC AUDITION



**Background:**
When you hear your favorite song play on the radio or listen to a band play at a concert, what you're really experiencing are a series of waves, causing vibrations within your ear. These vibrations cause signals to be sent to your brain which, in turn, translates those signals into the amazing variety of noises you hear every day.

Sound is simply energy that moves through a medium, usually air, in a wave pattern. The **frequency** of a sound is directly related to its **pitch**. The more waves per second that hit your ear, the higher in pitch the tone is and the smaller the wavelength. Instruments can have high or low frequencies and some instruments sound louder than others. Louder sounding instruments have higher **amplitudes,** meaning they can compress air to a greater extent.

When a musical instrument produces a note, what it's really doing is creating a sound wave with a unique frequency, pitch, and amplitude. However, not all musical instruments do this in the same way. One of the most common ways to organize musical instruments is by classifying them into families based on the materials used in their construction and the method by which they produce sounds. The most common families are percussion, string, brass, and woodwind. In percussion instruments, sound generating vibrations are caused by a striking action, such as when drums are hit or when piano strings are struck by the piano's hammer. String instruments, such as guitars, cause vibrations in a slightly different way. The string of the instrument is pulled or plucked and the sound occurs as the string returns to its original position. Finally, the sound produced by brass and woodwind instruments is created by forced air interacting with the instrument. Think of how air is pushed through a recorder or trumpet.

## Class Activity

### Problem

An award-winning school marching band has decided to audition for a televised talent competition. The band members are very excited about this opportunity and know they need to deliver a unique performance in order to qualify. The students have decided to design, create, and play their own musical instruments instead of traditional instruments to make them stand out. Since you have exceptional knowledge of waves, pitch, and amplitude, they have enlisted your help to make the endeavor a success.

**Task:**
You are tasked with applying what you have learned about the properties of sound and acoustics as you design and create a musical instrument to present to your class.

**Requirements:**

1. The instrument must be a string, percussion or wind instrument.
2. The instrument cannot contain parts taken from other musical instruments.
3. The instrument must be capable of playing the following eight notes in order of increasing pitch: C, D, E, F, G, A, B, C.
4. The song you play for the class must consist of at least six different musical notes.
5. The class presentation you deliver must include a discussion of the following:
   a. How pitch and amplitude can be adjusted on your instrument.
   b. Problems you encountered while building and tuning the instrument.
   c. The inspiration behind the design of your instrument.

### Definitions

**Frequency**
Frequency refers to the rate at which a wave is repeated over a specific period of time. It is typically measured in Hertz (which is calculated as the number of cycles per second).

**Pitch**
Pitch is related to frequency. The more waves per second hitting your ear, the higher in pitch the tone seems.

**Amplitude**
Amplitude is a measure of how “loud” a sound is. The greater the amplitude of the wave, the louder you perceive the sound.

## Class Activity

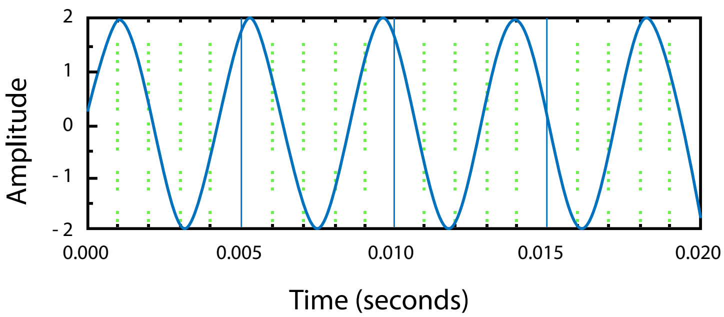
### Questions

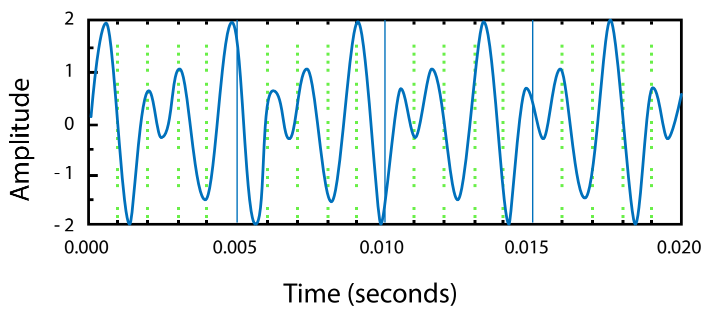
1. **Does frequency change based on the material used to create the instrument?**

2. **Do higher pitched sounds have a higher or lower frequency? Do they have a greater or shorter wavelength?**

3. **How can pitch and amplitude be adjusted for the following:**
   **i.** A string instrument?
   **ii.** A wind instrument?

4. **If the two waves below represent sound waves, how do the pitch and loudness compare?**




5. **What kind of work might an acoustical engineer do?**

# MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS4-1 |
|---|---|---|

**Notes:**
N.B. This activity can be modified to take less time by having students work in groups to create different instruments.

1. Students should be encouraged to research ideas for their instruments.
2. Set deadlines throughout the project, including a deadline for a design draft, a prototype, and the final product.
3. PVC pipe is cost efficient and can be used to create a wind instrument. Bamboo also works well.
4. Fishing line can be used for string instruments, but students should be cautioned that fishing line can stretch so they may need to adjust tuning periodically.
5. Rubber sheeting, metal pipe, PVC pipe, and copper tubing can be used to create a percussion instrument.
6. Remind students that while they may be concerned with appearance, they are graded on functionality and their ability to discuss the scientific concepts at work.
7. The timeline for this project is at the teacher's discretion. Note: If students are not permitted to work on the project at home, it may take up to a week longer to complete.

1. **Does frequency change based on the material used to create the instrument?**

   Yes. All objects have a natural frequency or set of frequencies at which they vibrate. For example, steel, brass, and wood all have different natural frequencies. However, some instruments may be more affected by material choice than others.

2. **Do higher pitched sounds have a higher or lower frequency? Do they have a greater or shorter wavelength?**

   Higher pitched sounds have a higher frequency and shorter wavelength.

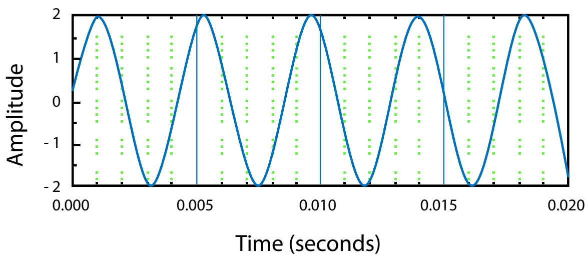
3. **How can pitch and amplitude be adjusted for the following:**
   **i.** A string instrument?
   **ii.** A wind instrument?

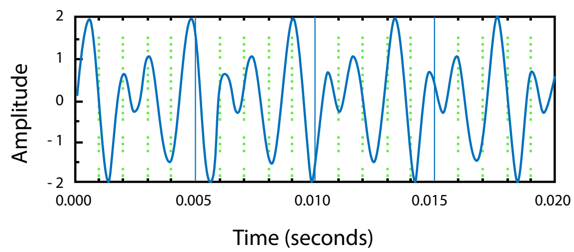
   i. String instrument: Pitch depends on the size of the string and the tension on the string. Amplitude depends on how hard the strings are plucked.

   ii. Wind instrument: Pitch depends on the size of the air column. Amplitude depends on how much air is forced through the column.

## Teacher Resources & Answer Key

**4. If the two waves below represent sound waves, how do the pitch and loudness compare?**




The pitch and loudness are the same because the period and frequency as well as the amplitude are the same.

**5. What kind of work might an acoustical engineer do?**

Student answers will vary. Some examples include: Work on the design and sound of performance spaces; ensure buildings comply with local noise ordinances and standards; work to minimize noise on the highway or in air traffic; design sound systems; or work with bioengineers to develop medical technology like hearing aids.

| Activity Grading Rubric | | | |
|---|---|---|---|
| **Points** | **Design** | **Pitch** | **Explanation** |
| **4** | Instrument and design is well thought out and supports the solution to the problem.<br><br>Song can be played fluently. | Seven or eight distinct pitches were played. | Information is clearly focused in an organized and thoughtful manner.<br><br>Information clearly addresses how pitch and loudness can be adjusted as well as construction challenges. |
| **3** | Instrument and design is well thought out and supports the solution to the problem.<br><br>Song could be played with 1 or 2 difficulties. | Five or six distinct pitches were played. | Information supports the solution to the challenge or question.<br><br>Information addresses how pitch and loudness can be adjusted as well as construction challenges. |
| **2** | Instrument and design supports the solution.<br><br>Song is a struggle to play. | Four or fewer distinct pitches were played. | Information loosely supports the solution.<br><br>Information does not clearly address how pitch and loudness can be adjusted. Construction challenges are mentioned. |
| **1** | Instrument and design does not support solution. | No distinct pitches were played. | Information does not support the solution.<br><br>Information does not clearly address how pitch and loudness can. |

## Extension Activity

# DO MATERIALS MATTER TO MUSIC?

When it comes to creating a musical instrument, one thing is certain. Materials matter. Instrument makers may use a signature material to differentiate their works from others, a rare material to add to the prestige of an instrument, or a pliable material to make production of the instrument easier. The choice of materials can also affect the sound an instrument creates and even traditional craftspeople have been known to tinker with advanced materials for better sound quality.

However, the influence of material choice on sound quality can vary vastly from one musical instrument to another. Take, for instance, the debate around brass instruments.

The prices of brass instruments can vary widely based on the type of material used to produce them, but players and manufacturers alike are divided on whether this makes any difference at all to the final sound. Researchers have set out to find an answer.

*At the Institute für Wiener Klangstil (IWK) in Austria, researchers tested seven identical flutes made out of silver, various degrees of gold, and platinum, as well as coated instruments, to determine if the sound quality from the different flutes was affected by the choice of material. (Photo courtesy of the IWK)*

### Testing Precious-Metal Flutes

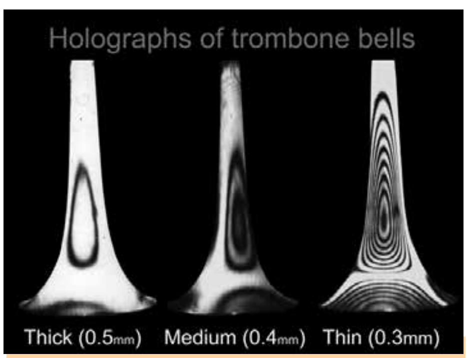
Gregor Widholm, who established the Institut für Wiener Klangstil (IWK) at the University of Music and Performing Arts in Vienna in 1980, conducts applied research in the field of musical acoustics. The institute credits Widholm with founding the scientific research field of musical acoustics in Austria by adapting scientific physical measuring methods to the investigation of the functionality of musical instruments.

Widholm and his colleagues set out to learn the effect of different metals on the sound of flutes. They chose seven identical flutes made by a single manufacturer, Muramatsu, in seven different materials: silver coated, full silver, 9 kt gold, 14 kt gold, 24 kt gold, platinum coated, and all-platinum. Seven professional flute players from Viennese orchestras were recruited to test the flutes by playing short solo pieces and individual notes on each of the seven flutes. These results were recorded and analyzed by IWK researchers, and the professionals listened to the results. What they found was that the instrument being played had little effect on the sound being produced.

“Silver, 24 kt gold, and platinum all have different vibrating properties,

## Extension Activity

of course, but the musician can mask all these properties by generating the sound," said Widholm. "That's the reason why there's really no difference between the $3,500 flute and the $150,000 flute. We conducted these tests with professional flute players, and when they heard the samples recorded, they heard no difference." These tests also measured the dynamic range of the instrument—that is, how loud or soft the musician can play. The platinum flute provided a slightly higher dynamic range, but, while measurable, it was not significant. The difference between musicians varied more than between instruments.




*This image shows holographic measurements of vibrations in trombone bells of various thicknesses. Though there is a measurable difference in vibration, instrument players were able to detect little difference in sound quality among the three.*
*(Photo courtesy of Richard Smith)*

### An Experiment in Brass

Unlike many instrument makers, who start out as musicians, Richard Smith began as a scientist, receiving master's and Ph.D. degrees in acoustics. His doctoral research dealt with the application of quantum physics to musical instruments.

Now, Smith uses his scientific background to manufacture brass instruments with high sound quality at his own company, SmithWatkins, where he designs instruments with trumpet player Derek Watkins.

Like Widholm, Smith has also put instruments to scientific tests–this time, to determine if varying the material of a trombone will change its sound. Smith conducted an experiment using several trombone bells of various materials and thicknesses. Although holographic measurements show differences in the vibration for the various thicknesses of material, Smith found that not one of the professional trombone players in his study was able to tell the difference either between different types of material or different thicknesses of material in the bell of the trombone.

Internal shape is important to the sound, bell shape is important, and the lead pipes are important, according to Smith. "Materials are really just the icing on top," he said.

*Instrument manufacturers are always experimenting with alternative materials. Ted Brewer's Vivo$^2$ electric violins deviate from traditional violins in both material and shape. (Photo courtesy of Ted Brewer Violins)*

However, sound quality isn't the only factor determining material choices and, for Smith, brass is still best. "It's all about what material is easiest to work with," said Smith. "Brass is ideal because it's malleable."

While the body material will likely stay the same, there is room for materials innovations in some of the instrument's smaller pieces. For example, Smith would like to see a materials redesign of trumpet valves to make them faster. Using lighter weight materials in the valves, such as magnesium or titanium, could be the solution, he suggested.

## Extension Activity

### Instruments are Like Golf Clubs...

If specific metals have not proven to make much difference in the sound of metallic instruments, why select one material over another? Some manufacturers use materials as a marketing device to differentiate themselves from competitors. For others, it is simply a way to offer musicians more choice.

Elizabeth Holm, a materials scientist and amateur musician, notes that another factor driving material choice is likely psychological. She compares it to the golf club industry, where new clubs made of "better materials" are introduced every year, claiming to improve your game. "There's a strong placebo effect. If you have more confidence in your clubs, doesn't it make you play a little better, at least for a while?" she said. "I don't know; I've never measured it. But it's the same with music."

*Elizabeth Holm (right), a materials scientist, plays violin with her friend Jude Rowe, as members of a band that performs primarily for Celtic dance groups and festivals. (JOM: December 2013)*

*This article is excerpted from "The Science of Sound: Examining the Role of Materials in Musical Instruments" by Kelly Roncone Zappas, published in JOM, August 2007, Volume 59, Issue 8, pp 13-17.*

## Questions

Whether the choice of material affects the sound, appearance or cost of an instrument, craftspeople give serious thought to the types of materials they use. While Widholm and Smith found that the choice of material did not affect the sound quality for their flutes or trombones, it has a major influence on the sound produced by a violin.

1. **How is sound produced in a traditional violin and why might the choice of materials be important to this?**

2. **What materials are violin bows traditionally made of and what challenges to this material have caused violin makers to explore new materials?**

3. **What alternative material is currently in use for bows? What are the pros and cons of using this material?**

4. **Kevlar, a material often used in bullet-proof vests, is also used in violins. What part of the violin is composed of Kevlar and what is the advantage of using this material?**

5. **While there are no restrictions on materials that can be used to make electric violins, what are some factors manufacturers should consider when selecting materials?**

## Extension Activity Answer Key

1. **How is sound produced in a traditional violin and why might the choice of materials be important to this?**

   A string which is attached to a soundboard can be vibrated by plucking or tapping it. The vibrations create compression waves in air. The compression waves result in sound according to the frequency of the waves. Materials are important to violins because the frequency or pitch is dependent upon the material the strings are composed of.

   The three types of strings available to use for violins are gut core, steel core, and synthetic core. Gut core strings are made from a natural fiber, making them pliable and sensitive to temperature and humidity. Steel core strings—consisting of thin fibers of roped or spiraled steel coated in metals such as aluminum, chrome, steel, tungsten, silver or titanium — are sturdy and create a stable pitch. Synthetic core strings are composed of nylon and sound similar to gut strings, but are more stable in pitch.

2. **What materials are violin bows traditionally made of and what challenges to this material have caused violin makers to explore new materials?**

   Violin bows are traditionally made from Pernambuco wood, however Pernambuco trees in Brazil are now considered endangered. This makes it both challenging and expensive to purchase the wood.

3. **What alternative material is currently in use for bows? What are the pros and cons of using this material?**

   Carbon fiber composite has been an alternative material used to make bows. Carbon fiber allows bows to be sturdier, lighter in weight, and less prone to warping. Carbon fiber is also less expensive and more uniform, which allows consumers to expect consistent quality from a manufacturer.

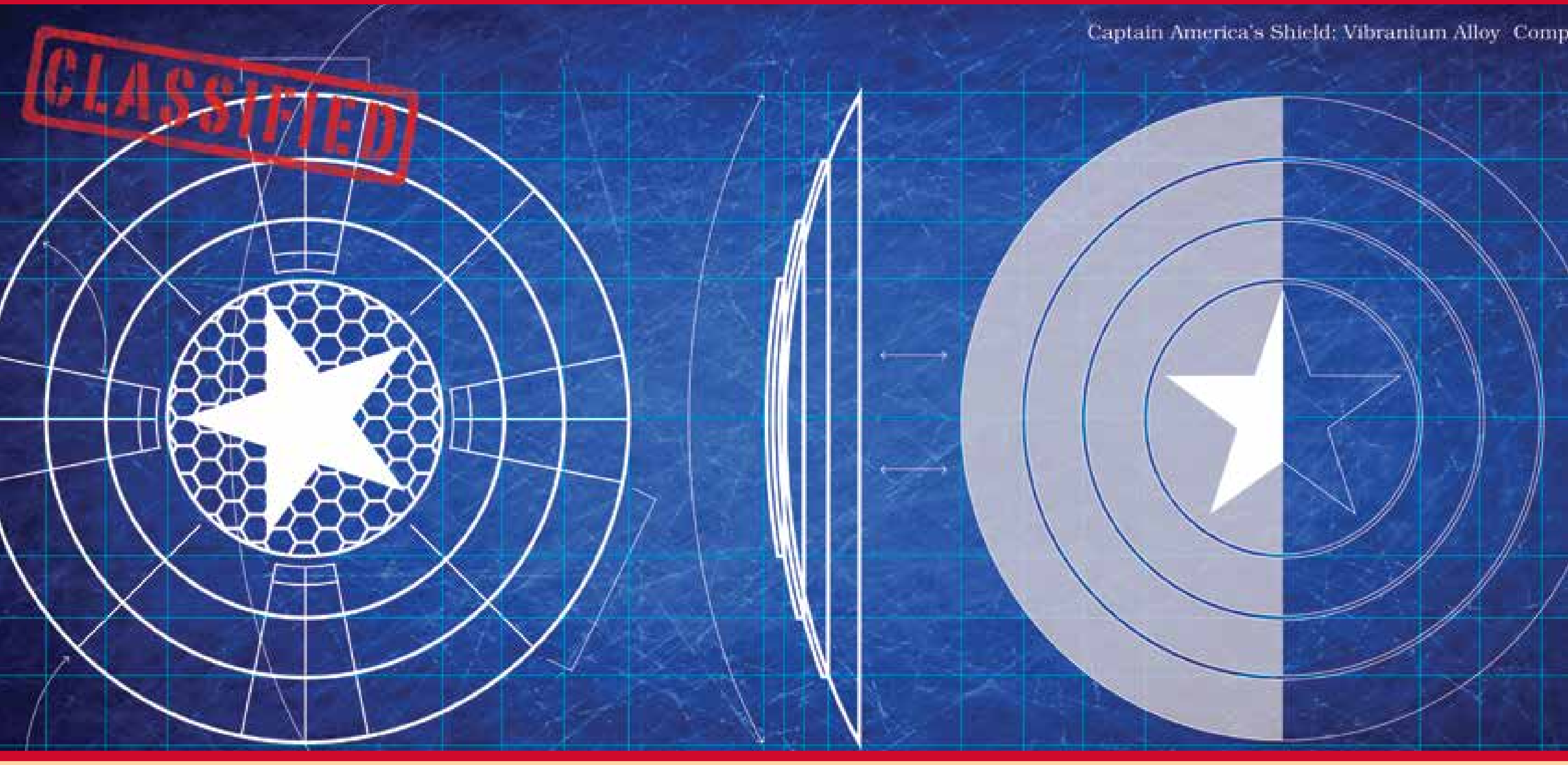
4. **Kevlar, a material often use in bullet-proof vests, is also used in violins. What part of the violin is composed of Kevlar and what is the advantage of using this material?**

   Kevlar string is used on the tailpiece in place of a traditionally stiff metal wire coated with plastic. Kevlar string improves the sound from the tailpiece.

5. **While there are no restrictions on materials that can be used to make electric violins, what are some factors manufacturers should consider when selecting materials?**

   Student answers will vary but should relate to important qualities such as durability, aesthetic appeal, ease of manufacturing or cost effectiveness. For example, a student may respond that the weight of the material should be taken into consideration so that the instrument is not cumbersome.

# MATERIALS SCIENCE OF SUPERHEROES




*Original artwork by David Rasel, TMS Media Manager*

**Scaling walls, super strength, and X-ray vision aren't just the stuff of comic books. In this chapter, you'll explore the importance of materials to the superhero world and learn about researchers who are accomplishing superhuman feats using science.**

**In this module students will be able to:**

- Compare theoretical superpowers to real-world scientific applications that make them possible
- Use their knowledge of an element to synthesize their own superhero
- Explain the arrangement of elements on the periodic table
- Research the role of materials science and engineering in simplifying modern life
- Discuss the relationship between valence electrons and reactivity, and the importance of reactivity in materials science

# Class Activity

## POWERS OF THE PERIODIC TABLE

**Background:**
Often, when superheroes face seemingly insurmountable odds and unbeatable villains, they gain an advantage by teaming up with other superheroes and combining their unique superpowers. A similar approach can be applied to science and engineering problems. In fact, the minerals, metals, and materials workforce needs professionals from a wide variety of backgrounds to contribute their unique viewpoints and approaches to solve complex problems. See how a few of these individuals are contributing to making our world a better place as members of their own version of a superhero league, The Minerals, Metals & Materials Society. Then, create a superhero of your own inspired by the elements of the periodic table.

NAME: Akane Suzuki

Base of Operations:
> Principal Engineer
> *GE Global Research, New York*

Last Seen: Developing new alloys that can withstand very high temperatures and harsh environments.

Mission: Make aircraft engines and electricity power plants work more efficiently and safely for longer hours.

Powers: Grants "superpowers" to alloys by designing and optimizing the chemical formula and processes.

NAME: Amy Clarke

Base of Operations:
> Associate Professor
> *Colorado School of Mines*

Last Seen: Filming the formation of metal structures to understand and control how they develop.

Mission: Create everyday materials that perform better, last longer, and use less energy to make.

Powers: Can see through metals, using x-ray and proton vision.

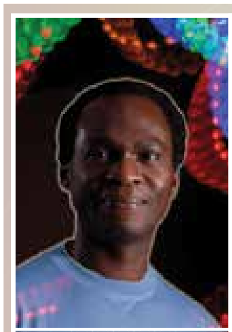


Photo Courtesy of Michelle S. Kim, University Communications

NAME: Dele Ogunseitan

Base of Operations:
> Professor of Public Health
> Chair, Department of Population Health and Disease Prevention
> *University of California, Irvine*

Last Seen: Identifying the risks of toxicity that can cause disease in humans or damage to the ecosystem due to materials used in every day products.

Mission: Help manufacturers use safer, less toxic materials in products such as cellphones, computers, batteries, and light bulbs.

Powers: Research that permits "time travel" to the past, present, and future of a material to know where the dangers are for people and for the environment.

Background Photo: Magnesium engine block, US Automotive Materials Partnership (USAMP)

NAME: Joy Hines Forsmark

Base of Operations:
> Technical Expert
> Research and Innovation Center
> *Ford Motor Company, Michigan*

Last Seen: Studying lightweight metals, such as aluminum and magnesium alloys, for use in automobiles.

Mission: Make lighter cars that use less gas and create less air pollution.

Powers: Starts with atoms to build the lightest and best parts for a car.

# MATERIALS™ EXPLORERS

## Class Activity

Background Photo: Francesco Tomasinelli and Emanuele Biggi

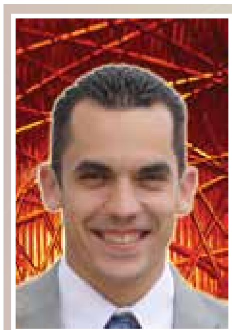
NAME: Markus J. Buehler

Base of Operations:
> Professor and Head
> Department of Civil and Environmental Engineering
> *Massachusetts Institute of Technology*

Last Seen: Discovering how the toughest materials found in nature are constructed at the molecular level, and then using that knowledge to develop new, synthetic materials.

Mission: Taking simple, natural ingredients, such as wood or protein, to make sustainable, durable materials.

Powers: Amazing insights into why spider silk is one of the Earth's strongest materials. Ability to work with many other scientific fields to someday create a "super fiber" that mimics what spiders naturally produce.



NAME: Paul R. Ohodnicki, Jr.

Base of Operations:
> Materials Scientist
> *U.S. National Energy Technology Laboratory*

Last Seen: Researching and developing materials that could lead to new types of sensors and devices for power generation and electrical energy conversion.

Mission: Improve energy efficiency of power plants and their transmission and distribution systems.

Powers: Designs unique materials in a way that makes them useful for application in devices.

NAME: Michele V. Manuel

Base of Operations:
> Professor and Department Chair
> *University of Florida*

Last Seen: Designing materials to make machines smarter.

Mission: Help create machines with unprecedented power and behavior through the use of designer materials.

Powers: Molecular Transmutation—the ability to manipulate matter on a molecular level for the betterment of human kind.

NAME: Ricardo J. Zednik

Base of Operations:
> Vice President / CTO / Principal Engineer, *Arrhenius Failure Analysis International (Arrhenius, Inc.)*
> Professor, *University of Quebec*

Last Seen: Collecting evidence and following clues hidden in materials to solve how engineering designs fail—often catastrophically—in applications like medical implants, natural gas pipelines, digital cameras, and satellite solar arrays.

Mission: Protect society by understanding what causes accidents, fractures, and explosions.

Powers: Brings smashed objects "back to life" so they can tell us what happened.

Now that you've learned about some of the materials science and engineering superheroes out there, it's time to create your own character inspired by the periodic table of elements.

As you review the Periodic Table, you may notice that elements are grouped by a certain logic. When Dmitri Mendeleev originally arranged the periodic table in 1869 he did so by atomic mass, but today's periodic table looks a little bit different. That is because Henry Mosely rearranged the table according to increasing atomic number. This arrangement means that elements in the same group have the same number of **valence electrons** and exhibit **periodicity**, meaning they have similar physical and chemical properties. Perhaps some of these properties will inspire your superhero.

## Problem

The Ensemble of Elements, a group of sophisticated superheroes, needs your help. Their membership is dwindling after surviving a surprise attack by trans-dimensional aliens. The Ensemble believes that anyone who understands the materials around them and how they function can become a superhero. They have reached out to you, urging you to develop your sophisticated superhero persona so that you can join them in defeating the alien invaders.

# Class Activity

**Task:**
Your task is to create a superhero persona inspired by one element on the periodic table.

**Requirements:**
You must create a digital presentation, poster, or mobile displaying the following information:

1. Name of superhero
2. Element symbol
3. Element atomic number
4. Element atomic mass
5. Element's location on the periodic table (i.e. group name)
6. Element's electron configuration
7. Physical and chemical properties of element
8. Strengths of the superhero (based on the element's properties)
9. Weaknesses of the superhero (based on the element's properties)
10. Superhero's powers (based on the element's properties)
11. Pictorial representation of the superhero

## Questions

1. **How are the elements arranged on the periodic table?**

2. **How do valence electrons relate to reactivity?**

3. **Why is the reactivity of materials particularly important in materials science?**

4. **Research a material or technology that has made your life better. Who invented it? How long has it been around? How does it improve your quality of life?**

5. **While scientists and engineers have their sights set on the future, discoveries are made each day that can simplify our lives now. List one material and one technology that you wish currently existed.**

## Definitions

**Valence electrons**
electrons in the outermost energy level of an atom that are responsible for the chemical properties of the atom

**Periodicity**
When elements are arranged in order of increasing atomic number they exhibit similar physical and chemical properties

MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS1-1 |
|---|---|---|

**Notes:**

1. Students may be assigned or self-select an element.
2. Students may use books, the periodic table, or the Internet to conduct their research.
3. Students may be directed to websites such as www.autodraw.com for assistance creating a digital drawing of their superhero.

1. **How are the elements arranged on the periodic table?**

   The elements on the periodic table are arranged according to increasing atomic number. The elements are also grouped according to their properties.

2. **How do valence electrons relate to reactivity?**

   Valence electrons are the outermost electrons in an atom, making them more likely to interact with other atoms. Valence electrons determine bonding behavior and are the highest energy electrons, making them most likely to participate in a chemical reaction.

3. **Why is the reactivity of materials particularly important in materials science?**

   Materials science requires scientists to make connections between the structure of a material and its properties. Once this connection is understood, the performance of the material in various applications can be tested.

4. **Research a material or technology that has simplified your life. Who invented it? How long has it been around? How does it improve your quality of life?**

   Student answers will vary. An example includes smartphones which were created in 1992 by IBM. Smartphones allow us to connect with one another via social media, phone calls, text messages, or emails.

5. **While scientists and engineers have their sights set on the future, discoveries are made each day that can simplify our lives now. List one material and one technology that you wish currently existed.**

   Student answers will vary. Examples include a material that would prevent water bottles from leaving condensation marks while cold or technology that would remotely alert homeowners of gas leaks.

## Teacher Resources & Answer Key

### Activity Grading Rubric

| CATEGORY | 5 | 4 | 3 | 2 | 1-0 |
|---|---|---|---|---|---|
| **Graphics - Clarity** | Graphics are all in focus and the content can be easily viewed and identified. | Most graphics are in focus and the content can be easily viewed and identified. | Most graphics are in focus and the content is easily viewed and identified. | Many graphics are not clear or are too small. | Assignment incomplete or not submitted. |
| **Creativity** | The strengths, weaknesses, and powers are creative and original. | The strengths, weaknesses, and powers are original, but lack creativity. | The strengths, weaknesses, and powers are creative, but not original. | The strengths, weaknesses, and powers are not creative or original. | Assignment incomplete or not submitted. |
| **Content - Accuracy** | All facts are accurately displayed on the project. | 4-3 accurate facts are displayed on the project. | 2-1 accurate facts are displayed on the project. | No accurate facts are displayed on the project. | Assignment incomplete or not submitted. |
| **Attractiveness** | The project is exceptionally attractive in terms of design, layout, and neatness. | The project is attractive in terms of design, layout and neatness. | The project is acceptably attractive though it may be a bit messy. | The project is distractingly messy or very poorly designed. It is not attractive. | Assignment incomplete or not submitted. |
| **Grammar/ Spelling** | There are no mistakes on the project. | There are 1-3 mistakes on the project. | There are 4-6 mistakes on the project. | There are more than 6 mistakes on the project. | Assignment incomplete or not submitted. |

Extension Activity

## THE SUPER MATERIALS OF THE SUPERHEROES

Peter Parker may have gained physical superpowers from the bite of a genetically altered spider. But, in *Spider-Man: Homecoming*, it's Peter's own scientific and engineering talents that create Spider-Man's main weapon—synthetic spider webbing that he can trigger from "web shooters" mounted on his wrists. In fact, it's the only part of Peter's original Spider-Man costume that Tony Stark doesn't openly ridicule when he meets him. ("This webbing! Tensile strength is off the charts.") Stark goes on to include his own web shooter technology in the super suit that he designs and gives to Peter (and later confiscates) in the film. Presumably, Stark's web formula is made from ingredients other than what Peter could find in his high school chemistry lab or Aunt May's household supplies.

This is just one of many, many examples of how the heroes and villains in the comic realm rely on materials to boost their powers, provide protection, and even define who they are.

The stories of how these materials are created and used do tend to push and exceed the boundaries of what may be possible. But, they are also rooted in the fact that scientists and engineers are "living superheroes" who change—and save—the world every day.

The real source of Iron Man's power, for instance, is the mind of Tony Stark, a brilliant engineer and wealthy industrialist. In the *Iron Man* and *Avengers* movies, Tony uses computational tools, 3D-visualization, and advanced manufacturing techniques to tailor his collection of Iron Man suits to specific needs. This also means that Iron Man's suits contain very little actual iron. Heavy, dense and prone to rust, it was not a suitable material for his superhero exploits. Instead, Stark has dabbled with various titanium alloys, carbon fiber, and nanotechnology. In *Iron Man 2*, he even synthesized a new element to replace the poisonous palladium core in his Arc Reactor.

Suveen Mathaudhu, a materials scientist at Pacific Northwest Laboratory, professor at the University of California, Riverside, and an avid comic fan, believes that modern processing approaches, advanced microscopy, and computational material design tools have closed the gap between comic fiction and science reality. "There really is very little reason that we should not be able to microstructurally engineer whatever materials we want for the future," he said.

*A materials scientist and avid comic fan, Suveen Mathaudhu has the "super power" of being able to modify the microstructure of metals by using advanced scientific tools and techniques. In this photo, he is shown erforming a compression test on a Dake 70-ton uniaxial load press, pushing a metal sample until it fails and recording the load and displacement along the way. This helps him determine how a material will perform in a real-world application.*

## Extension Activity

To illustrate his point, Suveen goes back to the origin story of Captain America's shield, as it was told in the comics (Captain America VI V303 March 1985). As also seen in the *Captain America* and *Avengers* movies, the shield is capable of absorbing, storing, and redirecting all the kinetic energy and vibrations hurled at it. The more energy it absorbs within the bonds between its molecules, the more powerful the material becomes. The fictional element making these unique properties possible is vibranium, obtained from a meteorite that fell to Earth and gave rise to the technologically advanced African kingdom of Wakanda—where Black Panther calls home. The shield was born when the vibranium bonded with steel and an unknown catalyst, forming a disc of indestructible alloy that could only be reshaped by molecular rearrangement.

*Replica of Thor's hammer, Mjölnir, signed by Chris Hemsworth, from the collection of The Minerals, Metals & Materials Society*

To Suveen, the real hero of this part of the Captain America legend is Dr. Myron MacLain, an American metallurgist. At the urging of President Roosevelt, Dr. MacLain was attempting to develop an indestructible tank armor that would give the Allied forces an edge on the battlefield. While experimenting with vibranium, he nodded off and the alloy mysteriously formed while he slept.

Dr. McLain was never able to recreate the material in his lab again, although Suveen believes he would have a fighting chance with technologies from the "real world" that have eclipsed what was being imagined at the time that comic was written. "We have control over the atomic world that we didn't have 20 years ago," he said. "Through high-end microscopy tools, we can visualize and manipulate the very microstructure of a material to achieve ultrahigh strength and other truly amazing characteristics. The next frontier is the ability to accurately predict how we can create materials with specific properties. An indestructible material like vibranium does not exist, but we might be able to come close."

*Replica of Captain America's shield, from the collection of The Minerals, Metals & Materials Society*

Shields, weapons, and superpowers enabled by science are actually a more recent concept explored in the comic world. The earliest superheroes tended to draw their superpowers from myth and magic—if they had any powers at all. This was particularly the case for Wonder Woman, who was introduced to the world in 1942, and as explained in the *Wonder Woman* movie 75 years later, "My mother sculpted me from clay and Zeus breathed life into me." A demi-god among the mythical race of Amazonian women, Wonder Woman's metal bracelets were her main defensive weapon, since they could repel nearly every projectile hurled at her. (And, as seen in the Wonder Woman movie, she uses the metal bracelets to channel her powers into seismic shockwaves. Take that, Ares.)

The nature of superheroes changed during the Cold War when the world was seized with anxiety by the prospect of nuclear war.

## Extension Activity

Americans embraced technology as a way to make life better, but also realized it could be the means of wiping us out. The superheroes and their villains that came up through this time were metaphors for that conflict. New comic characters were developed as flawed individuals wrestling with a multitude of demons, many of them brought on by scientific recklessness.

Marvel Comics is credited with introducing this contemporary breed of superhero when Reed Richards, the brilliant and arrogant leader of the Fantastic Four, launched his stolen rocket into space in 1961. He and his crew were accidently bombarded with "cosmic rays," giving them all superpowers, and horribly disfiguring the pilot, Ben Grimm.

Most of the Marvel characters in this new era of comics, in fact, started out as scientists—and they weren't the stereotypical "mad geniuses." Reed Richards was the smartest man in the world and used his science for good. But, there was also a dark side to his story. He and characters like him symbolized the overall mood of the country toward science.

Science in service of national defense also became a target of suspicion—while the Steve Rogers character introduced during World War II willingly subjected himself to the experiments that ultimately transformed him into Captain America, the Wolverine character in X-men was kidnapped by a shadowy military operation that forcible implanted adamantium, yet another super-strong fictional alloy, into his skeleton.

"A common theme about this time was the consequences of military research—both good and bad," said Suveen."Materials science technologies were particularly dominant in these stories because they underpin nearly everything and were immediately recognizable to the public."

Many of the stories told through the comic pages of the past are now finding new life (and fans) with a seemingly endless stream of superhero movies and television shows. Characters have been updated, but many of them are still carrying—and even expanding upon—the scientific themes first explored in comic books. But, as dazzling as it is, can this new generation of comic science be believed?

*Replica of Iron Man suit from the collection of The Minerals, Metals & Materials Society*

According to Rick Loverd of the National Academy of Science's (NAS) Science & Entertainment Exchange, many creators of fictional universes are very serious about accurately portraying science in their work. The Exchange was established by NAS in 2008 to provide a resource for accurate scientific information to the entertainment industry, and has provide technical consulting to such projects as *Thor* and the *Avengers*.

"What we have found is that the science is much further ahead of what entertainers usually envision. The creative people who attend our sessions come away inspired and excited to use these cutting edge ideas in their work, said Rick. "Many in the entertainment industry feel it's very important to 'get the science right.' They know that everyone in the audience now has a supercomputer in their pockets. Audiences are more savvy to science than they were in the past, and more questioning of some of the ideas. If what they see on the screen doesn't mesh with information that they have access to online, it takes them out of the story."

"That's not to say that everything in a movie needs to be deadly accurate," Rick continued. "The story will always overshadow the science, but plausible science makes the story line stronger and

## Extension Activity

more engaging. It creates the rules in which those imaginary worlds can logically operate."

Suveen agrees, both from his personal experience as a comic fan and in his attempts to inspire new thinking through comic mythology. "The superhero comic, like any science fiction, is the pulse of scientific possibilities," he said. "People relate to these stories and can tie them uniquely to their own ideas. I often use examples from comics in my presentations as a means of inspiring the next generation of engineers—to get them to think differently about what could be possible and then push to that next level."

"Even the superheroes born with powers have the technical acumen to augment them," Suveenn continued. "The focus in most superhero comic stories is a problem or puzzle that requires science to resolve. The hero is always the person who can figure it out and create the technology that saves the day."

"And, doesn't everyone want to be a superhero, when you come down to it?"

**Parts of this article are excerpted from "The Super Materials of the Superheroes" by Lynne Robinson, published in* JOM, *January 2012, Volume 64, Issue 1, pp 13-19, and* Comic-tanium™: The Super Materials of the Superheroes educational exhibit, *presented by TMS, the TMS Foundation, and the Toonseum of Pittsburgh in 2014 and 2015.*

## Questions

1. **Choose a superhero not already explained in this article who owes his or her powers to science. Research the science behind their powers. Which aspects of their powers are scientifically plausible and which are entirely fictional?**

2. **Choose a superhero whose powers are not created by science. How would you propose recreating some of those powers in the real world?**

3. **Vibranium, a fictitious element used in Captain America's shield, makes the shield capable of absorbing, storing, and redirecting all the kinetic energy and vibrations hurled at it. The more energy it absorbs within the bonds between its molecules, the more powerful the material becomes. If vibranium were a realistic element, describe where it would fit on the periodic table and why.**

4. **Tony Stark upgrades Peter Parker's webbing with materials that cannot be found in a high school chemistry class. Fiberglass, however, is a material that is easy to obtain and has some of the same desirable properties as Peter Parker's web. Describe the properties of fiberglass that would be useful if it were developed into a web.**

5. **Peter Parker was not only famous for shooting webs, but also has the ability to quickly scale buildings. Geckos are similar to Peter Parker in that they can "stick" to walls. Explain the science behind this ability and research materials in development that can make scaling walls like Spiderman a reality.**

MATERIALS™ EXPLORERS

## Extension Activity Answer Key

1. **Choose a superhero not already explained in this article who owes his or her powers to science. Research the science behind their powers. Which aspects of their powers are scientifically plausible and which are entirely fictional?**

   Answers will vary. For example, a student could expand on the dangers or radiation exposure, or research the work being done on robotic exoskeletons being developed.

2. **Choose a superhero whose powers are not created by science. How would you propose recreating some of those powers in the real world?**

   Answers will vary. Students may research answers such as mechatronic arms to create superhuman strength, the invention of jetpacks to create flight, x-rays to replace x-ray vision and so on.

3. **Vibranium, a fictitious element used in Captain America's shield, makes the shield capable of absorbing, storing, and redirecting all the kinetic energy and vibrations hurled at it. The more energy it absorbs within the bonds between its molecules, the more powerful the material becomes. If vibranium were a realistic element, describe where it would fit on the periodic table and why.**

   Answers will vary. For example, students may feel that it belongs with other transition metals or even close to the halogens indicating it is highly electronegative and has a high ionization energy.

4. **Tony Stark upgrades Peter Parker's webbing with materials that cannot be found in a high school chemistry class. Fiberglass, however, is a material that is easy to obtain and has some of the same desirable properties as Peter Parker's web. Describe the properties of fiberglass that would be useful if it were developed into a web.**

   Fiberglass is chemically resistant; it will not mildew or deteriorate and resists many acids. Fiberglass will not stretch or shrink. Fiberglass has good thermal properties and will dissipate heat rapidly. Fiberglass has a high strength-to-weight ratio and is twice as strong as steel wire. Fiberglass will not burn and maintains it strength at high temperatures. Fiberglass will not absorb moisture and is an excellent electrical insulator. Finally, fiberglass is cost effective compared to other synthetic and natural fibers.

5. **Peter Parker was not only famous for shooting webs, but also has the ability to quickly scale buildings. Geckos are similar to Peter Parker in that they can "stick" to walls. Explain the science behind this ability and research materials in development that can make scaling walls like Spiderman a reality.**

   Geckos "stick" to walls through intermolecular forces. Geckos foot hairs split, increasing surface density. A strong adhesive force is created as the foot hairs come into close contact with the surface. For materials in development, students may explore items such as "Geckskin," or "Synthetic Gecko" adhesives.

MATERIALS™ EXPLORERS

# SMARTPHONES

**If you're like a lot of people today, you just can't imagine life without your smartphone. But have you ever thought about what it takes to make the device that never leaves your side? In this module you'll learn about the materials that make smartphones possible and explore the implications of using rare materials in such a common item.**

**In this module students will be able to:**

- Identify the materials used to create a smartphone
- Test the chemical and physical properties of some of the metals used to create smartphones
- Write an evidence-based conclusion identifying each metal based on the physical and chemical properties
- Explore the uses of rare earth metals and the challenges created by a reliance on them
- Illustrate a metallic bond and explain how the bonding arrangement affects physical properties

**MATERIALS™ EXPLORERS**

## Class Activity

### THE MATERIALS THAT MAKE UP SMARTPHONES

**Background:**

According to the Minerals Education Coalition©, each baby born in the U.S. will use 3.188 million pounds of minerals, metals, and fuels in their lifetime. The 3.188 million pounds include 968 pounds of copper, 419 pounds of zinc, 828 pounds of lead, and 48,856 pounds of other minerals and metals. Many of the minerals and metals are utilized in technological devices such as smartphones. Smartphones are composed of about 40% metals (including copper, silver, gold, platinum, and tungsten), 40% plastics, and 20% ceramics. Most phones use lithium-ion batteries, which are generally composed of lithium cobalt oxide, although other metals, such as manganese, are sometimes used in place of cobalt.

Cellular phones also contain many **rare earth elements** such as neodymium, terbium, and dysprosium which provide phones with the power to vibrate. This heavy reliance on rare earth elements poses a challenge to future smartphone development since there is a limited supply of these elements and no suitable substitutions. Rare earth elements are essential for miniaturization of products like computers and smartphones. Without them, computers would still be the size of a classroom, instead of a pocket. Rare earth elements are also valuable because of their magnetic and conductive properties. These properties allow technological devices to be faster, stronger, lighter, and more efficient.

**Problem**

Your school is organizing a recycling initiative around discarded smartphones. In order to send materials to the right recycling facilities, your class must first identify the types of materials used in various components.

**Task:**

Using the directions provided, you will test four unknown samples and record your observations of their physical and chemical properties in order to determine the materials being tested.

**Requirements:**

1. Safety goggles and an apron must be worn at all times.
2. Hair must be pulled back.
3. No loose or baggy clothing is permitted and closed-toe shoes must be worn.

## Class Activity

4. Do not stare directly at burning samples.
5. Physical properties being examined should include appearance, mass, volume, and magnetism.
6. Chemical properties being examined should include reactivity with room temperature water, reactivity with hydrochloric acid, and reactivity with oxygen.
7. Samples should be tested using the following procedures and observations should be recorded in the data tables provided:

Complete each of the required tests for a sample before moving on to the next.

| |
|---|
| **NOTE:** The reaction with oxygen is performed only on samples A and D. |

i. **Appearance:** Observe the chemical and record your observations.

ii. **Volume and Density:** Determine volume and density via the water displacement method.

iii. **Magnetism:** Slowly wave the magnet over the sample and record any reaction.

iv. **Ability to React with Water:** Place a "pea-sized" amount of the sample in a petri dish and apply 15 drops of water. Look for evidence of a chemical change. If there is evidence, cite evidence. If there is no evidence, record "no evidence of a chemical change."

v. **Ability to react with an acid:** Place a "pea-sized" amount of the sample on a clean watch glass and add a few drops of acid. Look for evidence of a chemical change. If there is evidence, cite evidence. If there is no evidence, record "no evidence of a chemical change."

vi. **Reaction with Oxygen (with heat):** PERFORM THIS TEST ONLY ON SAMPLES A AND D. Light and adjust the burner. Use crucible tongs to burn a piece of Sample A while looking for evidence of a chemical change. Turn off the flame. If there is evidence, cite evidence. If there is no evidence, record "no evidence of a chemical change."
Repeat this procedure for Sample D but begin by vigorously rubbing the sample with steel wool to remove surface (oxide) impurities.





## Class Activity

### Questions

1. **Fill out the following data tables with your observations from the experiments above.**

| Data Table: Samples A-D | | | | |
|---|---|---|---|---|
| | **Sample A** | **Sample B** | **Sample C** | **Sample D** |
| **Appearance** | | | | |
| **Mass** | | | | |
| **Volume** | Initial:<br>Final:<br>Difference: | Initial:<br>Final:<br>Difference: | Initial:<br>Final:<br>Difference: | Initial:<br>Final:<br>Difference: |
| **Calculated Density** | | | | |
| **Magnetism**<br>Is sample magnetic? | Yes or No<br>Evidence: | Yes or No<br>Evidence: | Yes or No<br>Evidence: | Yes or No<br>Evidence: |

## Class Activity

| | | | | |
|---|---|---|---|---|
| **Reaction with Water**<br>Does sample react? | Yes or No<br>Evidence: | Yes or No<br>Evidence: | Yes or No<br>Evidence: | Yes or No<br>Evidence: |
| **Reaction with Acid**<br>Does sample react? | Yes or No<br>Evidence: | Yes or No<br>Evidence: | Yes or No<br>Evidence: | Yes or No<br>Evidence: |
| **Reaction with Oxygen**<br>Does sample react? | Yes or No<br>Evidence: | DO NOT PERFORM TEST ON SAMPLE B | DO NOT PERFORM TEST ON SAMPLE C | Yes or No<br>Evidence: |

2. **Write a response (including a claim, evidence, and reasoning) identifying Samples A through D based on their physical and chemical properties.**

3. **Sixteen out of the seventeen rare earth elements are used in cell phones. Select one of the sixteen elements and design a poster about the advantages and challenges of utilizing that rare earth element. Include information about how that element can be recycled or reused, or if there is a potential substitute for it. Be sure to include other uses of the element apart from smartphones.**

## Activity Grading Rubric

### Rare Earth Elements

Rare earth elements, or rare earth metals, refers to a set of seventeen elements which includes the fifteen lanthanides plus scandium and yttrium. Despite their name, most of these elements are not particularly rare but they are difficult to economically extract and process.

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS1-1 | HS-PS1-3 | HS-PS2-6 |
|---|---|---|---|---|

**Notes:**

1. Provide the following materials to students for testing: **Sample A:** copper shot, **Sample B:** zinc, **Sample C:** iron, and **Sample D:** magnesium.
2. Students must be reminded to observe all safety precautions. Additionally, as magnesium burns with a bright white flame, students should be told not to look directly into the flames as they test their samples.
3. Students should be reminded not to perform a flame test on samples B and C.
4. Students should be supervised to ensure proper clean-up of each station.
5. As an optional follow up service project, encourage students to seek out reputable recycling locations and host a cell phone recycling drive for the community.

**Data Table: Samples A-D**

| | **Sample A** Copper Shot | **Sample B** Zinc | **Sample C** Iron | **Sample D** Magnesium |
|---|---|---|---|---|
| **Appearance** | Reddish/brown | Gray | Silver | Silver |
| **Mass** | Answer will vary based on class sample. | Answer will vary based on class sample. | Answer will vary based on class sample. | Answer will vary based on class sample. |
| **Volume** | Answer will vary based on class sample. | Answer will vary based on class sample. | Answer will vary based on class sample. | Answer will vary based on class sample. |
| **Calculated Density** | 8.78 g/mL | 7.14 g/mL | 7.87 g/mL | 1.74 g/mL |

## Teacher Resources & Answer Key

| | | | | |
|---|---|---|---|---|
| **Magnetism**<br><br>Is sample magnetic? | Yes or No<br>Evidence:<br><br>No. Copper does not stick to the magnet. | Yes or No<br>Evidence:<br><br>No. Zinc does not stick to the magnet. | Yes or No<br>Evidence:<br><br>Yes. Iron does stick to the magnet. | Yes or No<br>Evidence:<br><br>No. Magnesium does not stick to the magnet. |
| **Reaction with Water**<br><br>Does sample react? | Yes or No<br>Evidence:<br><br>No. No evidence of a chemical change. | Yes or No<br>Evidence:<br><br>No. No evidence of a chemical change. | Yes or No<br>Evidence:<br><br>No. No evidence of a chemical change. | Yes or No<br>Evidence:<br><br>No. No evidence of a chemical change. |
| **Reaction with Acid**<br><br>Does sample react? | Yes or No<br>Evidence:<br><br>No. No evidence of a chemical change. | Yes or No<br>Evidence:<br><br>Yes. Hydrogen gas produced | Yes or No<br>Evidence:<br><br>Yes. Hydrogen gas produced | Yes or No<br>Evidence:<br><br>Yes. Hydrogen gas produced |
| **Reaction with Oxygen**<br><br>Does sample react? | Yes or No<br>Evidence:<br><br>Yes. Flame changes to a bluish/green color | DO NOT PERFORM TEST ON SAMPLE B | DO NOT PERFORM TEST ON SAMPLE C | Yes or No<br>Evidence:<br><br>Yes. Bright white light produced. |

2. **Write a response (including a claim, evidence, and reasoning) identifying Samples A through D based on their physical and chemical properties.**

| Metal | Color | Density (g/mL) | Magnetic | Reacts with Room Temperature Water | Reacts with HCl |
|---|---|---|---|---|---|
| Copper | Reddish/Brown | 8.78 | No | No | No |
| Zinc | Gray | 7.14 | No | No | Yes |
| Iron | Silver | 7.87 | Yes | No | Yes |
| Magnesium | Silver | 1.74 | No | No | Yes |

3. **Sixteen out of the seventeen rare earth elements are used in cell phones. Select one of the sixteen elements and design a poster about the advantages and challenges of utilizing that rare earth element. Include information about how that element can be recycled or reused, or if there is a potential substitute for it. Be sure to include other uses of the element apart from smartphones.**

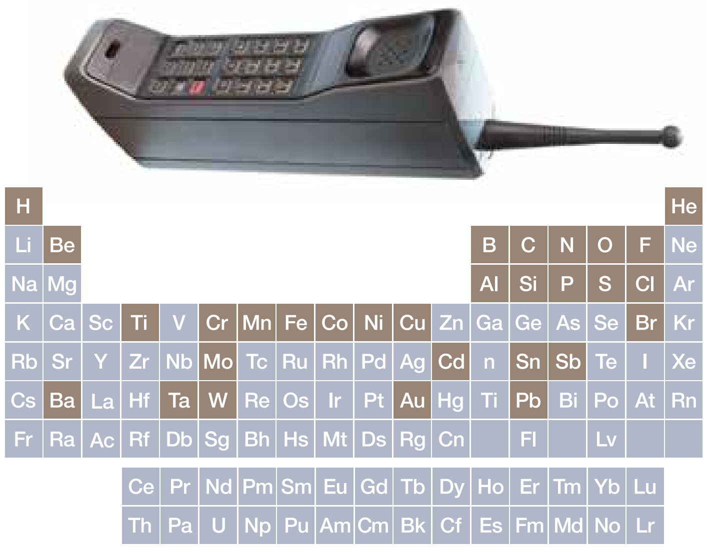
   Student answers will vary.

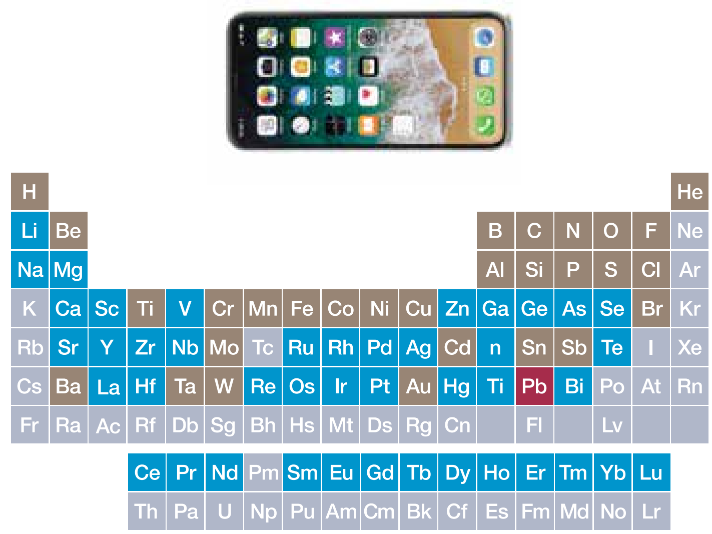
## Teacher Resources & Answer Key

| Activity Grading Rubric | | | | | |
|---|---|---|---|---|---|
| **CATEGORY** | **5** | **4** | **3** | **2** | **1-0** |
| **Graphics - Clarity** | Graphics are all in focus and the content can be easily viewed and identified. | Most graphics are in focus and the content can be easily viewed and identified. | Most graphics are in focus and the content is easily viewed and identified. | Many graphics are not clear or are too small. | Incomplete assignment. |
| **Graphics - Relevance** | All graphics are related to the topic and make it easier to understand. All borrowed graphics have a source citation. | All graphics are related to the topic and most make it easier to understand. All borrowed graphics have a source citation. | All graphics relate to the topic. Most borrowed graphics have a source citation. | Graphics do not relate to the topic OR several borrowed graphics do not have a source citation. | Incomplete assignment. |
| **Content - Accuracy** | At least 5 accurate facts are displayed on the poster. | 4-3 accurate facts are displayed on the poster. | 2-1 accurate facts are displayed on the poster. | No accurate facts are displayed on the poster. | Incomplete assignment. |
| **Attractiveness** | The poster is exceptionally attractive in terms of design, layout, and neatness. | The poster is attractive in terms of design, layout and neatness. | The poster is acceptably attractive though it may be a bit messy. | The poster is distractingly messy or very poorly designed. It is not attractive. | Incomplete assignment. |
| **Grammar/ Spelling** | There are no mistakes on the poster. | There are 1-3 mistakes on the poster. | There are 4-6 mistakes on the poster. | There are more than 6 mistakes on the poster. | Incomplete assignment. |

## Extension Activity

### WHAT'S IN YOUR POCKET?




Original Cell Phone Elements | Additional Elements Required for Smartphones | Elements that are no longer used.

**Motorola DynaTAC 8000X**

1. Released in 1983, this was the world's first commercial cell phone.
2. It weighed 1.75 pounds, stood 13 inches high, stored 30 phone numbers, and took 10 hours to recharge to support 30 minutes of talk time.

**30 Elements**

**Smartphone**

Today's smartphone uses exponentially more elements than early mobile devices to support numerous functions and digital features, more storage capacity, and an extended battery life in a lighter, smaller body.

**75 Elements**

CMI Critical Materials Institute

*(Chart reproduced with permission from the Critical Materials Institute, The Ames Laboratory, U.S. Department of Energy)*

## Questions

1. **Today's smartphones are dependent on a much wider variety of elements than early cellular phones. What are some of the major challenges that result from this?**

2. **The chart above indicates that only one element that was used in early mobile phones is no longer used in smartphones. Identify the element and suggest possible reasons why its use was discontinued.**

3. **Select one element used in the circuit board of both a smartphone and traditional cellular phone and discuss its importance to the phone's functioning.**

4. **Select one interesting feature of a smartphone and research some of the materials that make it possible. You may choose to discuss touchscreens, batteries, or vibration.**

## Extension Activity Answer Key

1. **Today's smartphones are dependent on a much wider variety of elements than early cellular phones. What are some of the major challenges that result from this?**
   Some of these elements are in very limited supply or difficult to mine with no real alternatives to replace them when they run out.

2. **The chart above indicates that only one element that was used in early mobile phones is no longer used in smartphones. Identify the element and suggest possible reasons why its use was discontinued.**
   Lead is no longer used due to concerns about its toxic nature. It has now been replaced by alternative materials such as lead-free solders made with metals such as tin, silver, and copper are now used instead.

3. **Select one element used in the circuit board of both a smartphone and traditional cellular phone and discuss its importance to the phone's functioning.**
   Student answers will vary but a possible example is the use of gold as a coating where wires will later be inserted in the circuit boards.

4. **Select one interesting feature of a smartphone and research some of the materials that make it possible. You may choose to discuss touchscreens, batteries, or vibration.**
   Touchscreens: Indium oxide and tin oxide are commonly used because of their ability to conduct electricity.

   Batteries: Most smartphones use lithium-ion batteries which are made up of lithium cobalt oxide and graphite, though other elements are also used by many producers.

   Vibration: Rare earth metals such as neodymium, terbium, and dysprosium are used to give smartphones the ability to vibrate.

# MATERIALS™ EXPLORERS

## STRUCTURAL MATERIALS

**From bridges to automobile parts to helmets, the world is full of products designed to safely transmit or support a force. Researchers developing products don't select materials by guessing–they study the conditions the product has to withstand and carefully select a material that fits their needs.**

**In this module students will be able to:**

- Identify examples of structural failures in everyday life
- Calculate stress and strain
- Determine Young's modulus
- Tabulate and graph calculated results for stress and strain
- Investigate the real life applications of structural materials

## Class Activity

# MATERIALS IN CONSTRUCTION

**Background:**
While no one likes failure, the stakes are much higher when it comes to construction and structural failures. To avoid bridge collapses or to keep skyscrapers pointing skyward, engineers have to design structures capable of withstanding significant amounts of **stress** and **strain**. To do so, they need an understanding of the forces that will be working on a structure but also, an understanding of the materials being used in its construction.

In engineering, stress refers to force exerted per unit area. Engineers must determine how much stress will be applied to different areas of an object and select a material capable of withstanding that stress. Stress can be calculated according to the following equation:

$\sigma = \frac{F}{A}$ where $\sigma$ = stress ($N/m^2$), F = force (Newtons or lbs.), and A= Cross-sectional area ($m^2$ or $in^2$)

This equation shows that if force is constant over a small area, the stress will increase. Conversely, if the force is constant over a large area, stress will decrease. Strain, on the other hand, refers to how an object reacts to stress. Strain measures the percentage change in an object's shape when stress is applied. Strain can be calculated according to the following equation:

$\varepsilon = \frac{L-L_o}{L_o}$ where $\varepsilon$= strain, L= new length (mm or in), and $L_o$= original length (mm or in)

Once stress and strain have been calculated, Young's modulus can also be calculated. Young's modulus is the ratio of stress to strain and determines the elasticity of a material. The equation for Young's modulus is:

$E = \frac{s}{t}$ where E= Young's modulus (Pascals), s= stress, and t= strain

MATERIALS™ EXPLORERS

## Class Activity

The higher the value of Young's modulus, the stiffer the material.

Every material can withstand a different amount of stress, so it's critical that engineers understand the properties of each material they select.

### Problem

Your fellow students are decorating for the school dance by suspending decorations of various weight around the gym. The students would like to use clear fishing line, but are concerned that it may not be able to support the weight of heavy decorations such as lanterns.  Your teacher has advised your class to test the strength of the wire first and to determine its Young's modulus.

**Task:**
Your task is to determine Young's modulus for the nylon wire by first calculating the strain on the material when stress is applied.

**Requirements:**
Determine Young's modulus for the wire by working as a group. Each group will be assigned to a workstation and will receive a ruler and a set of weights. Using your ruler, record the initial length of the wire. Then, add weights one at a time and record the new length with each weight added. Finally, remove all the weights and record the final length of the wire. Results should be recorded in the table provided.

Remember that, for accurate measurements, you should start at the same point each time you measure the wire. This can be done by fastening your ruler to the side of the table.

### Questions

1. **Using the table below, record your results beginning with no load and ending with the final length of the wire after all the load has been removed. Then, calculate stress and strain for each step.**

| Total Weight Applied (N) | Cross-sectional Area ($m^2$) | Stress ($N/m^2$) | Strain |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

## Class Activity

2. **Graph your results for stress versus strain, placing strain on the x-axis.**

3. **What is the relationship between stress and strain? Use your data to support your answer.**

4. **Calculate Young's modulus for the wire.**

5. **How would your results differ if you used a material with a higher Young's modulus? Research two materials with a higher Young's modulus and discuss their applications in the real world.**

### Definitions

**Stress**
A measurement of the force applied to the object per unit area. It can be calculated by dividing the force applied to the material by its cross-sectional area.

**Strain**
A measurement of the change in an object's shape when a certain stress is applied. Strain can be calculated by dividing the change in the material's length by its original length.

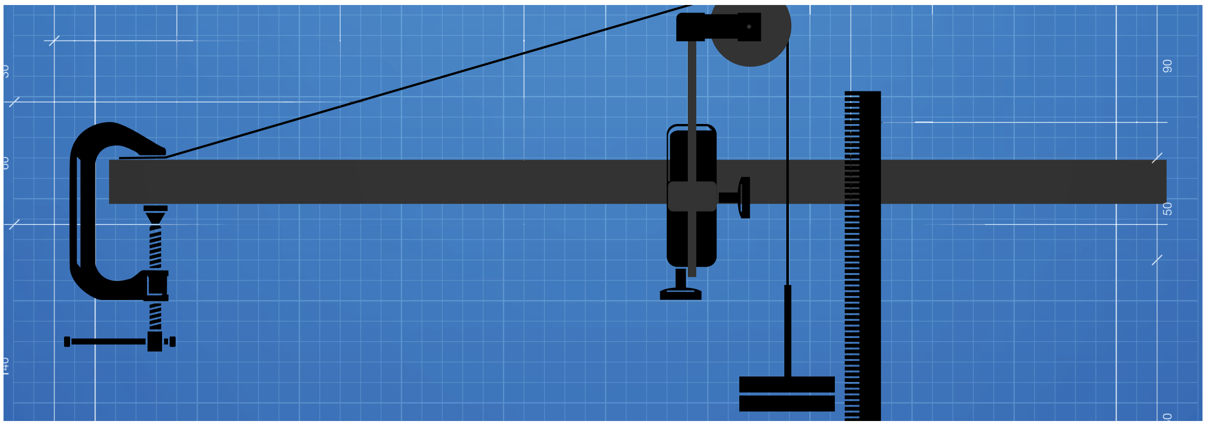
**Young's Modulus**
Also known as the elastic modulus, Young's modulus is a measure of the elasticity of a material. The higher the Young's modulus of a material, the more the material will resist stretching. It can be calculated by dividing stress by strain.

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS2-3 |
|---|---|---|

**Notes:**
N.B. This activity can be modified to take less time by having students work in larger groups.

1. Provide students with measurements for the diameter of the nylon wire/fishing line chosen for the experiment.
2. Set up multiple work stations based on the diagram provided. Advanced classes may be permitted to set up their own apparatus.
3. Students should be reminded to convert units as needed.



1. **Using the table provided, record your results beginning with no load and ending with the final length of the wire after all the load has been removed. Then, calculate stress and strain for each step.**
   Group answers will vary, but should increase with each new weight added.

2. **Graph your results for stress versus strain, placing strain on the x-axis.**
   Group answers will vary.

3. **What is the relationship between stress and strain? Use your data to support your answer.**
   There is a direct relationship between stress and strain.

4. **Calculate Young's modulus for the wire.**
   Group answers will vary based on the wire provided and the accuracy of recorded results. Should be calculated using the formula E=s/t where E= Young's modulus (Pascals), s= stress, and t= strain.

5. **How would your results differ if you used a material with a higher Young's modulus? Research two materials with a higher Young's modulus and discuss their applications in the real world.**
   If a material with a higher Young's modulus was used, the material would be able to endure additional stress and strain. Student answers will vary. An example includes copper wire which is used for electrical wiring.

## Extension Activity

# MAKING THE OLD NEW: HOW MODERN SCIENCE BRINGS NEW LIFE TO FOSSILS

Curators at the Carnegie Museum of Natural History in Pittsburgh, Pennsylvania, took on a mammoth project in 2008 when they decided to renovate the museum's dinosaur exhibit.

For 60 years, a Tyrannosaurus rex had stood tall in the museum, its ancient bones posed awkwardly erect, more like a sharp-toothed kangaroo than a tyrant lizard king. It was time for a change that would return the prehistoric giants to their original grandeur.

Today, visitors to the "Dinosaurs in Their Time" exhibit are treated to dynamic poses that make the fossils appear more lifelike and tell a story of the predator-prey relationships at play. The once-towering T. rex can be seen crouching low, neck practically parallel to the ground, ready for a Cretaceous period showdown with another T. rex. Over in the Jurassic section, the stately Apatosaurus cranes its long neck gracefully backward, facing a predator that seems to be closing in.

To be sure, the stars of the $36 million restoration are the Carnegie's renowned collection of fossils. But the supporting players, unnoticed and yet essential to the drama on the museum floor, are the steel **armatures** that encase them. These handcrafted frameworks allow the T. rex to crouch low, ready to fight. They raise the Diplodocus tail off the ground and support its unwieldy neck. And yet, the general public is unlikely to appreciate this one-of-a-kind hardware. That, says Matt Lamanna, the museum's assistant curator of vertebrate paleontology, is the sign of expert dinosaur mounting. "There is such attention to detail that a lot of people don't even see the armatures. That's the beauty of it," he said.

## Deconstructing Dinosaurs

The museum tasked Phil Fraley, founder of Phil Fraley Productions, with what would be the largest renovation since the museum opened in 1895. Of course, the primary goal was to give the skeletons poses that reflected new thoughts on dinosaur **biomechanics**, but the secondary goal of the project was to imply action with enough color and drama to enthrall modern-day museum goers. That was where the art of metalworking was essential. When molded expertly, the steel framework brings an organic quality to the fossils, Fraley said. "Really, what an armature is doing is replacing all the tendons and ligaments—the soft tissue that used to hold the animal together," he said.

Safely dismantling the existing structures was no easy task.

*Bob Zeller and Paul Zawisha attach dorsal ribs of the holotype T. rex to the armature during installation at the Carnegie Museum of Natural History. (Photo courtesy of Phil Fraley Productions)*

Fraley's team had to remove the ancient bones from their pre-existing armatures, some of which had been in place for 100 years. They also had to safely move the bones without placing stresses on them—no easy task considering that the pelvic bones of some of the larger specimens weighed more than 3,000 lbs!

While the team anticipated the weight and age of the fossils, they could not predict the condition of either the metal or the fossils until the work began, and there were some surprises.

"When Carnegie began collecting dinosaur skeletons, their display was a relatively new art in the early

## Extension Activity

20th century," said Phil Fraley, "The armatures for the Diplodocus and the Apatosaurus were really underbuilt…over the decades, shifting occurred. Two vertical supports under the pectoral girdle and the shoulder of the Apatosaurus, meant to share the weight of the structure equally, had spread over the years, three and a half inches in each direction." Fraley said, "They were going in opposite directions."

The separation was caused by a combination of the weight of the specimen and the likelihood that the skeleton was moved at some point without people taking proper precautions to stabilize it. In addition, during the disarticulation of the Apatosaurus, Fraley's team found that metal plates that had been bolted onto the pelvis had stress fractures in two places. "That was a pretty dangerous situation for the specimen," Fraley said. "Had there been a sudden jolt that would have caused this to move in one particular direction, there was a high probability that it would have broken," and with potentially disastrous consequences, he added.

Damage was also caused by what Project Manager Larry Lee described as "metallurgical mistakes." In particular, a **galvanic effect** resulted from welds of cast steel to cast bronze. "It kind of diseased those metals," he said. Lee found evidence of those poorly planned welds in the T. rex and the Allosaurus, where bronze was used in the underside of some vertebrae to create a seat that would hold the bone in position.

The bronze-steel welds held up, Lee noted, but the metal was deteriorated. Needless to say, no bronze mounts were used when Fraley's company reconstructed the dinosaurs. Instead, new steel cradles were made individually to fit each vertebra of the dinosaurs. And, in Lamanna's eyes, those cradles were more than steel supports. "Each cradle is a customized work of art that keeps the specimen safe," he said.

### 21St Century Dinosaurs

There may have been flaws in some of the original dinosaur mounts, but there was also a level of artistry that surprised Fraley and Lee. On the Apatosaurus and Diplodocus, in particular, the armatures were unique, Lee said, made of cast steel underneath the vertebra to create a support system.

"We did a metallurgical analysis of it and found it was an excellent mild steel," he said. "We were able to TIG-weld with it, bend it, drill it, and tap into it—it had excellent qualities. They used excellent iron in their castings. We really lucked out." For that reason, some of the oldest mounts could be reused and built upon, Lee said.

Those early castings were so unique that Fraley reused them in the new display. "We couldn't do a better job than what they had done in casting those ourselves," he said. "In some ways, it was our way of recognizing and appreciating the work that all these people a hundred years ago had done on the specimen. They were part of that specimen's history, and we're now a part of that specimen's history."

### A Bona Fide Hidden Metals Craft

Lee's background was in sculpture when he turned his talents to dinosaur armatures. As he explored the workshops of the American Museum, he found remnants of the craftspeople who came before him. "I discovered this whole tradition of metal mount-making for dinosaurs. It included casting and blacksmithing, machining, all kinds of bending, all kinds of metal work. I discovered this bona fide hidden metals craft—a tradition that started with the folks at the Carnegie and at the American Museum at the turn of the 20th century."

Remounting dinosaurs at the Fraley studios extends that tradition. Once the skeletons have been painstakingly disassembled, the bones are stripped of all adhesives, paints, and shellacs layered on over the years to hide flaws. Then, for the larger pieces, such as femurs, the artisans make

## Extension Activity

a cast so they can use those shapes without damaging the actual bones. The steel armatures are shaped while hot on the cast. For the smaller pieces, Lee said, "It's a process of bending steel with heat, then cooling the steel, and then checking it to see how close it is to the shape we want to achieve. It's rather painstaking: heating, bending, cooling, and comparing, and on and on, to make these custom fittings. It's a process akin to jewelry making. You take a precious stone and make a setting for it—that's what we're doing."

*This article is excerpted from "Steel and Science Bring Dinosaurs into the 21st Century at the Carnegie Museum of Natural History" by Maureen Byko, published in* JOM*, June 2008, Volume 60, Issue 6, pp 12-16.*

### Questions

1. **What caused the supports under pectoral girdle and the shoulder of the Apatosaurus to spread apart?**

2. **What is the difference between ductile and brittle fractures?**

3. **What is casting and how is it used to study fossils?**

4. **Why is steel an important material not only in supporting dinosaurs in the Carnegie Museum of Natural History, but in all construction today?**

5. **Dinosaur armatures are not the only areas where designers marry function with artistry. Some popular smartphone makers switched their phone cases from aluminum to glass. Discuss some of the advantages and disadvantages of this decision for both the aesthetics and the function of the phone.**

### Definitions

**Armatures**
A framework used to support heavy sculptures or displays. In fossil displays, armatures must be strong but also unobtrusive and delicate so they do not damage fossils or distract viewers.

**Biomechanics**
The study of movement in living organisms. This includes how bones and muscles create movement but the mechanics of other body functions such as blood circulation.

**Galvanic Effect**
The corrosion of a metal or a substance as a result of electrolytic action. This occurs when two different metals are in electrical contact in an electrolyte.

# Extension Activity Answer Key

1. **What caused the supports under pectoral girdle and the shoulder of the Apatosaurus to spread apart?**
   The weight of the skeleton and the likelihood that the structure was moved without being properly stabilized.

2. **What is the difference between ductile and brittle fractures?**
   Fractures in ductile materials move slowly and can be accompanied by deformation around the crack tip. Brittle fractures spread rapidly and do not typically show signs of deformation, as such brittle fractures occur suddenly.

3. **What is casting and how is it used to study fossils?**
   Casting is when a liquid material like plaster or resin is poured into a mold that has been created from the surface of the specimen. Fossils can be fragile, so casts of fossils are created so they can be studied and displayed.

4. **Why is steel an important material not only in supporting dinosaurs in the Carnegie Museum of Natural History, but in all construction today?**
   Steel is durable and requires little maintenance. Steel can be recycled and steel-framed structures do not age as quickly as other building materials. It combines low cost with high availability, and desirable properties such as strength and toughness.

5. **Dinosaur armatures are not the only areas where designers marry function with artistry. Some popular smartphone makers switched their phone cases from aluminum to glass. Discuss some of the advantages and disadvantages of this decision for both the aesthetics and the function of the phone.**
   *Functional*: Switching from an aluminum case to glass allows them to use wireless charging technology. However, aluminum is lighter and cheaper than glass.
   *Aesthetic:* Because of the unique design, glass is more visually appealing but glass is also more likely to scratch or break than aluminum.

MATERIALS™ EXPLORERS

# THE MATERIALS THAT MOVE US: DATA COLLECTION AND GRAPHING

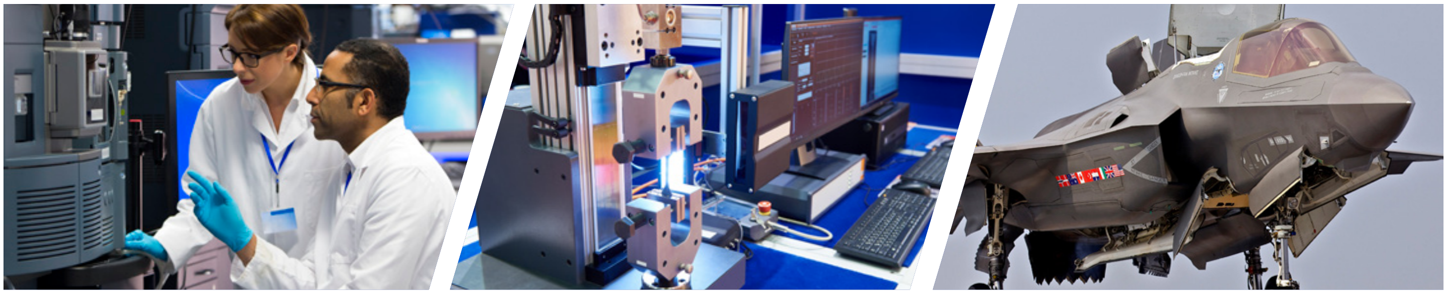
**Learn about the scientific method by selecting the best materials for use in a commercial jet engine. Then, learn how rigorous testing helps ensure the safety and performance of parts used in military fighter jets.**

**In this module students will be able to:**

- Identify the steps of the scientific method
- Analyze data and create a graph to reveal trends in the data
- Use data and graphs as evidence to draw conclusions about the relationship between two variables
- Compare composites to raw materials and explain the advantages of using composites in various industries

# Class Activity

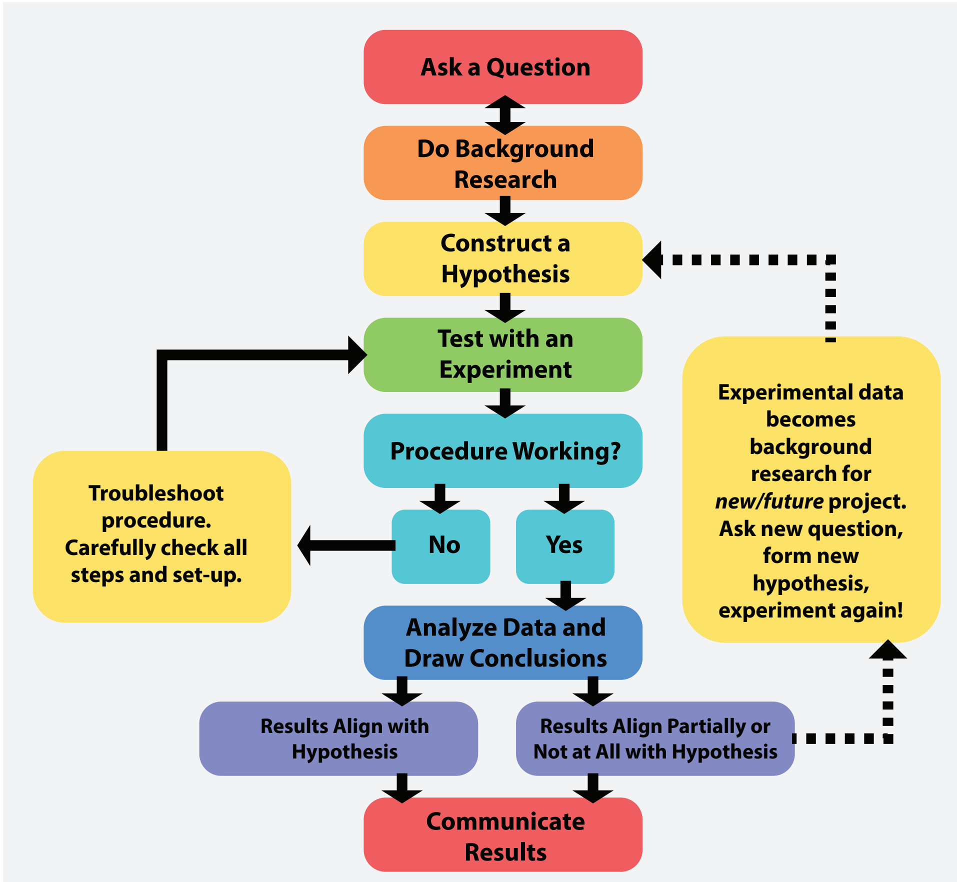
## TESTING THE LIMITS



## Background

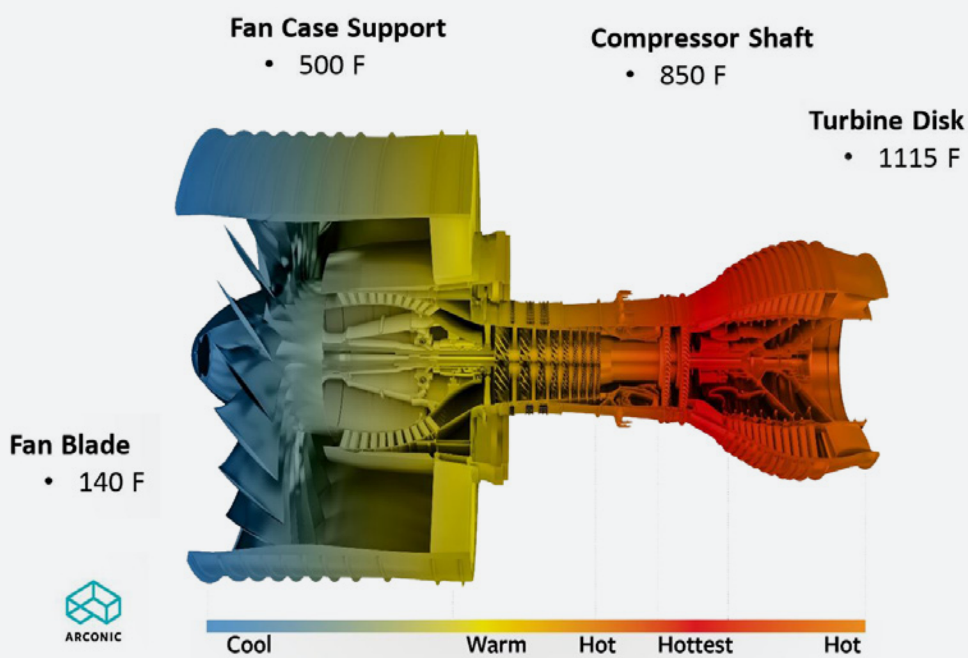
Have you ever noticed that scientists on television always seem to be taking measurements and gathering data? It's not just for dramatic effect.

Collecting data is an important part of the scientific method process. The scientific method is a logical or systematic approach to problem solving. The process is made up of a series of important steps: recording observations and developing questions; generating a hypothesis; experimenting; analyzing results; drawing conclusions; and reporting results. Access to accurate data enables researchers to test their hypotheses and draw scientifically sound conclusions.




*The scientific method helps researches solve problems by guiding them through developing potential solutions and testing them. This chart shows the steps involved from the development of an idea to determining whether or not it will work.*

## Class Activity




*This depiction of a jet engine shows the maximum temperature of various components when in use. (Photo courtesy of Arconic.)*

If the steps of the scientific method sound too abstract, let's observe the method at work through a real-world example. Consider the image above which shows just how hot a jet engine can become when in use. When researchers are selecting the best material for a specific component, they can't just look up properties such as strength or elasticity because those qualities may be affected by other conditions such as the high temperatures the material must endure. Instead, they must employ the scientific method to ensure they are making the right choice.

Researchers must first *record observations* about the component and the conditions it will be exposed to. Then, they must develop questions that will guide their line of research such as, "what material can endure a great deal of stress above 500°F?" The team may then construct a *hypothesis* that specific materials might meet the identified need.

At this point, the team can begin testing their hypothesis through *experimentation* to see how the materials perform under different temperatures. After *analyzing* their results, and drawing a *conclusion* about the best material, the team can finally write a report which outlines their results and makes a suggestion for which material should be used.

How would you go about making your recommendations if you were a member of the research team? The following activity will show you.

## Class Activity

### Problem:

A new airplane manufacturer has hired your company to redesign their jet engine. You are the lead researcher tasked with determining the best materials for constructing various components.

### Task:

Your team has conducted extensive testing on the properties of four alloys and presented their initial results to you. You must analyze their results to draw a conclusion about the best materials for building each component.

The tables below contain the results of your team's testing. They show how each alloy's **yield strength** and **Young's modulus** are affected by temperature.

**Aluminum Alloy**

Density = 0.100 lbs / in^3
Max Use Temperature = 300 F
Price = $1.62 / lb

| Yield Stength | | Modulus | |
|---|---|---|---|
| °F | ksi | °F | 10^6 psi |
| -374 | 57 | -262 | 9 |
| -287 | 53 | -198 | 9 |
| -205 | 49 | -120 | 9 |
| -114 | 47 | -27 | 9 |
| -13 | 46 | 57 | 9 |
| 102 | 44 | 122 | 9 |
| 165 | 44 | 181 | 9 |
| 210 | 42 | 260 | 9 |
| 246 | 39 | 341 | 8 |
| 269 | 36 | 411 | 8 |
| 296 | 28 | 481 | 7 |
| 325 | 20 | 539 | 7 |
| 363 | 14 | 588 | 6 |
| 396 | 10 | 643 | 5 |
| 443 | 7 | | |
| 506 | 6 | | |
| 575 | 5 | | |
| 651 | 5 | | |

**Titanium Alloy**

Density = 0.160 lbs / in^3
Max Use Temperature = 850 F
Price = $9.33 / lb

| Yield Stength | | Modulus | |
|---|---|---|---|
| °F | ksi | °F | 10^6 psi |
| -318 | 242 | 83 | 15 |
| -272 | 222 | 297 | 15 |
| -219 | 204 | 489 | 14 |
| -168 | 190 | 703 | 13 |
| -107 | 178 | 797 | 13 |
| -33 | 167 | 869 | 13 |
| 58 | 155 | 933 | 12 |
| 136 | 145 | 996 | 11 |
| 207 | 135 | | |
| 312 | 121 | | |
| 424 | 107 | | |
| 493 | 102 | | |
| 565 | 99 | | |
| 643 | 99 | | |
| 746 | 96 | | |
| 829 | 92 | | |
| 898 | 85 | | |
| 950 | 76 | | |
| 992 | 64 | | |

**Nickel Alloy**

Density = 0.315 lbs / in^3
Max Use Temperature = 1275 F
Price = $7.15 / lb

| Yield Stength | | Modulus | |
|---|---|---|---|
| °F | ksi | °F | 10^6 psi |
| -325 | 167 | -285 | 29 |
| -245 | 161 | -185 | 29 |
| -165 | 156 | -85 | 28 |
| -85 | 151 | 15 | 28 |
| -5 | 147 | 115 | 27 |
| 75 | 144 | 215 | 27 |
| 155 | 141 | 315 | 27 |
| 235 | 139 | 415 | 26 |
| 315 | 137 | 515 | 26 |
| 395 | 136 | 615 | 25 |
| 475 | 136 | 715 | 25 |
| 555 | 135 | 815 | 24 |
| 635 | 135 | 915 | 24 |
| 715 | 134 | 1015 | 23 |
| 795 | 134 | 1115 | 23 |
| 875 | 133 | 1215 | 22 |
| 955 | 132 | 1315 | 21 |
| 1035 | 131 | 1415 | 21 |
| 1115 | 128 | 1515 | 20 |
| 1195 | 121 | 1615 | 19 |
| 1275 | 114 | 1715 | 17 |
| 1355 | 97 | 1815 | 16 |
| 1435 | 73 | 1915 | 14 |
| 1515 | 57 | 2015 | 13 |

**Iron Alloy (e.g. Steel)**

Density = 0.285 lbs / in^3
Max Use Temperature = 900 F
Price = $0.49 / lb

| Yield Stength | | Modulus | |
|---|---|---|---|
| °F | ksi | °F | 10^6 psi |
| -320 | 289 | -113 | 26 |
| -203 | 259 | 71 | 25 |
| -75 | 246 | 363 | 24 |
| 72 | 236 | 567 | 24 |
| 236 | 223 | 662 | 23 |
| 375 | 214 | 795 | 22 |
| 509 | 203 | 915 | 21 |
| 648 | 193 | 980 | 20 |
| 778 | 183 | | |
| 849 | 178 | | |
| 904 | 169 | | |
| 953 | 151 | | |
| 983 | 130 | | |

*Table 1: Data showing how the properties yield strength and Young's Modulus are affected by temperature for four different alloys. This table is available for download as an Excel file on the* Materials Explorers™ *website in the Extra Resources section of the "Materials That Move Us" web page. (Courtesy of Arconic.)*

MATERIALS™ EXPLORERS

## Class Activity

### Questions

1. Plot the following graphs in Excel, Google Sheets, or on graph paper. Make sure each graph TALKS (Title, Axes, Labels, Key, Spacing).
    a. Temperature vs yield strength. Include the results for all four alloys on the same graph.
    b. Temperature vs Young's modulus. Include the results for all four alloys on the same graph.

2. List the alloys from lowest to highest in terms of:
    i. Density
    ii. Maximum use temperature
    iii. Price

3. The compressor shaft operates at 850°F and needs a material with a very high yield strength at this temperature. Which alloy would be best for this part?

4. The fan blade operates at 140°F and needs a material with modulus (stiffness) between 10-20 x106 psi at this temperature. Which alloy would be best for this part?

5. The fan case support is currently made from aluminum but a next generation design will need to operate at temperatures as high as 350°F. A new fan case support design would need to be as lightweight as possible and be at least as stiff (modulus) and as strong (yield) as aluminum. What is the next preferred alternative to aluminum? Explain your answer.

6. You are designing a turbine disk operating at 1115°F. List the yield strength and Young's Modulus for the alloys that work at this temperature.

7. The use of raw or pure materials is limited in the transportation industry because alloys or composites (materials made from two different materials with significantly different chemical and physical properties) often have more desirable properties. Research a composite material such as carbon fiber, glass fiber, or fiberglass reinforced plastic utilized in any industry and explain the properties of the composite and why it is more desirable than the raw or pure materials.

### Definitions

**Alloy**
A mixture of two or more metals, or a metal and other elements.

**Yield Strength**
The magnitude of stress at the point at which a material ceases to be elastic and becomes plastic.

**Young's Modulus**
Also known as the elastic modulus, Young's modulus is a measure of the elasticity of a material. The higher the Young's modulus of a material, the more the material will resist stretching. It can be calculated by dividing stress by strain.

MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

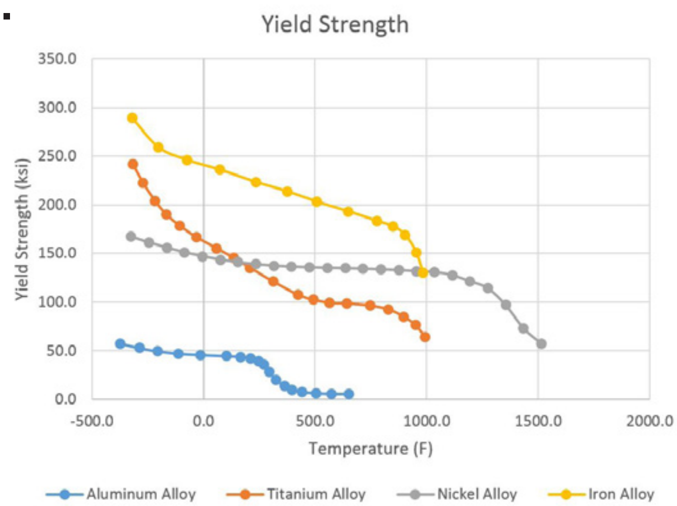
| | | |
|---|---|---|
| Standards: | NGSS: | HS-PS2-1 |

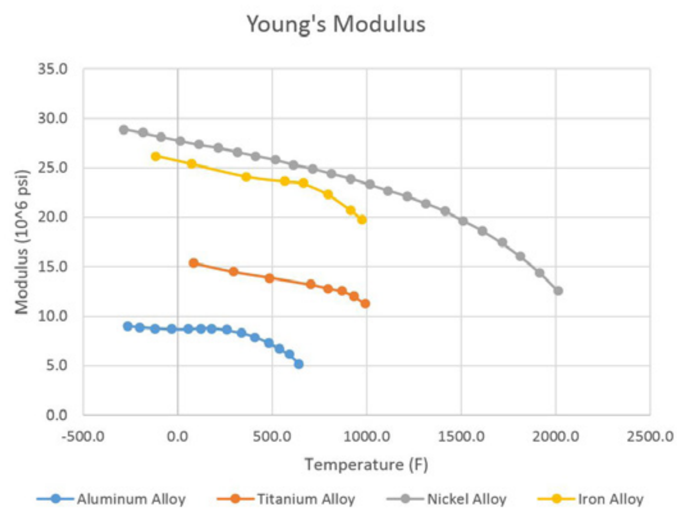
### Notes:

1. Materials needed:
    - Option 1: Computer with Microsoft Excel or Google Sheets
    - Option 2: Graphing Paper
2. Students should work with a partner or in small groups to complete this activity.
3. **Optional Modification (No plotting of graphs)**: To simplify this activity, teachers may print the graphs provided below and ask students to interpret the data in order to answer the questions.

### Answer Key:

**1.**




**2.** List the alloys from lowest to highest in terms of:

**Answer**:
i. *Density*: Aluminum, Titanium, Iron, Nickel
ii. *Maximum use temperature*: Aluminum, Titanium, Iron, Nickel
iii. *Price*: Iron, Aluminum, Nickel, Titanium

**3.** The compressor shaft operates at 850°F and needs a material with a very high yield strength at this temperature. Which alloy would be best for this part?

**Answer**: Iron

**4.** The fan blade operates at 140°F and needs a material with modulus (stiffness) between 10-20 x106 psi at this temperature. Which alloy would be best for this part?

**Answer**: Titanium

## Teacher Resources & Answer Key

**5.** The fan case support is currently made from aluminum but a next generation design will need to operate at temperatures as high as 350°F. A new fan case support design would need to be as lightweight as possible and be at least as stiff (modulus) and as strong (yield) as aluminum. What is the next preferred alternative to aluminum? Explain your answer.

**Answer**: Titanium. While titanium, nickel, and iron alloys are all stiffer and stronger than aluminum at 350°F, titanium is the lightest of the three.

**6.** You are designing a turbine disk operating at 1115°F. List the Yield Strength and Young's Modulus for the alloys that work at this temperature.

**Answer**: Nickel (Yield = 127.7 ksi and Modulus = 22.7 x 106 psi)

**7.** The use of raw or pure materials is limited in the transportation industry because alloys or composites (material made from two different materials with significantly different chemical and physical properties) often have more desirable properties. Research a composite material such as carbon fiber, glass fiber, or fiberglass reinforced plastic utilized in any industry and explain the properties of the composite and why it is more desirable than the raw or pure materials.

**Answer**: Student answers will vary. Examples include:

*Carbon fiber*: Used to produce lightweight motorcycle helmets to prevent neck fatigue (carbon fiber is better at deflecting impacts and increases safety)

*Glass fiber*: Glass fiber can be used in composite piles to support docks. The composite piles are corrosion resistant and designed to withstand extreme weather, temperature, and salt content in water. Composite piles were used to rebuild docks around the Statue of Liberty after Hurricane Sandy.

*Fiberglass reinforced plastic*: Used in a Miami art museum to create a vertical garden that grows down from the ceiling. The FRP tubes are designed to bend, but not break and hurricane force winds.

Websites such as **http://compositeslab.com/** are helpful places for students to begin their research

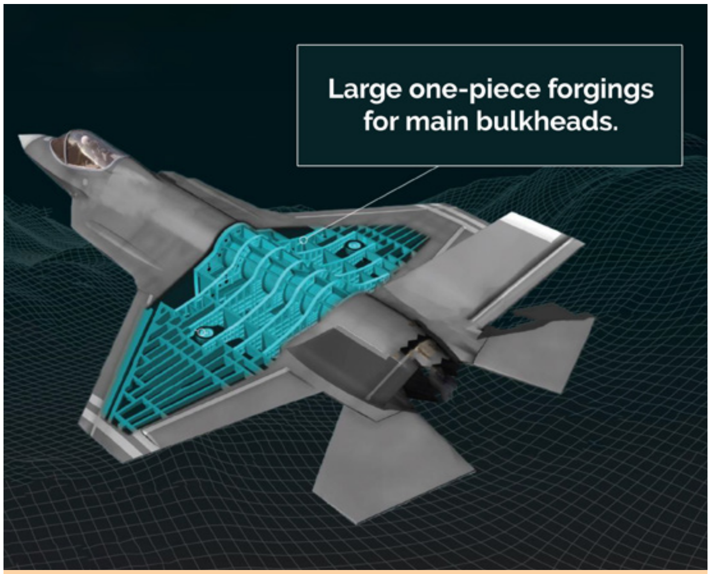
## Extension Activity

### SOARING TO NEW HEIGHTS

Numerous industries rely on materials science and engineering innovations to help make tougher, lighter, and more efficient products.

Take the example of the Lockheed Martin F-35 Lightning II, also known as the Joint Strike Fighter (JSF). This advanced defense aircraft is made up of single-piece forged aluminum or titanium bulkheads that form the "backbone" of the aircraft structure. This design helps save up to 400 pounds per jet—this translates into further costs savings and greater fuel efficiency.

*Aircraft such as the F-35 Lightning II rely on extensive testing to make them tough enough to protect the men and women using them.*




*The F-35 Lightning II uses bulkheads that are forged in a single piece. These bulkheads make up the "backbone" of the aircraft. (Image courtesy of Arconic.)*

As you can imagine, a military aircraft such as the JSF needs to be able to tolerate some pretty extreme conditions and because the bulkheads are centrally located within the aircraft, they need to remain stable and intact. It must endure air-to-air or air-to-ground combat, be stealthy and agile, and reach speeds faster than the speed of sound!

The people operating or relying on this military aircraft need to be confident that it can handle all of these conditions. This is why researchers extensively test the materials used on the JSF to see how they will perform in real world conditions.

An example of this is seen in the rigorous **fracture toughness** testing that the JSF's bulkheads must undergo. Fracture toughness testing helps scientists quantify how well a material can resist fracturing once a sharp crack has been established. In other words, fracture toughness testing helps researchers know how quickly a crack will spread once it has formed. The pictures below will give you a better idea of how the test works.

## Extension Activity

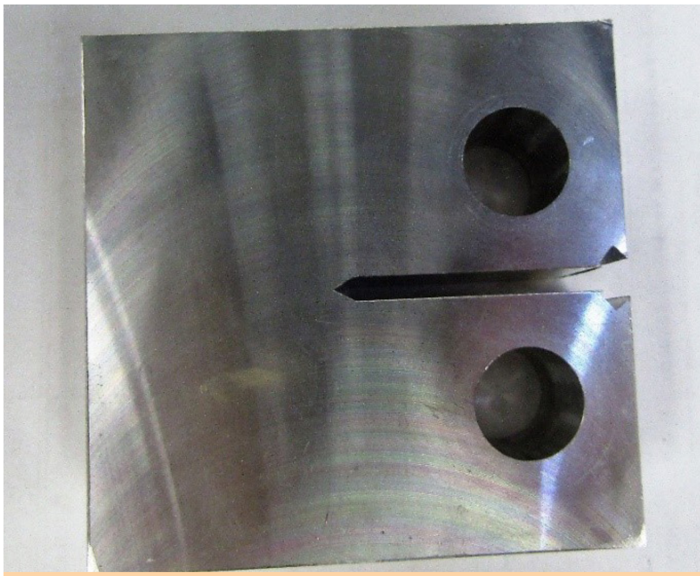


*Figure 1: Testing starts by selecting the right specimen. Notice the notch in the specimen; as a load is repeatedly applied to the specimen, a small crack will begin to grow from the notched area. (Photo courtesy of Arconic.)*

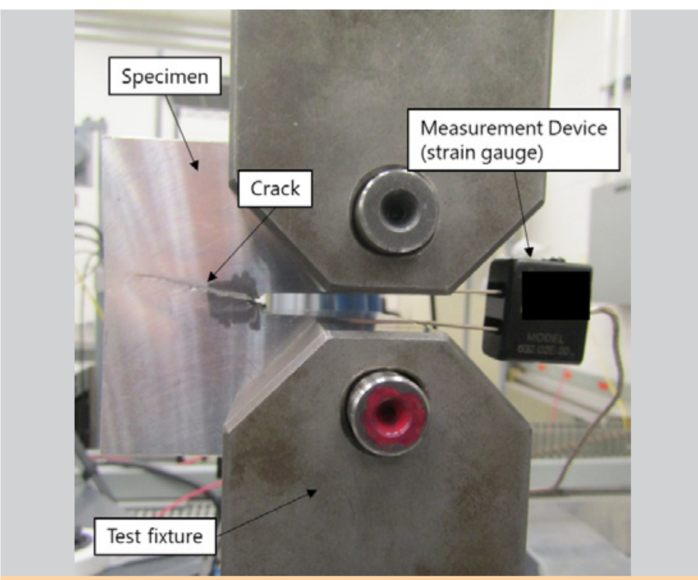



*Figure 2: After a crack forms in the specimen, a measurement device is attached to the notch to measure how much the distance between the top and bottom of the notch grows as an increasing load is applied. (Photo courtesy of Arconic.)*

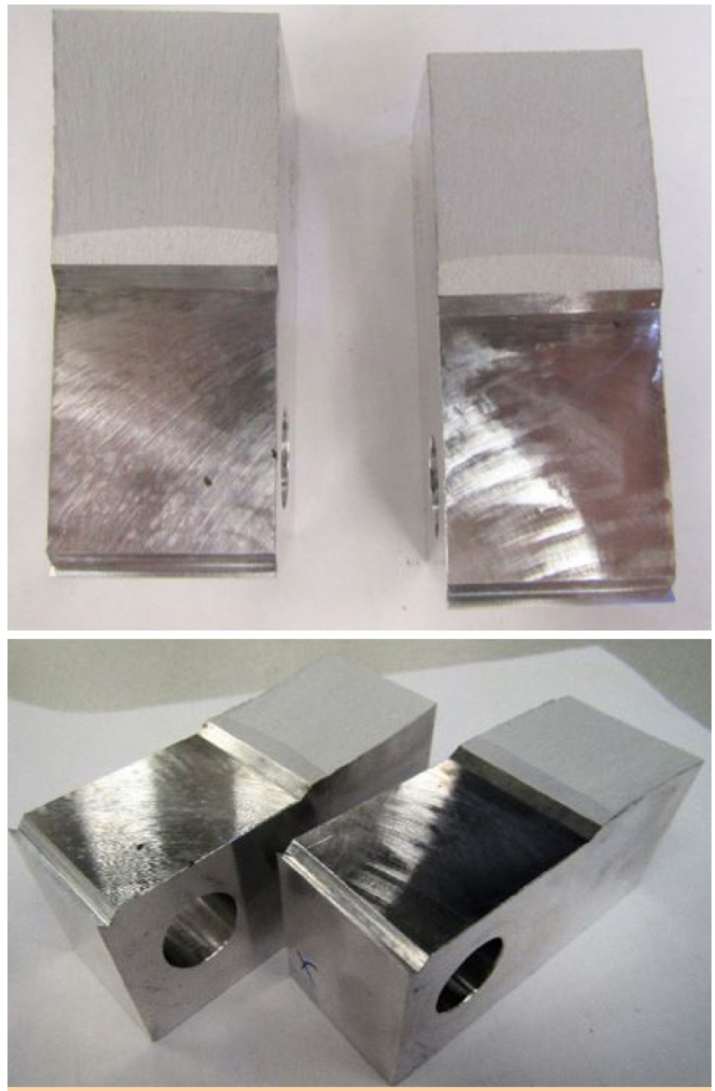
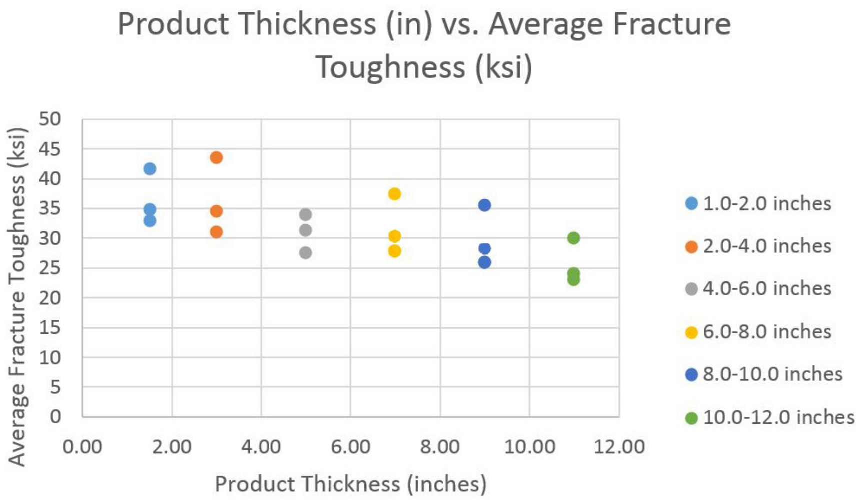


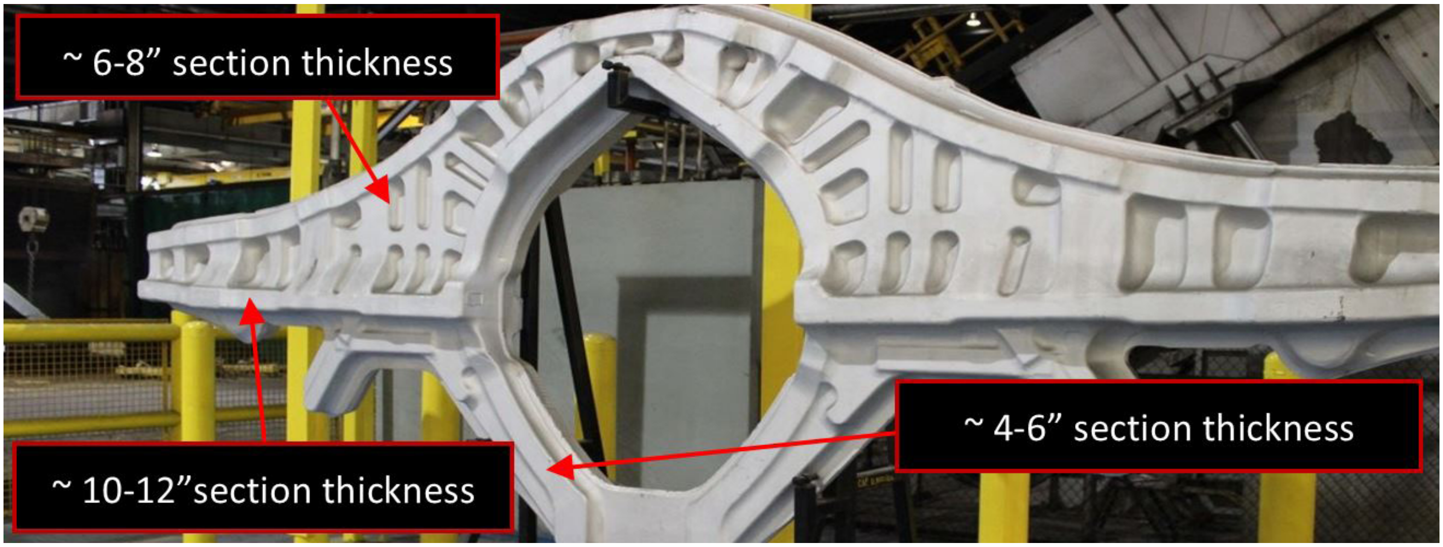
*Figure 3: At the end of the test, the specimen is broken open to look at the microstructure of the crack. Lastly the fracture toughness values are calculated, and the results are validated. (Photos courtesy of Arconic.)*

## Extension Activity

1. The graph to the right shows the fracture toughness for the various section thicknesses required to compose the one-piece forgings for the main bulkheads in an F-35 Lightning II. Which section thickness actually had the highest fracture toughness?




2. The figure below shows the material thickness required to compose the one-piece forgings for the main bulkheads in a F-35 Lightning II. Which thickness would you expect to have the highest fracture toughness? Why?




3. Thinner materials are more susceptible to ductile fractures as opposed to brittle fractures. Research both ductile and brittle fractures and distinguish between each.

**Definition**

**Fracture Toughness**
The ability of a material to resist fracture.

# MATERIALS™ EXPLORERS

## Answers to Extension Activities

### Questions and Answers

1. **The graph below shows the fracture toughness for the various section thicknesses required to compose the one-piece forgings for the main bulkheads in a F-35 Lightning II. Which section thickness actually had the highest fracture toughness?**

   **Answer:** The 2.0”-4.0” section thickness had the highest fracture toughness.

2. **The figure below shows the material thickness required to compose the one-piece forgings for the main bulkheads in a F-35 Lightning II. Which thickness would you expect to have the highest fracture toughness? Why?**

   **Answer:** Many students will likely predict the 10-12” section will have the highest fracture toughness since it is the thickest and should therefore be able to withstand a heavier load. However, the data shows that this is not the case and that the thinnest sections were most resistant to fracturing.

3. **Thinner materials are more susceptible to ductile fractures as opposed to brittle fractures. Research both ductile and brittle fractures and distinguish between each.**

   **Answer:**
   *Ductile fractures*:
   - Occur with plastic deformation
   - Physical warning before fracture
   - Most common fractures are moderately ductile

   *Brittle fractures*:
   - Sudden, very rapid cracking of equipment under stress where the material exhibited little or no evidence of ductility or plastic degradation before the fracture occurred
   - Typically caused by low temperatures

# MATERIALS™ EXPLORERS

# THE MATERIALS THAT MOVE US: MEASUREMENT AND SCALE


**From discussions of the weather to complex scientific applications, measurements help define the world around us. Explore the importance of accurate measurements through a simulation of hail damage on car hoods. Then, go even further by learning what gives units of measurement any meaning at all.**

**In this module students will be able to:**

- Select the appropriate device for measuring impact impressions
- Apply significant figures to measurements
- Identify the limitations of measuring devices in relation to significant figures
- Discuss the importance of measurements using a specific example from industrial applications
- Understand the importance of standardizing measurements and their units

## Class Activity

# MEASURING UP


## Background

Measurements are at the heart of our understanding of the world around us. The very act of describing qualities such as temperature, length, time or mass requires some basic measurement as we are comparing a physical quality to some known unit of reference. To illustrate this concept, try describing how tall you are without referencing any unit of measurement or explaining the temperature outside without using degrees.

While you can probably get by with generalizations such as “a warm summer day” or comparisons such as “slightly taller than the average girl my age,” these aren’t accurate enough for the types of measurements taken in industries such as farming, engineering, construction, manufacturing, and commerce.

Measurements are composed of three parts:

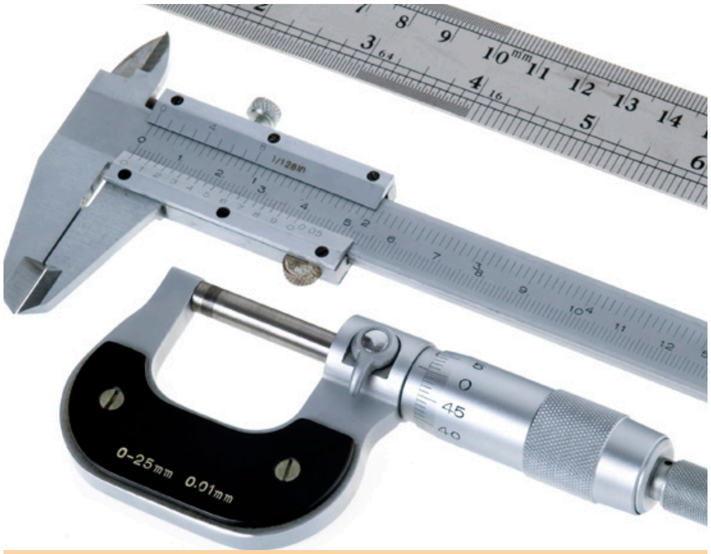
- A numerical value
- A unit of measurement that denotes the scale
- An estimate of the uncertainty of the measurement

The numerical value of a measurement should always be recorded with the proper number of **significant figures**. The number of significant figures depends on the instrument or measuring device used and is equal to the certain digits (obtained from the scale divisions marked on the instrument) plus one estimated digit. The estimated digit represents the uncertainty in the measurement and provides an indication of the minor scale markings on the instrument. For example, try measuring your pen using a standard ruler. If the ruler has millimeter markings, the millimeters are your certain digits and your result might be close to 108mm. However you can also add one further significant figure by estimating how far between two millimeter markings your pen tip ends. In this way, your measurement might now be 108.2mm instead (your one estimated digit has now been added).

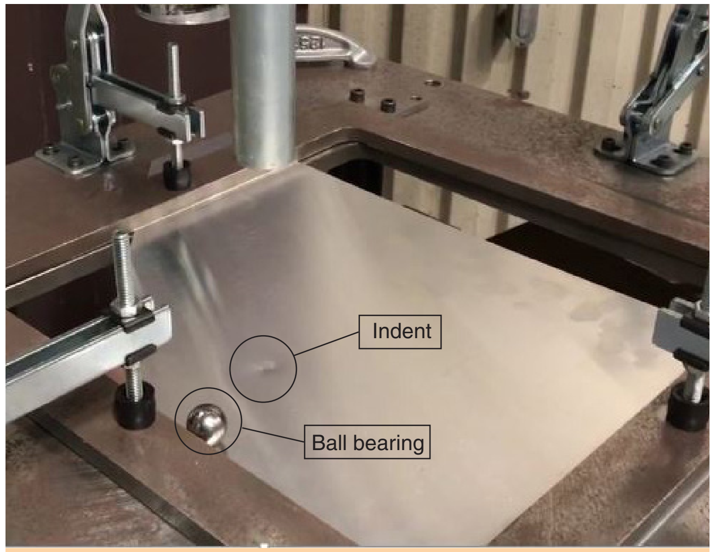
Significant figures are important in measurement because they indicate how precise the measurement is or the level of uncertainty in the measurement. Applying significant figure rules to measurements prevents the measurement from appearing to be more accurate than the measuring device allows.

Accurate measurements are especially important when products are being developed or tested as they

## Class Activity



*Measurements are only as accurate as the device used since the instrument determines how many significant figures you can obtain. A standard ruler cannot be read beyond 2 or 3 significant figures, but a micrometer might allow you to provide a more detailed measurement.*




*The experiment you are conducting is similar to how scientists test the extent to which car hoods can withstand hail damage. A large ball bearing is dropped onto a sheet of metal and the indentation is then measured and recorded. (Photo courtesy of Arconic.)*

provide an objective, scientific method of comparing results. Scientists and engineers working in research and development labs often design accelerated tests that help simulate the conditions a product must operate in. For example, when scientists develop a sheet product for use on car hoods, they must test how it will perform when hit by hail. Instead of waiting for a hailstorm to occur, scientists and engineers create an experiment that simulates the effect of hail dropping on the sheet. The width and depth of the impacted areas are measured and the results are reported to the number of significant figures appropriate for the measurement device. The material is then given a pass/fail rating. This helps companies ensure that their products will meet the high standards customers expect.

### Problem:

An insurance company has been receiving several claims regarding hail damage to vehicles. The company wants to cross-reference the damage recorded in these claims with the size of hailstones recorded in the day's weather reports. You have been asked to investigate these claims by determining the impact of different sized hailstones on aluminum.

### Task:

You and your partner are tasked with developing a procedure to simulate the impact of hail on car hoods using the materials provided by your teacher. Your procedure must measure the size of the impact impressions and must be approved by the teacher before you begin. After you conclude your experiment, you must write a report for the insurance company detailing the extent of impact damage they can expect to see for different sizes of hail stones.

# Class Activity

**Requirements:**

1. Collect data by measuring the impact different sizes of hail have on the piece of aluminum. The width of the indent should be measured using a micrometer and the depth of the indent should be measured using water and a graduated cylinder. Be sure to apply significant figures when measuring!
2. Write up a report for the insurance agency detailing your experiment procedure and results.

## Questions

1. **Identify the independent and dependent variables as well as any constants or controls in your experiment.**

2. **How would the data differ in terms of accuracy if you did not apply significant figures to your measurements?**

3. **Compose a report for the insurance agent including:**
    i. **Procedure**
    ii. **Data**
    iii. **Summary of results (i.e. trends in the data)**

4. **Identify at least one source of experimental error and explain how this error could be mitigated in future experiments.**

5. **Ask a family member or friend who routinely uses measuring devices in their job to explain how they record measurements. Summarize their explanation and conclude whether or not they apply significant figures. If they do not apply significant figures, why not?**

## Definitions

**Significant Figures**
These apply to measured quantities and are equal to the number of digits known with certainty plus an estimated digit.

## Teacher Resources & Answer Key

| Standards: | NGSS: | HS-PS1-1 |
| --- | --- | --- |

### Notes:

1. Materials needed:
   - Ball bearings
   - Aluminum cookie sheets
   - Disposable metallic pie pans or casserole dishes
   - Sand box (or a larger disposable dish filled with sand or kitty litter)
   - Aluminum foil
   - Micrometers
   - Graduated cylinders
   - Water
2. Students should work with a partner or in small groups to complete this activity.
3. Students could test all three pieces of aluminum (i.e. cookie sheet, disposable casserole dish, and sheet of foil) or each group could be assigned to one piece of aluminum and share their results with the class. Note: These sheets should be laid on a sand box during the experiment).
4. If different size ball bearings are unavailable, students can experiment with dropping ball bearings from various heights and measuring the impact velocity.
5. When designing their procedure, students should be encouraged to measure multiple ball bearing indents (controlled to the same drop height and ball bearing size) on one sheet of aluminum. This procedure reinforces the importance of recording the average of many measurements versus one measurement.
6. **Optional Modification:** If students have a strong background in physics, they could be challenged to design an experiment that utilizes Newton's Laws of Motion. If Newton's Laws of Motion are applied and students consider the kinetic energy of the ball bearings, they can produce more accurate results.
7. **Optional Modification:** To further stress the importance of significant figures in measuring, students could be challenged to record their data using various measuring devices such as a ruler, a paint stick which they scale, or a meter stick.

## Teacher Resources & Answer Key

**Grading Rubric for Report:**

| | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| **Precision** | Clearly explains why measurements need to be precise and provides two examples. | Clearly explains why measurements need to be precise and provides one example. | Clearly explains why measurements need to be precise. No example provided. | Does not clearly explain why measurements need to be precise. |
| **Accuracy** | Clearly explains why measurements need to be accurate and provides two examples. | Clearly explains why measurements need to be accurate and provides one example. | Clearly explains why measurements need to be accurate. No example provided. | Does not clearly explain why measurements need to be accurate. |
| **Reproducibility** | Clearly explains why measurements need to be reproducible and provides two examples. | Clearly explains why measurements need to be reproducible and provides one example. | Clearly explains why measurements need to be reproducible. No example provided. | Does not clearly explain why measurements need to be reproducible. |
| **Potential Problems** | Clearly explains potential problems when significant figures are not used in measurement and provides two examples. | Clearly explains potential problems when significant figures are not used in measurement and provides one example. | Clearly explains potential problems when significant figures are not used in measurement. No example provided. | Does not clearly explain potential problems when significant figures are not used in measurement. |
| **Mechanics and Grammar** | Contains few, if any punctuation, spelling or grammatical errors. | Contains several punctuation, spelling or grammar errors that do not interfere with meaning. | Contains many punctuation, spelling and/or grammatical errors that interfere with meaning. | Contains many punctuation, spelling and/or grammatical errors that make the piece illegible. |

## Teacher Resources & Answer Key

**Answer Key:**

1. **Identify the independent and dependent variables as well as any constants or controls in your experiment.**
   **Answer:**
   i. *Independent Variable:* Height or Size of Ball Bearing
   ii. *Dependent Variables:* Size (width and depth) of indent
   iii. *Constants:* Height (if changing size) or Ball bearing (if changing height)
   iv. *Control:* Could use piece of ice or golf ball

2. **How would the data differ in terms of accuracy if you did not apply significant figures to your measurements?**
   **Answer:** The data would be less accurate because the measurements would be reported to fewer places. If too many significant figures were reported, there would be a false indication of the accuracy of the measurement.

3. **Compose a report for the insurance agent including:**
   **i. Procedure**
   **ii. Data**
   **iii. Summary of results (i.e. trends in the data)**
   **Answer:** Student answers will vary.

4. **Identify at least one source of experimental error and explain how this error could be mitigated in future experiments.**
   **Answer:** Answers will vary but may include:
   - overlapping indentations (use a bigger piece of aluminum)
   -limitation of measuring device (use measuring device with a smaller scale)
   -aluminum foil ripped or dents were difficult to identify (layer several pieces of aluminum foil together)

5. **Ask a family member or friend who routinely uses measuring devices in their job to explain how they record measurements. Summarize their explanation and conclude whether or not they apply significant figures. If they do not apply significant figures, why not?**
   **Answer:** Answers will vary. If students struggle identifying someone who uses measurement suggest they ask someone in construction, nurses, designers, seamstress, a furniture store employee, etc.

MATERIALS™ EXPLORERS

## Extension Activity

# The Kilogram Controversy

Here's something to think about: when you place an item on a scale or use a stopwatch to record a race, you're making an assumption that those devices are going to give you an accurate reading. For example, you expect that the scale will give you a numerical value, in a specified unit such as a kilogram. It's also likely that the manual for the scale references the degree of uncertainty caused by the limitations of the equipment. However at an even deeper level, you're assuming that the unit means something: that a kilogram is a universal standard. And it is—sort of.


*The International prototype kilogram was once the primary standard kilogram for the entire scientific community but was replaced in 2019 with a new definition based on constants occurring in nature. (Photo courtesy of The National Institute of Standards.)*

### What's in a Kilogram?

A kilogram is one of the seven basic units of measurement within the **International System of Units**, or SI. You're probably already familiar with this system from your science classes because it is the international standard for science, but have you ever wondered how we determine exactly what counts as one kilogram? For 130 years, the value of a kilogram was based on a real object called the "**international prototype kilogram**" (IPK). The IPK is a closely guarded platinum-iridium alloy cylinder housed in a vault at the International Bureau of Weights and Measures near Paris, France. For something to count as a true kilogram, it had to exactly match the mass of the IPK. Therein lay the problem.

The kilogram was the only basic SI unit still defined by a physical artifact rather than a natural phenomenon. The meter, for example, is determined based on the speed that light travels in a vacuum over a specific period of time. By definition, this natural phenomenon is unchanging and can be measured anywhere (with the right tools). As durable as the IPK is, it could be damaged over time or even destroyed—not to mention

## Extension Activity

that you have to get into a vault controlled by three independent keys in order to weigh it. That's why, in 2018, representatives from 60 countries came together to vote on a new definition for the kilogram. As of 2019, the kilogram will now be measured based on three fundamental constants (the Planck constant, the speed of light, and the cesium atom's natural microwave radiation) instead of a physical artifact.

### Laboratory Standards

Regardless of how the kilogram is defined, it's important to understand why standardizing measurements are so critical to the everyday applications of science and engineering. Just like you, scientists are operating under the assumption that a measurement in their laboratory is exactly the same as a measurement their colleague makes somewhere else. They need to be able to trust that their equipment is giving them accurate results.

That's where **Certified Reference Materials**, or CRMs, come in. CRMs are samples that act as a standard to test against. To return to our earlier example of a scale: imagine measuring 100 objects of unknown weight. What would happen if you then added a one kilogram weight to the scale but received a readout of 1.5kg? You would be left questioning the accuracy of all 100 measurements you took before! Now imagine if the same problem was applied to a company testing the chemical makeup of an alloy being used on a bridge, a medical laboratory testing blood samples, or a food company testing the level of arsenic present. Suddenly accurate measurements seem much more important.

Many laboratory  or industry-grade measuring devices need to either be checked periodically for accuracy, or **calibrated** against a sample of known value. CRMs act as that known standard that allows scientists and engineers to calibrate their equipment or to double-check that the measurements being taken are still accurate.

CRMs help ensure precise measurement and testing in everything from DNA, to greenhouse gas emissions, to the nutritional value of supposed "superfoods." Think about that the next time you read the nutritional label of a food package.

## Extension Activity

### Questions

1. The International System of Units has seven base units. Identify all seven and indicate what each is used to measure.

2. The International Prototype Kilogram needed to last a long time. Research the IPK to determine why it was made of a platinum iridium alloy.

3. The IPK has recently gained tens of micrograms of mass from surface contamination. Although tens of micrograms may seem insignificant, how could adding this mass to the standard unit of mass impact the accuracy of measurements?

4. List and describe the 5 types of reference materials.

### Definitions

**Calibrate**
Correlate an instrument's readings with a standard to determine accuracy of the instrument.

**Certified Reference Materials (CRM)**
Control or standard used to validate analytical measurements.

**International prototype kilogram (IPK)**
An artifact that defines the current SI unit of mass.

**International System of Units (SI)**
A system of measurement based on seven base units: meter, kilogram, second, ampere, Kelvin, mole, and candela.

## Teacher Resources & Answer Key

1. **The International System of Units has seven base units. Identify all seven and indicate what each is used to measure.**
   **Answer:** meter (length), kilogram (mass), second (time), ampere (electric current), Kelvin (temperature), mole (quantity), and candela (brightness).

2. **The International Prototype Kilogram needed to last a long time, research the IPK to determine why it was made of a platinum iridium alloy.**
   **Answer:** The IPK was made of a platinum iridium alloy because iridium increased the hardness while retaining platinum's characteristics such as extreme resistance to oxidation, high density, satisfactory electrical and thermal conductivities, and low magnetic susceptibility.

3. **The IPK has recently gained tens of micrograms of mass from surface contamination. Although tens of micrograms may seem insignificant, how could adding this mass to the standard unit of mass impact the accuracy of measurements?**
   **Answer:** The tens of micrograms added to the IPK causes a slightly different definition of the kilogram which could cause inaccuracies in experiments that require very precise weight measurements or international trade in highly restricted items that are restricted by weight, such as radioactive materials.

4. **List and describe the 5 types of reference materials.**
   **Answer:**
   *i.* *Pure substances:* Characterized for chemical purity or trace impurities
   *ii.* *Standard solutions and gas mixtures:* Prepared gravimetrically from pure substances
   *iii.* *Matrix reference materials:* Characterized for the composition of specified major, minor, or trace chemical constituents
   *iv.* *Physico-Chemical reference materials:* Characterized for properties such as melting point or viscosity
   *v.* *Reference objects or artifacts:* Characterized for functional properties such as taste, odor, and hardness

MATERIALS™ EXPLORERS

# THE MATERIALS THAT MOVE US: CHEMICAL AND PHYSICAL PROPERTIES

*(Photo courtesy the U.S. Library of Congress Prints and Photographs Division.)*

**Distinguish between chemical and physical properties through real-world examples of each. Learn about chemical changes by watching corrosion at work then see how ship failures in World War II led to improvements in how we test materials.**

**In this module students will be able to:**

- Identify both physical changes and chemical changes
- Recognize corrosion as an example of a chemical change and identify different examples of corrosion
- Recognize the importance of understanding physical properties when working with a material
- See how scientists and engineers learn from failure to improve their understanding of a material
- Explain what a coating is, provide examples of coatings used in industrial applications, and identify the physical and chemical properties of those coatings

## Class Activity

# CORROSION AND COATINGS

## Background

From ice melting to food digesting, you encounter physical and chemical changes on a daily basis but can you distinguish one from the other?

By definition, a **chemical change** requires that the atoms of one or more substances are rearranged to create a new substance with a different chemical composition. In a chemical change, some of the bonds between the electrons of atoms will break or reconnect in different patterns. In contrast, a **physical change** may alter the substance's physical properties (such as shape, size, state or appearance) but the substance itself remains the same. To understand these concepts more easily, think of the following real-world examples.

All changes of state such as ice cubes melting or alcohol evaporating are physical changes because the properties of the materials themselves do not change. The water and alcohol are still the same, but they exist in different forms. On the other hand, baking a cake or burning paper are considered chemical changes because they result in the production of a whole new compound. After all, a finished cake has very different properties than all of the individual ingredients used to produce it.

Another common example of a chemical change you may see every day is **corrosion**. Corrosion is the deterioration of a material due to a chemical reaction between it and its environment. One example is steel rusting.  A major component of steel is the element iron (Fe). When iron comes in contact with oxygen (O), such as from moisture in the air, it undergoes a chemical reaction to become iron oxide, $Fe_2O_3$. Since there is always some moisture in the air, if no action is taken, over time all the iron in the steel can be consumed in the chemical reaction to form rust. As you can imagine, this deterioration is a major concern to manufacturers and to people everywhere who use these products.

It is possible to add elements into the **alloy** to help protect it from corrosion.  For example, stainless steels are a group of steel alloys that have chromium added to them to help prevent rusting.  Another way to prevent corrosion is through **surface engineering**, which is an interdisciplinary field combining aspects of materials science, chemistry, physics, process engineering, and chemical engineering to make materials more robust by protecting them at the surface level. In the example of iron reacting with oxygen to form rust, it is possible to put a surface coating on the steel to prevent oxygen from reaching the iron atoms, and thus prevent corrosion.

## Class Activity

*When vinegar is added to baking soda a chemical change takes place because an entirely new product is being formed. The baking soda (sodium bicarbonate) and vinegar (acetic acid and water) react to form carbon dioxide gas and sodium acetate. The bubbles that form are actually the carbon dioxide being released.*

*Corrosion is a serious concern when working with steel. In fact, a 2002 federal study by NACE International indicated that corrosion affects nearly every U.S. industry sector and, at the time, created cost the U.S, $276 billion a year! A lot of this money goes into inspection, maintenance, and repair.*

The first step to designing a successful surface treatment is understanding what function the product needs to serve. In some cases, scientists and engineers are tasked with making attractive yet durable products (imagine a shiny bathroom faucet). In other cases, the appearance does not matter at all (as with a large pipe that will be buried underground), but the product's surface must withstand use in very harsh environments or protect against corrosion, chemicals or heat.

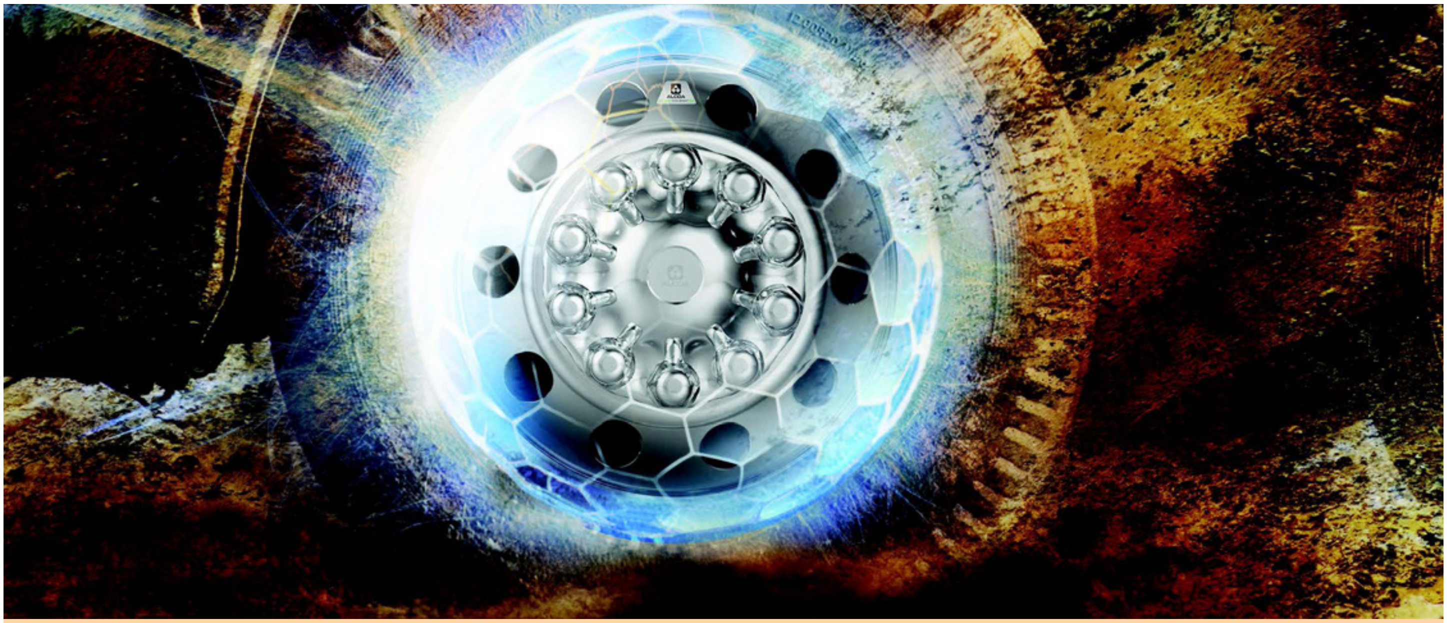
The second step to designing a successful surface treatment is understanding how your substrate material and the surface treatment process will interact. For example, cleaning your substrate first will help a coating stick, but using an improper chemical might damage the appearance of the surface. Scientists and engineers rely on a thorough understanding of the processes and materials being used to help determine the right course of action.

The last step in designing a successful surface treatment is testing the product against customer requirements. Usually this is done in an accelerated manner in the laboratory. For example, if the final product will be exposed to erosive elements (as with a car driving through a sandy desert) a test where it is exposed to abrasives such as blast media or sand paper can help to predict the part's performance once in use. Extensive testing ensures that the final product meets customer requirements.

## Class Activity

To gain a better understanding of engineered surface treatments, consider the example of the Dura-Bright® surface treatment on the Alcoa Wheels commonly used by commercial vehicles. The Dura-Bright® surface treatment was developed by Arconic to protect aluminum vehicle wheels. Aluminum is used because it is lighter than steel—and a lighter wheel means improved fuel efficiency and a potential increase in payload capability. However, wheels used on tractor trailers are exposed to road salt, gravel, sand, and cleaning chemicals, all of which can cause aluminum to corrode, thereby degrading both the appearance and the performance of the material.

So how can Arconic promise customers the benefits of aluminum wheels without an increased risk of corrosion? The Dura-Bright® surface treatment forms a protective barrier on the aluminum wheels to help it resist the corrosive effects of harsh environments. This surface treatment also protects against other chemical attacks, abrasion, and scratching. Additionally, Dura-Bright® is engineered to have a low surface energy that makes the wheels easy to clean with only soap and water, keeping them looking bright and shiny with low maintenance costs. This is surface engineering at work.



*Surface engineering has made it possible for the Alcoa Wheels to gain the benefits of an aluminum wheel, without the risk of corrosion. (Photo courtesy of Arconic.)*

### Problem:

Many automotive companies are switching to making car frames out of aluminum rather than steel because aluminum is a lightweight metal and less weight generally translates into greater fuel efficiency. A major automotive company is considering making this switch, but has expressed concerns over the possible corrosion of the aluminum frames. The company has asked you to investigate one of the conditions that might cause aluminum and steel to corrode.

MATERIALS™ EXPLORERS

## Class Activity

**Task:**

You and your partner are tasked with recording the pH of various solutions and predicting at what pH levels aluminum and steel might begin to corrode.

**Procedure:**

1. Using pH paper, record the pH of the following substances:
   a. Carbonated soft drink
   b. Orange juice
   c. Acetone
   d. Milk
   e. Energy drink
   f. Car wash concentrate
   g. Shampoo
   h. Water
   i. Salt water

2. Use the pH data collected to predict which types of conditions will cause corrosion for aluminum and for steel.
3. After observing the demonstrations conducted by the teacher, obtain 9 squares of aluminum prepared by the teacher (be careful—the edges may be sharp) and gather 9 paperclips (steel).
4. Label 9 containers (one for each of the available substrates in step one) and place one square of aluminum and one paperclip in each.
5. Place 15-30 drops of each substance in its corresponding container.
6. Set aside your containers where they will not be disturbed,
7. Create a data table to record which solutions, if any, caused the aluminum and steel to corrode. Check the squares for corrosion at the end of the class period, and once a day over the course of a week. For each solution, record when you begin to see evidence of a chemical reaction or corrosion on the foil or on the paperclip. This evidence may be noticed as a color change, change in the surface roughness of the material, an extra layer being deposited, or pits/erosion of the surface.

## Questions

1. **Based on your observations in this experiment, would you classify corrosion as a physical or chemical property? Justify your answer with evidence.**

2. **Based upon the observations made during your experiment, what conditions caused the aluminum to corrode? Are there any recommendations you would make to the car manufacturer to help them avoid corrosion?**

## Class Activity

3. **Based upon the observations made during your experiment, what conditions caused the steel paperclips to corrode? How did these results vary from aluminum and what does that indicate about the properties of steel?**

4. **Corrosion is just as important to consider when developing packaging for the food and beverage industry. Research two types of coatings used in this industry and explain the types of products that use these coatings.**

5. **The effects of corrosion also impact many structures and buildings. In fact, some statues have become faceless over time due to the effects of acid rain.**
    i. **Research the causes of acid rain.**
    ii. **Identify a statue or building that has been impacted by acid rain and explain the acid rain's impact on that structure.**
    iii. **Not all materials are easily damaged by acid rain. Identify three materials that you would recommend to sculptors who wish to make their art more durable.**

### Definitions

**Alloy**
A material composed of two or more metals or of a metal and another element.

**Chemical Change**
A change that occurs when one or more substances change into entirely new substances with different properties.

**Corrosion**
The process by which a material deteriorates due to a chemical or electrochemical reaction with the environment.

**Physical Change**
A change of matter from one form to another without a change in chemical properties.

**Substrate Material**
The material that is being surface treated.

**Surface Engineering**
An interdisciplinary field aimed at making materials more robust by protecting them at the surface level.

## Teacher Resources & Answer Key

| Standards: | NGSS | HS-PS1-2 |
|---|---|---|

### Notes:

**1.** Materials needed for class activity:

- Carbonated soft drink
- Orange juice
- Acetone
- Milk
- Energy drink
- Car cleaner
- Shampoo
- Water
- Salt water
- Water
- pH paper
- Paperclips
- Empty aluminum can
- Sandpaper
- Scissors
- 0.5M $CuCl_2$ solution
- Beakers or petri dishes
- Stirring rods
- Dropper

**2.** The teacher will need to prepare the squares of aluminum by rubbing off the coating on the can with sandpaper. The teacher will then need to carefully cut the aluminum can into squares of aluminum. This step should be completed with caution as the aluminum edges will be sharp.

*Note: Aluminum foil can be substituted for this activity, however the samples would need to sit longer than a week to the oxidation layer on aluminum foil that works to prevent corrosion.

**3.** Students should work in small groups to complete this activity.

**4.** **Teacher demonstration:**

a. Cut a piece of aluminum and place it in a petri dish or beaker. Use the dropper to add 0.5M $CuCl_2$ solution.
b. Students should be able to observe the process of corrosion taking place.
c. Repeat this activity using a metal paperclip (steel) in place of the aluminum. Ask students to observe which material corroded at a quicker rate.

**5.** **Optional Modification:** If time permits, an extension of the activity could be to paint over some of the aluminum squares with epoxy before placing them in the various substrates. Students could then compare the corrosion rates of regular aluminum to the aluminum coated in epoxy.

## Teacher Resources & Answer Key

**Answer Key:**

1. **Based on your observations in this experiment, would you classify corrosion as a physical or chemical property? Justify your answer with evidence.**
   **Answer:** Corrosion is a chemical property because it is a chemical reaction resulting in a different chemical compound. Evidence will vary.

2. **Based upon the observations made during your experiment, what conditions caused the aluminum to corrode? Are there any recommendations you would make to the car manufacturer to help them avoid corrosion?**
   **Answer:** An acidic environment caused the aluminum sqaure to corrode when the surface treatment was removed. In an effort to prevent corrosion, car manufacturers should ensure that aluminum parts are treated with a surface treatment, such as epoxy resin, that will prevent corrosion. The treatment should also be able to resist being scratched off by common use conditions such as sand and dirt.

3. **Based upon the observations made during your experiment, what conditions caused the steel paperclips to corrode? How did these results vary from aluminum and what does that indicate about the properties of steel?**
   **Answer:** Steel also corroded in an acidic environment but corroded more quickly than the aluminum. This indicates that steel is less corrosion resistant than aluminum.

4. **Corrosion is just as important to consider when developing packaging for the food and beverage industry. Research two types of coatings used in this industry and explain the types of products that use these coatings.**
   **Answer:** Student answers will vary but possible coatings include:
   - *Epoxy:* Used to coat aluminum and steel cans, stable and functional, most commonly used coating
   - *Oleoresins:* mixture of oil and resin extracted from plants, flexible but do not adhere to metal, used to coat food containers, may change the properties of food
   - *Vinyl:* very flexible and stable under acidic conditions, often blended with other resins, used for architectural coatings
   - *Phenolic:* highly corrosion resistant, not very flexible, may change odor and taste of food, used to coat drums and pails
   - *Acrylic:* brittle, change the taste and odor of foods, primarily used as a decorative or architect ural coating
   - *Polyester:* adheres well to metal, not corrosion resistance, used as a base coat or top coat
   - *Polyolefins:* corrosion resistance, flexible, does not impact flavor of the food, used to protect gas pipelines

## Teacher Resources & Answer Key

**5. The effects of corrosion also impact many structures and buildings. In fact, some statues have become faceless over time due to the effects of acid rain.**

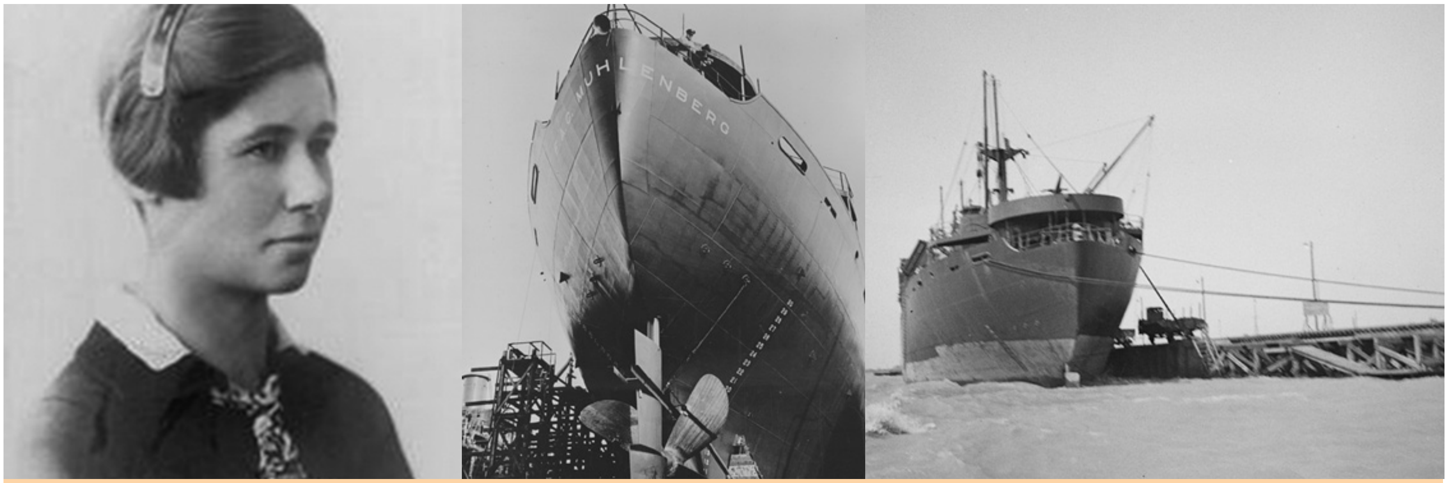
i. Research the causes of acid rain.
**Answer:** Pollution from the burning of fossil fuels cause sulfur dioxide and nitrogen oxides to be emitted. These molecules then mix with water molecules in the atmosphere to produce acids.

ii. Identify a statue or building that has been impacted by acid rain and explain the acid rain's impact on that structure.
**Answer:** Student answers may vary. Examples include:
- The Taj Mahal where acid rain due to local foundries and an oil refinery reacted with the marble (calcium carbonate).
- The Leshan Giant Buddha statue where coal fired power plants led to acid rain which damaged the structural integrity of the statue.
- The Parthenon where acid rain has caused the structure's marble panels to change to soft gypsum.

iii. Not all materials are easily damaged by acid rain. Identify three materials that you would rec ommend to sculptors who wish to make their art more durable.
**Answer:** Student answers may vary. Examples include granite, stainless steel, glass, plastic or specially coated materials.

## Extension Activity

### Learning from Our Mistakes



*Constance Tipper was able to solve the mystery of why the Liberty Ships were suddenly and catastrophically failing in use thanks to her research on the temperature at which steel became brittle. (Photo courtesy the U.S. Library of Congress Prints and Photographs Division.)*

Try as we might to avoid them, mistakes happen. What matters is learning from those mistakes in order to avoid repeating them. The same is true within engineering as we owe some of our standard practices, and even legal regulations, to the lessons learned from earlier failures. With German U-boats rapidly sinking British ships during WWII, the United States developed a way to mass produce cargo ships to carry vital supplies to the British army. Instead of riveting together the slabs of metal that made up the ship, the shipyards simply welded the pieces together. This cut production time by months, making it possible to produce a ship in just 42 days. There was just one problem—the ships were failing catastrophically. In the cold ocean waters of the North Atlantic, some of the ships literally broke in half after developing cracks that instantly traveled the whole way around them.

#### The Liberty Ships Problem

Researching failures can help revolutionize the way we develop or use various materials; transform design philosophies; establish strict guidelines for inspection, testing and maintenance of structures; and even give birth to entirely new fields of study. Consider the example of the World War II “Liberty Ships” which, because of poorly understood material properties, had an unfortunate habit of breaking in half.

In trying to determine the cause of these failures suspicion naturally fell on the radically new approach of an all-welded pre-fabricated ship. Then Constance Tipper entered the picture.

#### Constance Tipper

Constance Fligg Tipper (née Elam) was born February 6, 1894, and distinguished herself early on by becoming one of the first women to take the Natural Science Tripos (the framework within which most of the sciences are taught at the University of Cambridge) at Newnham College, Cambridge. From there, Tipper

## Extension Activity

went on to work briefly at the Royal School of Mines (part of the Imperial College London) where she was a research student working with Henry Cort Harold Carpenter on crystal growth and recrystallization in metals. This early research with Carpenter turned out to be foundational work in the field. Tipper next went on to work with G.I. Taylor at Cambridge where she once again was a part of groundbreaking work. Tipper continued her work in this area, publishing *The Deformation of Crystals*, a book that became the most commonly referenced work on the subject at the time.

Despite her success, Tipper struggled to gain recognition within a male dominated field. In fact, she continued her research at Cambridge for many years without holding an official title! Eventually, she gained her long overdue recognition and became a lecturer in the Faculty of Engineering and leader of the department's Heat Treatment Laboratory. It was at this stage in her career that she was consulted as a technical expert on the Liberty Ships dilemma.

### Cracking the Case

Tipper, who at this point had spent years investigating the failure of metals, obtained a sample of the failed ships for testing. She suggested that the fault did not lie with the welding at all, but with the steel itself. She demonstrated that there was a temperature at which the steel became **brittle** rather than **ductile** and that the cold waters of the North Atlantic were causing the ships to rapidly fracture. In materials science the word "brittle" means that when a load is applied to a material, it will not stretch but will fracture suddenly (think of dropping a ceramic mug). "Ductile" means that when a load is applied, the material will be able to stretch and deform some before finally breaking (think of crushing an aluminum can). Some materials have a transition temperature where they are ductile at higher temperatures but can become brittle at low temperatures; the steel of the ships was such a material. The temperatures in the region where the ships were manufactured was high enough for the metal to be ductile. However, when the ships passed through much colder waters, the metal became brittle and a change in stress, a pre-existing flaw, or a small crack would lead to a catastrophic brittle failure of the ship.

In the course of the investigation of the Liberty Ships, Tipper developed a test that became the standard method for determining brittleness in steel—now commonly known as the "Tipper test." Tipper didn't just identify what had gone wrong, she showed the shipyards how to test the steel and prevent the failure from reoccurring. Even more critically, her work established the field of **fracture mechanics** that continues to be a critical field within engineering.

The case of the Liberty Ships just goes to show that, even when we think we know all of the physical properties of a material, there may still be factors we have not considered. While the problem of the Liberty Ships is a dramatic example of a material failure leading to improved understanding, it's important to know that many material failures take place on a much smaller scale or within the controlled environment of laboratories. Like Constance Tipper, today's engineers research these failures to understand why they occurred and, more importantly, ensure that they never pose a risk to individuals.

**Parts of this article are excerpted from "Constance Tipper Cracks the Case of the Liberty Ships" by Kelly Zappas, published in JOM, December 2015, Volume 67, Issue 12, pp 2774-2776*

## Extension Activity

### Questions

1. Mechanical, physical, chemical, and manufacturing properties directly influence material selection in engineering. List an example of each property.

2. Constance Tipper discovered that at a certain temperature steel becomes brittle as opposed to ductile. This transition temperature is different for every alloy of steel. Research one specific steel alloy and its ductile to brittle transition temperature. List the name of the steel, its transition temperature, and the source where you found the information.

3. Ships initially made from timber transitioned to iron and then steel. Based on your observations from the activity and research, why is it unlikely that ships will eventually be constructed from aluminum as opposed to steel?

### Definitions

**Brittle**
A brittle material will break suddenly rather than deform when a load is applied.

**Ductile**
Able to be drawn into a thin wire without becoming weaker or more brittle.

**Fracture mechanics**
Mechanics of solids containing cracks with a focus on a crack's growth.

MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

1. **Mechanical, physical, chemical, and manufacturing properties directly influence material selection in engineering. List an example of each property.**
   **Answer:**
   *Mechanical properties:* strength, ductility, hardness, toughness
   *Physical properties:* density, electrical conductivity, thermal conductivity
   *Chemical properties:* corrosion resistance in various environments
   *Manufacturing properties:* formability, machinability, ease of joining

2. **Constance Tipper discovered that at a certain temperature steel becomes brittle as opposed to ductile. This transition temperature is different for every alloy of steel. Research one specific steel alloy and its ductile to brittle transition temperature. List the name of the steel, its transition temperature, and the source where you found the information.**
   **Answer:** These answers will vary widely; some steels (such as those used on the Liberty ships) have a transition temperature around 0°C. Other steels may have much higher or much lower transition temperatures.

3. **Ships initially made from timber transitioned to iron and then steel. Based on your observations from the activity and research, why is it unlikely that ships will eventually be constructed from aluminum as opposed to steel?**
   **Answer:** Aluminum will corrode in a saltwater environment. Aluminum is also difficult to weld and can react with air and water during the welding process therefore if a ship was made from aluminum it would need to be constructed indoors which would be very expensive.

MATERIALS™ EXPLORERS

# THE MATERIALS THAT MOVE US: STATES OF MATTER

**Having an understanding of a material's melting and evaporation points is essential to many scientific applications; this chapter explores states of matter through a practical classroom activity and highlights the relationship between atomic structure and physical properties by creating an alloy within the classroom.**

**In this module students will be able to:**

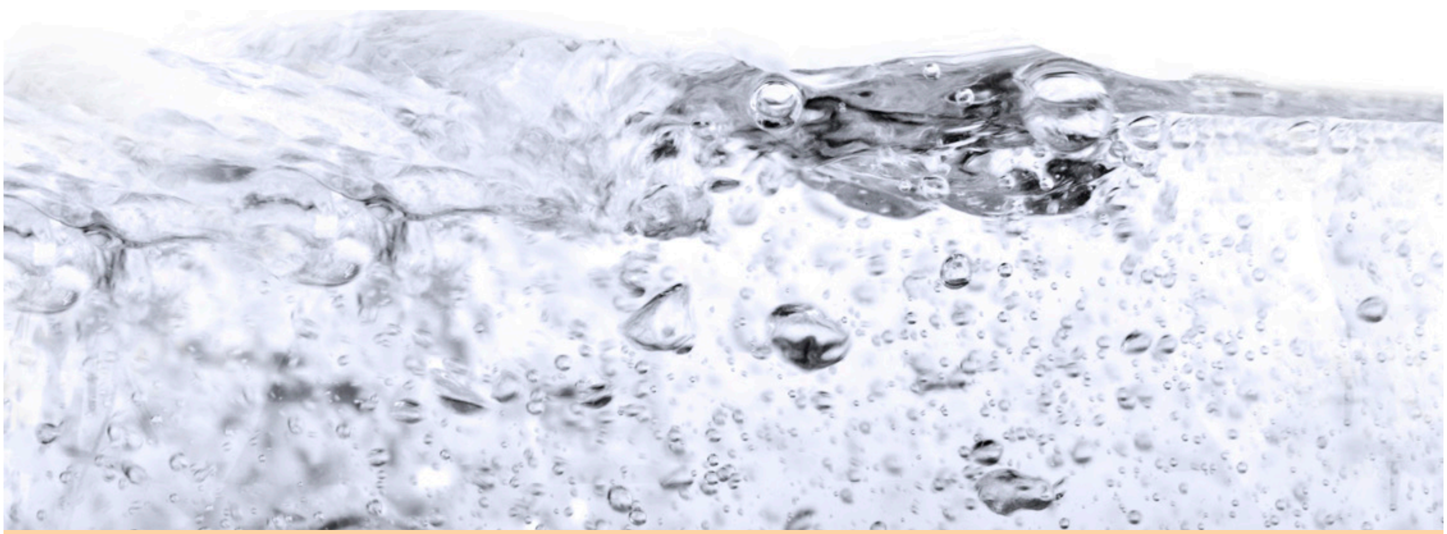
- Collect data and generate a heating curve for water
- Explain how intermolecular forces affect states of matter
- Observe the fusion and solidification points for a tin/bismuth alloy
- Experiment with alloys by recording the temperature of various combinations of tin and bismuth
- Compare the melting point of pure substance to alloys

## Class Activity

# WHAT'S THE MATTER?

## Background

You probably haven't considered it but when the ice in your glass melts or the water in your pot begins to boil you're witnessing science at work . As the water changes from one state of matter to another (from solid to liquid or liquid to gas) a phase change is taking place right before your eyes. This everyday example probably doesn't sound that exciting, but consider for a moment that the same scientific principles at work here are also behind creating aluminum components for jet engines or titanium tanks for spaceships.

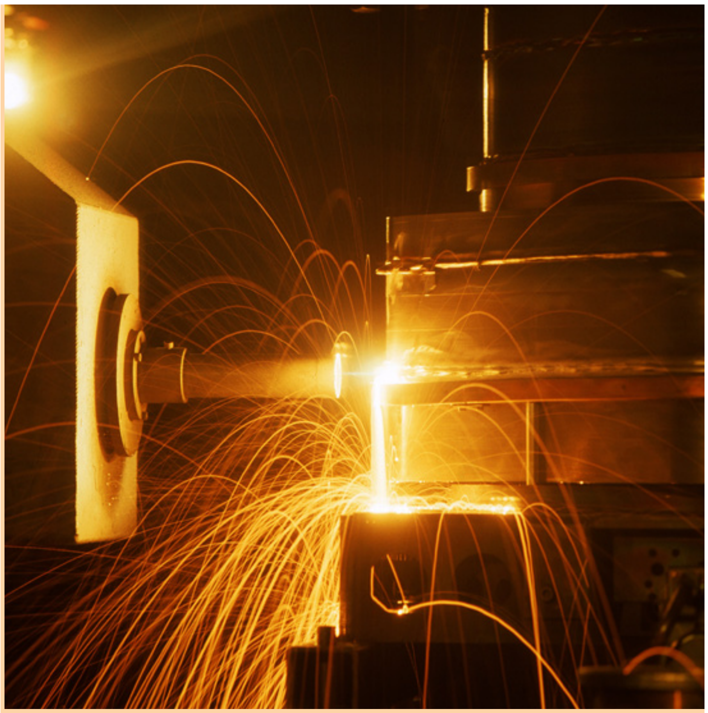


*Understanding how materials change from one state of matter to another is a fundamental concept in science. What's more, knowing the temperatures at which these changes might take place can be critical when working with a material.*

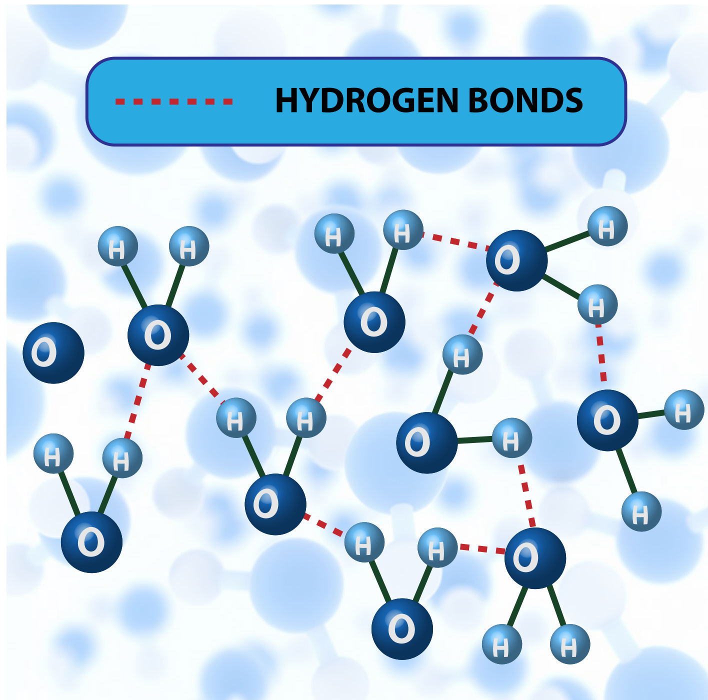
How, you might ask? Let's explore the example of an aluminum component created by electron beam welding: a process which relies on phase changes to join two parts into one with a seam that is narrower than the width of a human hair. To accomplish this, a narrow beam of electrons is shot at the aluminum. This heats the aluminum to its melting point (1200°F) where, much like ice turning to water, the solid aluminum becomes

## Class Activity

liquid. As the two pieces of aluminum cool they solidify together to form one piece. On occasion, the beam can be so strong that it reaches the evaporation point of aluminum—that's about 4500°F: nearly half the temperature of the surface of the sun!



*Electron beam welding was embraced by the aerospace industry because it creates strong, precise welds. (Photo courtesy of TWI Limited.)*




*In order to change from solid to liquid, or liquid to gas, the molecules of a substance must vibrate with sufficient energy to break free of their bonds. (Graphic by Dave Rasel)*

The following experiment will explore phase changes in water. One difference that is important to remember is that water molecules are held together by intermolecular forces but metals (with the exception of mercury) are held together by metallic bonds. Although the forces being overcome are different, the process taking place at the molecular level is quite similar in that heat is being used to create enough energy to overcome the forces that keep something solid, liquid, or gaseous. As more heat is applied, the molecules gain more and more energy vibrating with increasing excitement until they break free of the bonds or forces that hold them in place.

### Materials

- 250 mL beaker
- Hot plate
- Beaker tongs
- Ice
- Thermometer
- Water

## Class Activity

**Procedure:**

**1.** Fill a 250 mL beaker half full with ice and water.
**2.** Pre-heat a hot plate to 100°C. Do not place the beaker on the hot plate yet.
**3.** Insert a thermometer into the beaker containing ice and water. Make sure the thermometer does not touch the sides or bottom of the beaker.
**4.** Gently stir the ice and water throughout the experiment.
**5.** When the thermometer reaches its lowest reading, record the temperature in °C under time 0 in the data table.
**6.** Promptly place the beaker on the hot plate.
**7.** Read and record the temperature every 30 seconds for a minimum of 10 minutes after the water reaches a full, rolling boil. Continue stirring throughout the experiment.
**8.** Note the following times:
   **a.** When the ice begins to melt
   **b.** When the ice has melted entirely
   **c.** When the water begins to boil

**Data:**

Draw a table similar to the one below, continuing to fill rows as needed.

| **Time** | | **Temperature** |
|---|---|---|
| **(min.)** | **(s)** | **(°C)** |
| 0 0 | | |
| 0 30 | | |
| 1 0 | | |
| 1 30 | | |
| 2 0 | | |
| 2 30 | | |
| 3 0 | | |
| 3 30 | | |
| … … | | |

## Class Activity

### Questions

1. Graph the data, placing time on the x-axis. Label the states of matter and phase changes on the graph.
2. How did the temperature of the water/ice mixture change while the ice was melting?
3. How did the temperature of the water change between the time the ice melted and the water boiled?
4. Which phase change required the most added heat energy? Why?
5. If temperature is a measure of the average kinetic energy of particles, what can you conclude about kinetic energy during phase changes?

### Definitions

**Intermolecular Forces**
Forces of attraction (attractive and repulsive) between molecules.

**Metallic Bonds**
The chemical bond that holds the atoms of a metal together. It is formed by the attraction between the metal's atoms and free (valence) electrons that move between the fixed atoms.

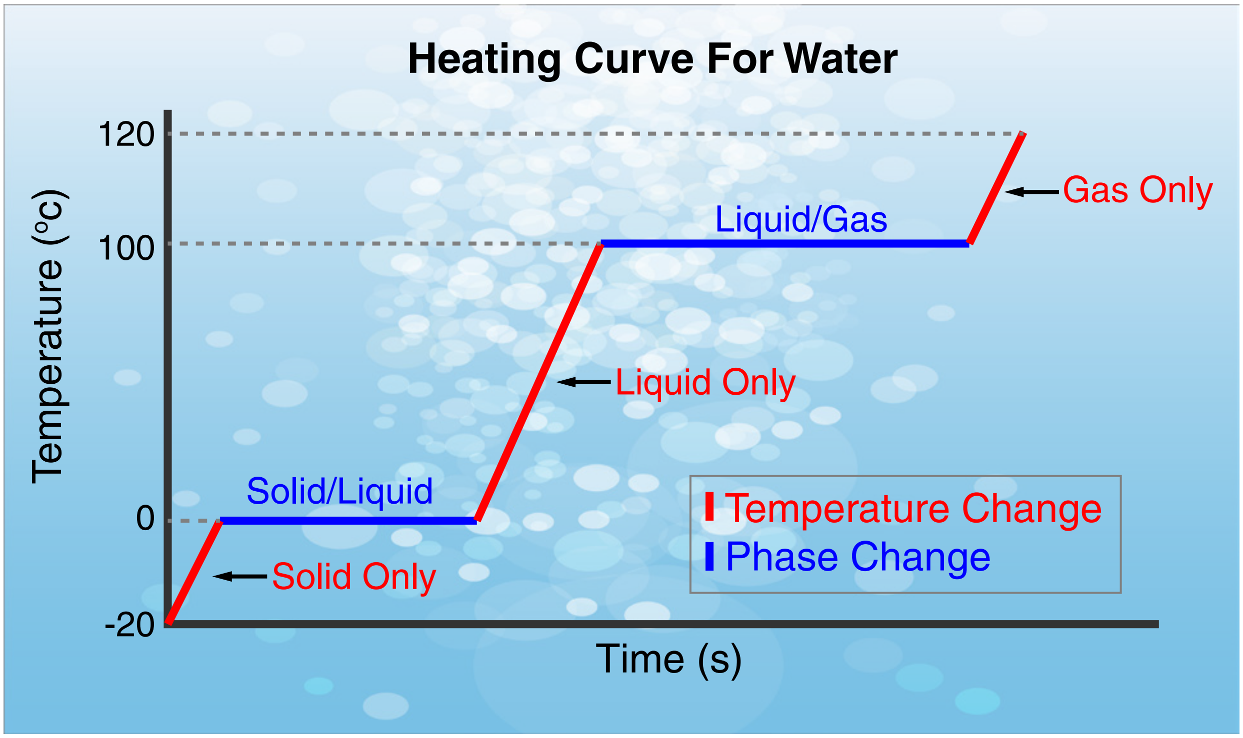
**Phase Change**
A transition from one state of matter to another.

MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

### Questions

1. **Graph the data, placing time on the x-axis. Label the states of matter and phase changes on the graph.**
   **Answer:** The graph should appear as follows:




2. **How did the temperature of the water/ice mixture change while the ice was melting?**
   **Answer:** During melting, the temperature remained relatively constant.

3. **How did the temperature of the water change between the time the ice melted and the water boiled?**
   **Answer:** The temperature increased.

4. **Which phase change required the most added heat energy? Why?**
   **Answer:** The phase change from liquid to vapor required the most added heat energy because all of the intermolecular forces had to be broken so the particles could move freely in the vapor phase.

5. **If temperature is a measure of the average kinetic energy of particles, what can you conclude about kinetic energy during phase changes?**
   **Answer:** During phase changes the temperature remains constant.

MATERIALS™ EXPLORERS

## Extension Activity

### THE SUM OF OUR PARTS?

The atomic structure of a material helps determine almost everything about it. From the material's chemical properties to its physical, thermal, electrical, and even magnetic properties, so much depends on what is occurring at the atomic level. But pure elements rarely have the specific properties that are needed for a particular application so scientists often find themselves combining two or more elements to create a completely new material that meets their needs. When at least one of these elements is a metal, we say that an **alloy** has been created.

To better understand the need for alloys, consider the use of aluminum alloys in aerospace applications. Because aluminum is a lightweight material, it can often reduce the weight of a part by replacing a heavier metal such as steel. In aerospace applications, this means creating a plane that is more fuel efficient and cheaper to operate. However, pure aluminum also has very low strength—an often undesirable trait. This is why many strength-driven aerospace applications rely on alloys. For example, scientists may mix aluminum with copper to create a material that has a high strength to weight ratio and good **fatigue** resistance.

*In order to create an alloy, metals are melted down and mixed together. Those responsible for creating the alloy must closely monitor the temperatures at which the metals are being melted.*

*Did you know that aluminum alloys are also used on spaceships? Spaceships need to be strong but they also need to be light and fuel efficient since rocket fuel is both heavy and expensive.*

So, how does that mixture of aluminum and copper become strong while remaining lightweight? The reason an alloy's properties differ from its constituent parts is because the very atomic structure of the alloy differs from the original elements used to create it. In other words, the whole isn't exactly the sum of its parts. In this activity, you'll make your very own alloy out of two metals and see how changing the ratio of your mixture affects the melting point of your alloy.

## Extension Activity

### Problem

A friend asks you to assist him with re-soldering the leaking joint of a pipe in his home. You know that the solder must be lead free for the water to be safe and, for fire-safety reasons, you also suggest that the solder melt at a relatively low temperature.

**Task:**

You are asked to make a recommendation for effectively fixing the broken part. You know that individually, tin and bismuth have high melting points, but suspect that an alloy composed of both metals will have a lower melting point. You and your partner will need to record the amount of tin (Sn) and bismuth (Bi) used (by mass %) to create the alloy and monitor the temperature of the alloy over time. After collecting all data you will plot the Mass % Bi versus temperature to generate a graph showing the melting point at various concentrations of bismuth to tin.

**Safety Precautions:**

- Students must wear close-toed shoes, goggles, gloves, and aprons at all times during this activity.
- If exposed to skin, wash area thoroughly with soap and plenty of water.

**Procedure:**

**1.** Gather materials including:
   - Safety goggles
   - Lab aprons
   - Gloves
   - Bismuth shot
   - Granular tin
   - Balance
   - Hot plate
   - 5 Pyrex beakers (400 mL)
   - Thermocouple sheath
   - Data collection device and software
   - Beaker tongs or heat resistant gloves
   - Hot pads or wire gauze

**2.** Measure out the following combinations (by mass) of tin and bismuth into 5 different Pyrex beakers:
   a. 0% Sn/100% Bi
   b. 40% Sn/60% Bi
   c. 50% Sn/50% Bi
   d. 60% Sn/40% Bi
   e. 100% Sn/0% Bi

**3.** Place the beaker on the pre-heated hot plate to melt the metals, stirring with a glass stirring rod.

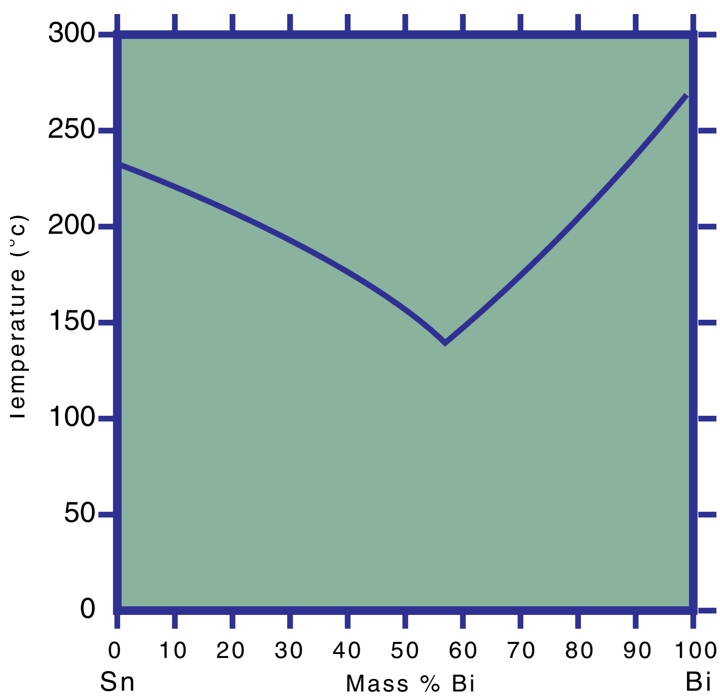
**4.** Heat the metals until they are completely melted. Using the thermocouple sheath and data collection device, monitor and record the temperatures up to the point at which the metals are fully melted.

# Extension Activity

5. Remove the beaker from the hot plate and place on a heating pad to cool.
6. Observe the shiny surface to see the first crystal formation and record the temperature at which this occurs. Solidify completely by waiting until the temperature reaches below 138°C.
7. Re-heat the metals to above 138°C and record the temperature at which the metals begin to melt and the final melting point.
8. Plot the mass % Bi versus temperature (°C) at which the material is fully liquid.

## Questions

1. **What are the melting points of pure tin and pure bismuth?**
2. **What was the lowest melting point recorded during the experiment?**
3. **What mass % of each metal was used to reach the melting point identified in #2?**
4. **Compare your graph to the graph below. How are they similar? How are they different?**
5. **The 60% bismuth and 40% tin alloy is primarily used as alternatives to lead-based solders for low-temperature applications. Research other products that are created using this alloy.**




## Definitions

**Alloy**
A combination of metals or a metal and another element to create a substance with more desirable properties such as resistance to corrosion or greater strength.

**Fatigue**
Fatigue is the weakening of a material caused by repeatedly applied loads. If the loads are too heavy microscopic cracks will begin to form. These will eventually reach a critical size and the crack will spread suddenly, causing the material to fail.

MATERIALS™ EXPLORERS

## Teacher Resources & Answer Key

| Standards: | NGSS: | HS-PS2-6 | HS-PS1-3 |
|---|---|---|---|

## Notes

1. Students should complete this activity in small groups.
2. Students should preheat the hot plates to 100°C.

### Safety Precautions:

- Students must wear close-toed shoes, goggles, gloves, and aprons at all times during this activity
- If either metal is exposed to skin, wash area thoroughly with soap and plenty of water
- This activity should be performed in a well-ventilated area such as a fume hood
- Containers should be kept in dry, well-ventilated areas with lids secured

### Answer Key:

1. **What are the melting points of pure tin and pure bismuth?**
   **Answer:** Sn- 231.9°C and Bi- 271.4°C
2. **What was the lowest melting point recorded during the experiment?**
   **Answer:** Students should have an answer of approximately 138°C
3. **What mass % of each metal was used to reach the melting point identified in #2?**
   **Answer:** 60% Bi/40% Sn
4. **Compare your graph to the graph below. How are they similar? How are they different?**
   **Answer:** Student answers will vary. Teachers can use this as an opportunity to discuss the limitations of performing this experiment in a classroom setting (such as less accurate measuring equipment, laboratory access to purer samples, human error in mixing).
5. **The 60% bismuth and 40% tin alloy is primarily used as alternatives to lead-based solders for low-temperature applications. Research other products that are created using this alloy.**
   **Answer:** Student answers will vary. An example response includes lead-free fishing tackle weights and bullets used for hunting (the bismuth-tin alloy provides similar ballistic performance to lead).

# THE MATERIALS THAT MOVE US: PUTTING IT ALL TOGETHER

**Throughout *Materials Explorers*™ you've seen the importance of materials selection in designing a product. You've also learned about the scientific method, a logical or systematic approach to problem solving. Now, you'll be able to apply that knowledge to conceptualize and design your very own product.**

**In this module students will be able to:**

- Evaluate a solution to a complex, real-world problem that can be solved through materials applications
- Analyze and evaluate different material properties
- Develop a practical solution to a complex, real-world problem
- Present the solution through a poster presentation and optional prototype

## Capstone Project

# MAKING A DIFFERENCE

## Background

From airplanes, to smartphones, to medical advancements: the entire history of our world has been shaped by scientists and engineers who identified a problem and worked towards a solution. Sometimes it was by challenging what was considered possible but, many times, it was by looking at a commonplace object and figuring out how it could be improved.

When designing a new product or part, scientists must also select the most suitable material. This is done by carefully considering the qualities their product will need and the conditions it has to endure before selecting the material that best meets those needs. Here's a practical example: if you were asked to design a new type of baseball bat, what qualities would be most important to your final product? Cost would certainly be an important factor to you since it's also important to your customers. Weight would also matter because players don't want a bat that is too heavy to swing comfortably. The bat would also need to be durable enough to withstand the impact of a baseball (often several thousand **Newtons** of force) yet malleable enough for your machines to easily produce their iconic shape. Finally, you might want a bat that resists corrosion despite years of being stored in field houses or storage sheds.

With all these requirements, it's easy to see why aluminum baseball bats are almost as popular as the traditional wood design. Aluminum is malleable, durable, lightweight, corrosion resistant, and cost effective—meeting all the requirements identified above. However, innovation doesn't stop just because a new product is created: there's always the chance to improve through another generation of designs and products.

*Although aluminum and wood are very different from one another, both have properties that make excellent baseball bats. What are some important qualities to consider when producing a bat?*

## Capstone Project

You can also make the world a better place by identifying opportunities for improvement around you and proposing either a “next generation” design or something radically new. Stumped for ideas? Try asking classmates, friends or family about something they use frequently that causes them frustration. Or, try looking around at your school or community for situations that could be improved by a new or different application of materials. Then, think about what kinds of materials you would need in order to address these problems.

*The use of iron and steel in building construction allowed the creation of skyscrapers in the late 1800s. Since then, materials innovations have made it possible to construct even taller skyscrapers at a lower price.*

### Problem:

Look around your home, school or greater community: there are likely many opportunities for improvement through a closer consideration of material selection and product design. You have the opportunity to make those improvements by either designing a completely new product or by improving a preexisting design and by selecting the best materials for creating your product.

### Task:

1. Think about your home, school, neighborhood or even the world. Identify a problem that can be solved by constructing something original or by designing a radical improvement to a current product. If you are struggling to think of an idea, conduct a needs assessment by questioning your peers, family members, teachers or neighbors. Keep in mind that sometimes the day-to-day products that we take for granted can also benefit from a redesign.
2. Consider the way your design will be used and how this will influence it. Review the following list of properties and determine which three would be most important when selecting materials for your creation. Keep in mind, some parts of your design may have different requirements. If so, you must identify the three most important properties for each part or component.

    - Appearance
    - Conductivity
    - Corrosion resistance
    - Cost
    - Density
    - Formability
    - Melting point
    - Strength
    - Toughness

**Definition**

**Newtons**
The International System of Units (SI) unit of force.

## Capstone Project

3. After selecting the three most important properties for your product, research which material(s) best fit those properties.
4. Create a poster to present your design concept, highlighting the materials used for your design and the properties that made you select them. Your poster must meet all of the requirements listed below.
5. Present your design to your class.

### Requirements:

Develop a poster that outlines the following:

- The problem that is solved by constructing your item.
- The three essential properties that guided your material selection.
  *Note*: If the essential properties vary by component, list three essential properties for each part of your design.
- The materials selected and the reason you selected them.
- A sketch of your proposed product including a scale and labels of the material(s) being used.

## Questions

1. **Material selection is an important step in designing products. Address each of the following material selection considerations with regards to your project: cost, reliability, ease of joining materials, ease of fabrication, mechanical properties, and electrical properties.**
2. **Materials belong to different "classes" or categories such as metals, ceramics, foams, polymers, composites, and elastomers. For each of the materials used in your product design, research and identify the class of materials to which it belongs.**
3. **When deciding which materials are appropriate for a specific task, material scientists often reference "materials selection charts." These charts map out the properties of different classes of materials and help scientists easily compare materials to one another.**
   i. **Research a materials selection chart that uses any one of the three material properties identified as "essential" in your poster presentation (for example, you may wish to search a materials selection chart showing density and strength, or one showing strength and cost).**
   ii. **Which class of materials performs best according to the chart?**
   iii. **Is it the same class of material as the one you initially selected for your design? If not, would you change your design now? Explain why, or why not.**

## Teacher Resources & Answer Key

| Standards: | NGSS: | HS-ETS1-3 |
|---|---|---|

**Notes:**

1. Encourage students to get creative with their projects, so long as their solutions are realistic. For example, they can make a project out of beautifying a local space by designing statues or park equipment, but their discussion of material choice would have to consider materials that could withstand environmental conditions, would be durable, and affordable. On the other hand, their project could also be improving an existing product. For example, they might want to develop a more durable phone charger since they frequently have problems with their chargers breaking.

2. Student sketches should include a scale and should be labeled to identify each material used. Posters must explain why each material was selected.

**Rubric:**

| | 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| **Need** | Clear connection to community. Problem is clearly situated in community context with a clear solution. | Connection to community is present. Problem is situated in community context with a clear solution. | Connection to community is present, but weak. Problem is not situated in community context and has no clear solution. | Does not clearly connect to community. No context. No clear solution. |
| **Properties** | Identifies three properties essential for materials selection. | Identifies two properties essential for materials selection. | Identifies one property essential for materials selection. | Does not identify properties essential for materials selection. |
| **Material Selection** | Clearly identifies materials and explains why materials were selected. | Materials are not clearly identified but there is an explanation of why materials were selected. | Materials are clearly identified but there is no explanation of why materials were selected. | Does not identify materials or explain why materials were selected. |
| **Sketch** | Sketch is created to scale and address each material used. | Sketch is created to scale but does not address each material used. | Sketch is not to scale and addresses most materials used. | Sketch is not to scale and does not address each material used. |

## Teacher Resources & Answer Key

### Questions and Answers

1. **Material selection is an important step in designing products. Address each of the following material selection considerations in regards to your project: cost, reliability, ease of joining materials, ease of fabrication, mechanical properties, and electrical properties.**

   **Answer:** Student answers will vary but should demonstrate an understanding that properties vary by materials and that factors such as production process and consumer preferences influence the design of a product.

2. **Materials belong to different "classes" or categories such as metals, ceramics, foams, polymers, composites, and elastomers. For each of the materials used in your product design, research and identify the class of materials to which it belongs.**

   **Answer:** Student answers will vary.

3. **When deciding which materials are appropriate for a specific task, material scientists often reference "materials selection charts." These charts map out the properties of different classes of materials and help scientists easily compare materials to one another.**
   i. **Research a materials selection chart that uses any one of the three material properties identified as "essential" in your poster presentation (for example, you may wish to search a materials selection chart showing density and strength, or one showing strength and cost).**
   ii. **Which class of materials performs best according to the chart?**
   iii. **Is it the same class of material as the one you initially selected for your design? If not, would you change your design now? Explain why, or why not.**

   **Answer:** Student answers will vary but should take into account that the material that ranks highest in one category may not automatically be the best choice (for example, the strongest material might be difficult to form into the desired shape or may corrode easily or might make the product too expensive).

MATERIALS™ EXPLORERS

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ARCONIC FOUNDATION

*Materials Explorers™* is a STEM educational outreach initiative of The Minerals, Metals & Materials Society (TMS). TMS is non-profit, international professional society with a mission to promote the global science and engineering professions concerned with minerals, metals, and materials.

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