Engineering Design Inspired by Nature

A POST-PRIMARY ENGINEERING CURRICULUM

Bio-inspired innovation. Student creativity. Sustainable solutions.

The Center for
Learning with Nature

Education should be a means to improving our world and enriching individual lives. The Center for Learning with Nature, a non-profit organization, is dedicated to this idea by integrating wonder and technological mentorship from the natural world into everyday STEM curricula. Our goal is to simultaneously build awe and capacity in students and teachers alike, through unique, exceptional STEM curricula and teacher training.

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^ Inspired by the boxfish (*Ostracion* spp.), the bionic car developed by Mercedes Benz gets 84 miles per gallon – without a hybrid engine. The roomy interior of this tropical reef fish and its surprisingly streamlined body attracted the attention of automotive engineers. Additional weight savings in the car's frame were achieved using computer-aided design software inspired by bone growth. The lightweight frame results in a car 1/3 the weight of a comparable, conventionally designed vehicle while being just as crash safe.

^ The plastic in this chair is made out of thin air and without a drop of oil. Like the material of trees, the carbon comprising this chair’s plastic polymers are sourced 100% from the atmosphere. Acquiring this ability long practiced by plants is a manufacturing game changer.

^ This watch's electronic screen requires no battery power to view clearly (unlike the cell phone). The watch's brightness is generated solely by ambient sunlight. Like the Morpho butterfly that inspired the screen technology, the screen relies on the spacing of microscopic optical elements to split sunshine into specific color wavelengths and reflect these back to our eyes.

“This course has been, without a doubt, my most absolute favorite course we've had at school so far! I wish we could have it all year like we have math.”

Ashlynn, 17

“This was a fantastic course. I learned a lot and am now really inspired to follow along this path. The final project gave me a new goal in life.”

Mandy, 16

“I thought that the course was extremely fascinating. I enjoyed learning about the extent to which we can apply nature to humankinds' problems. I would say that this course has influenced me in that I now realize that science can be as ingeniously creative as it is methodical and about experimentation. Before this class I typically thought of science as all experiments and equations or discoveries. Biomimetics opened up a different side of science for me.”

Natalie, 17

“I thought that the course opened new doors for me into the future and for my generation. It taught me to be more clearer in how I see the things around me now. It influenced me to be more creative and careful in our world.”

Nick, 18

“Since beginning our class I have been looking at the world differently and I can see the possibilities that Earth gives us. The course was amazing, don't change anything.”

Max, 17

An astronomer or a microscopist might introduce us to an otherwise unseen world. The account here, by contrast, aims to reveal an otherwise unnoticed world.

Steven Vogel

Acknowledgements

This work would not have been possible without the help and influence of many other people. I especially would like to thank my wife, Tammy Mildenstein, who has taught me so much about what it means to be human. I would also like to mention Janine Benyus, who changed forever how I see the natural world and the possibility of a sustainable human way of life. Finally, I'd like to thank the Board of Directors of the Center for Learning with Nature, Ken Blum of the Dean Witter Foundation, and Cynthia Loebig of the Kalliopeia Foundation, who helped make possible the work you see before you.

For Julio and Kestrel, and all other school children everywhere

TABLE OF CONTENTS

HELLO

Welcome to *Engineering Design Inspired by Nature*. If you choose to teach this course, things may not remain the same for you. You might have students wanting to speak to you after class, their eyes wide, looking as though they haven't blinked for the entire period. You might find yourself standing for long periods of time looking up at the tree overhanging your car in the school parking lot. And you might find yourself wondering why we teach biology separate from engineering (and chemistry and physics and math…).

Technology inspired by Nature has a way of doing these things to people. Somehow we grow up thinking technology and Nature are two different worlds, when they aren't. Our modern world is already filled with technologies inspired by Nature, which is exciting and fascinating to discover. And what engineers today are inventing based on what they're learning from the natural world is simply startling.

Students do many things in this course. They make a solar cell based on tree leaves. They simulate computer software programs inspired by ants. They make cement out of car exhaust, using a chemical process learned from coral reefs. They redesign household products to use less material, based on how bones grow. They literally watch as mechanical forces pass through materials before their own eyes, coming to understand why trees are stronger than even steel. And, amongst other inventions of their own design, students work together to design a wildlife-friendly metropolis for millions of humans.

In the process, students in this course will learn many things. Foremost they learn that Nature itself is a formidable engineer, whose millions of life forms have already solved thousands of technological challenges in elegant ways that are effective not only during the lifetime of the organism, but over the epoch of the species. Students in the course learn to recognize Nature's extensive talents, understand what makes them work, and how to apply these inventive ideas to solve humankind's own technological challenges. In short, students in this course learn how to invent like engineers who have access to Nature's wealth of routinely surprising, effective, and enduring technological ideas.

In the end, students in this course begin a transformation, a transformation of themselves – of who they are, what they want to be and do with their lives, and how they experience the world around them. And a transformation of how these future engineers will change our world with their creations.

A NOTE ON K-12 ENGINEERING EDUCATION

Engineering, in its broadest sense, covers a great deal of human activity. Engineers not only design cars, they also design the chemical composition of the road surfaces, the way the traffic signals work, and the layout of cities. They design computers but also the software running on the computers and the protocol for how computers talk to one another, as well as the power grids, telephone lines, and satellites that make this communication possible. They design everything from the architecture of hospitals to the medical devices implanted in its patients.

Like other fields, engineering is subdivided into concentrations and there is no such thing as a general “engineer”. In the development of a new product, for instance, design engineers might drive the conception of new prototypes, test engineers might evaluate these prototypes, and the final aesthetic and ergonomic features of the product would fall under the purview of industrial designers. Besides these kinds of distinctions in the “vertical” development of things, there are distinctions amongst engineers of a more “horizontal” type: mechanical engineers, electrical engineers, civil engineers and the like, which is less about what one does within the development process of a single new item, and more about what types of items one works on in the first place.

As a consequence, no single curriculum can cover all of engineering, nor should it try. Rather, the goal of an engineering curriculum for K-12 students might arguably be simply building students’ general interest in the topic, so that they may continue to pursue the subject, either professionally or less formally. Relatively few students will likely pursue the subject professionally (no matter how good the curriculum), so we should be guided by a still more ultimate aim. That more fundamental purpose is less vocationally instrumental and more social in nature, namely, *the enrichment of each students’ experience of life through the subject of engineering.* And also, a deeper appreciation for the impact engineering practices have on our lives and the world we live in. All of these are goals of the present curriculum.

This curriculum covers many areas of engineering: material science, structural and mechanical engineering, manufacturing, software design, biomedical engineering, urban design and more. The skill areas emphasized here have less to do with math than the development of critical thinking skills bio-inspired engineers use on a daily basis, largely having to do with creativity, analogical reasoning, and social need. As an introduction to engineering, this curriculum endeavors to cover many fundamental aspects of the discipline while keeping its ultimate goals in mind, to build students’ awe and capacity – in the general topic area of engineering, in improving the human-built world through innovation inspired by Nature, and in experiencing the endless engineering wonder that is Life itself.

WHY ENGINEERING INSPIRED BY NATURE?

Bio-inspired engineering (also known as biomimicry or biomimetics[1]) is the abstraction of good design from the natural world to inspire engineering solutions. Such a theme for engineering curricula can sound exotic, but it's in fact rather conventional: telephones, airplanes, and computers are fundamentally bio-inspired technologies substantially shaping modern society today (inspired by the middle ear, soaring birds, and the human brain, respectively). The world's most famous engineer of all time, Leonardo da Vinci, himself a student of Nature, spoke of Nature's relevance to engineering this way:

> "Human ingenuity may make various inventions… but it will never devise any inventions more beautiful, nor more simple, nor more to the purpose than Nature does…".

Famous inventors and engineers have echoed this viewpoint throughout time, including Buckminster Fuller, the Wright Brothers, and Thomas Edison, who said:

> "Until man duplicates a blade of grass, nature can laugh at his so-called scientific knowledge."

Fortunately, we don't have to take sides: it is the whole point of bio-inspired engineering that by being alert to what the rest of the natural world has learned about engineering over 3.8 billion years, our undeniably clever species can better advance its own efforts to improve the world through engineering.

Such a theme for engineering curricula is quite timely: the role of bio-inspired technologies in the global economy today is in the billions of dollars, stretching across every industry from software development to health care. Projections of biomimetics' near-term influence on labor markets (and part of the reason for education is to improve employment prospects) are all in strongly positive territory.[2] Largely in response to these economic forces, the introduction of bio-inspired design into post-secondary educational institutions – Harvard, Arizona State, Georgia Institute of Technology, to name just a few – has been nothing short of meteoric, with bio-inspired curriculum, courses, concentrations, and full degrees emerging at design and engineering schools all over the world in just the last few years.

The story in K-12 education is much less discernible, however, and here, bio-inspireation as a theme for engineering curricula is more forward-looking. True, with the new Next Generation

[1] These terms are used interchangeably, because despite their various histories and nuances, for most purposes they all mean the same thing: innovation inspired by Nature.

[2] One economic projection concluded that "…in 15 years biomimicry could represent $300 billion annually of U.S. gross domestic product (GDP) in 2010 dollars…Biomimicry could account for 1.6 million U.S. jobs by 2025. Globally, biomimicry could represent about $1.0 trillion of GDP in 15 years…" (Fermanian Business and Economic Institute 2010)

Science Standards placing engineering on essentially the same level as science education for all primary and secondary grades for the first time in U.S. history, there is clearly a recognition that there is value in teaching engineering at younger ages. But how? With what emphases? Fortunately, a bio-inspired emphasis not only makes vocational sense, but what better way to teach engineering than by framing this new subject area in terms of Nature, for students who still find Nature innately engaging? This thematic approach also appears to have resonance with underrepresented demographic groups, such as young women, possibly related to biomimicry's unique connection with the natural world, environmental responsibility, and human well-being. Bio-inspiration is certainly solution-oriented and hopeful, an important feature for young minds becoming aware of a complex and sometimes troubling world for the first time. Finally, many of the technologies emerging today from bio-inspired approaches have undeniable promise and are just plain fascinating, a great number of these to be explored in the present curriculum.

With no further introduction, then, let's get started.

HOW TO USE THIS CURRICULUM

Teaching a new subject or teaching a subject in a new way takes time, especially to do it well. This curriculum is designed to provide teachers with as much as possible to add a significant subject area to your repertoire and school curricula program.

The curriculum consists of a series of lesson plans arranged in a methodical sequence designed to guide student development in bio-inspired engineering. Lesson plans include a mix of presentation, student reading, discussion, and hands-on activity to help students discover ideas for themselves. This is a pedagogical philosophy we believe strongly in, evinced, we hope, in how each lesson plan is designed. In many class periods, students work in groups on projects largely self-directed. In other classes, teachers conduct presentations, lead discussions, and provide mentorship to students in order to guide students' own exploration and discovery of ideas.

Slides have been provided for many of the lesson plans, which help emphasize or are vital to understanding the narrative. When you review each lesson plan before class, have the associated PowerPoint open as you go, so that you can see the slides at full size as they will appear during the lesson. In the Teacher's Guide, thumbnails of these slides accompany the narrative so that you can keep the slides appearing at the appropriate time (e.g., while students read aloud from the Student Reader).

Student Readers are provided so that the students take a more active role in the course's information. The tone of the Student Reader is conversational, and includes opportunities for the rest of the class to participate (e.g., in response to questions). All of this is to aid in the goal of engaging the students. Note: teachers are heavily discouraged from providing the students with the material from the Student Reader in advance of each class, as the lessons frequently work by building up curiosity over a question and then revealing an answer, which could be spoiled if students read ahead in the Student Reader. The best option may be to project the reader on the wall, while second best may be to provide students with print outs from the Student Reader for each lesson as you go along.

Teachers will naturally use this material in different ways. Our aim has been to provide a structured-enough resource that can be used "as is" without customization, while providing a rich-enough amount of material and suggestions for adaptation for those teachers that wish to tailor the material to varying degrees. Teachers may wish to adjust, for example, which lesson plans they use (depending on time), and what parts of each lesson plan students read aloud to the class (from the Student Reader) and which parts teachers elect to present verbally to the class. Simply add your notes below each slide in the slideshow, and click "presenter view" when presenting the slideshow. You'll be able to see your notes on your computer, but your students will only see the slides.

Each lesson plan is designed to be engaging while being consciously "low-tech" in that they generally require no specialized training, equipment or materials, and can be conducted in any type of educational setting. We feel that financial considerations should not exclude school districts and educators from using the curriculum, and that curricula, in order to be engaging, do not need to rely on hard-to-obtain materials or overly-extensive professional development. That said, the lesson plans will need to be thoroughly absorbed, and the activities practiced before-hand to the extent possible by each teacher using the curriculum. Like any new curriculum, the first year will be a steep learning curve. Professional development using the curriculum may prove helpful when available.

The current curriculum is designed as an inspiring introduction to engineering for middle to high school students, depending on their previous exposure to engineering. In schools without an existing engineering program, this curriculum could serve as an excellent introduction, whether conducted in middle or high school. For high schools that already have a technical engineering program, this curriculum could serve well to build interest in engineering for middle schoolers, or, to enrich the high school program.

Lastly, while the curriculum is designed as a stand-alone course, it could be adapted so that the materials augment existing curricula. Aligned to various educational standards, particularly the Next Generation Science Standards, the curriculum is nonetheless designed to constitute a substantive addition to students' regular, existing school curricula.

"I recently graduated high school and until just a few days ago, I had no idea what path to pursue concerning college and career choices… Reading about how biologists use science to design and build solutions for real world issues led me to the area of biomimicry. I really love nature, science, and using my own two hands to build ideas from my head. How does one make a career out of biomimicry?"

Female high school graduate

"After I graduate high school, I would like to get an engineering degree. My goal is to solve some of the earth's problems before I finish high school. For example, when settlers first came to Texas, they burned wood and buffalo dung for fuel. They were unaware of all the oil beneath their feet. We may be that way right now. There may be potential energy sources all around us and we do not realize it. Using 3.8 billion years of natural solutions, the answer to energy that will not harm the environment may be all around us if we look. I plan to keep looking."

5th grader, after participating in a bio-inspired design project

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PART I

If we did all the things we are capable of doing,

we would literally

ASTOUND OURSELVES.

-Thomas Edison

1. STUDENT ORIENTATION TO THE COURSE

You can be creative in anything - in math, science, engineering, philosophy - as much as you can in music or in painting or in dance.

Sir Ken Robinson

Summary: The lesson provides students with an orientation to engineering as a broad human endeavor which profoundly impacts our world and ourselves, using the students' immediate surroundings and having students physically deconstruct a common technological device.

Main ideas: Engineering is a major part of our world, whose far-reaching impacts extend beyond ourselves, as well as within ourselves.

Above: Using high speed videography, collaborators from the School of Mechanical Engineering and School of Biology at the Georgia Institute of Technology found mammals from mice to bears all shake dry at optimized speeds following the same underlying mathematical pattern. Amongst various applications, the findings could improve the efficiency of washing machines. Dickerson, Andrew K., Zachary G. Mills, and David L. Hu. "Wet mammals shake at tuned frequencies to dry." *Journal of The Royal Society Interface* 9, no. 77 (2012): 3208-3218. Dog photo by Mike Allyn; washing machine by dixit M.

Introduction for teachers: The lesson begins with an introduction to what the course is about, and what the students will do in the course. For all lessons, teaching directions are in italics while the narrative (spoken or read aloud portions) is in non-italicized letters. Thumbnail images of slides appear near or next-to where they should appear on-screen when you or the students are reading out loud.

Concepts/skills covered: Engineering is an important and prevalent part of our world.

What you need: Each student should have a device that can be taken apart with tools (e.g., a screwdriver), such as a VCR, toaster, etc. Ideas for sourcing these materials include: ask students/parents/teachers to bring these from home (they will not get them back), call repair shops in town to see if they have anything not yet in the garbage, or purchase items from thrift stores.

> The word "engineering" comes from the Latin "ingenerare," meaning *to create*.

Time required: 1 class period (e.g., 50 minutes).

Teaching approach: The lesson begins with raising basic awareness about the importance of engineering in human society, by making use of the students' immediate physical environment and a short slide presentation. The second part of the lesson builds on the preceding discussion through a hands-on deconstruction of a technological object, to further emphasize in a visceral way the prevalence of engineered objects in our society. The deconstructed object also becomes a concrete, tangible impetus in a discussion about engineering and sustainability.

Narrative:

Teacher says: In this course, we'll be exploring the world of engineering, of design, and innovation. We'll pay special attention to technological innovation inspired by Nature. We'll be investigating a wide variety of phenomena, at many spatial scales, and exploring a number of questions. For example, what do dandelions and skyscrapers have in common that makes them both good at standing up? What can sharks teach us about fighting bacteria? Why are ants good for the environment, even though there's more of them than people? How would Nature design a car, or a cell phone, or a video game? These are just a few of the kinds of questions we'll explore in this course. We'll look deep, deep inside trees to discover the secret of their extraordinary strength. We'll explore how Nature can help us design our cities to better cope with rising human populations. We'll look at how people invent, how inventors think, sometimes pulling ideas literally out of thin air. And in this class *you'll* invent things too – not only things you haven't thought of yet, but things you don't even know *how* to think of yet. This is a course about the importance of engineering and technology, the power of your imagination, and the extraordinary creativity of the natural world around us.

Students take turns reading aloud: Whether you've thought about engineering before or not, engineering has a huge impact on our lives. Everything made by people is first thought of and translated from an idea into something physically real by individuals we call engineers. You may have a picture in your head about what an engineer is. In this course, an engineer is anyone who makes things people use for a concrete purpose. It could be a medical device, it could be a computer program, or it could be the layout of a city. Engineers make the human-built world, from synthetic atoms to cell phones to traffic intersection rules. Engineers first imagine and then build our world.

This isn't abstract. Just take a look around you: the clothes you're wearing began as a design in someone's sketchbook; the material fibers were spun from farmed or fossilized plants; dyed using probably engineered chemicals; and cut and sewn by machines, all designed by engineers. The paper in your notebooks was grown in forests, shredded in lumber mills and bleached and pressed and cut and bound and shipped to the stores you bought them in. The tables and chairs in this classroom also began first as drawings in a designer's sketchbook, every bit of metal or wood or plastic in them measured, shaped, heated, cut, and assembled according to these designs. The glass of our classroom windows began as quartzite sand, mined, trucked, and then cooked until molten, poured into molds, and cooled into the extraordinary clear material you see – or don't see – in front of you.[1]

Teacher says: The point is, our world is an engineered one, and one we sometimes unfortunately learn to ignore. But in this class, we'll wake up to that world and explore it.

Take a look at this deconstructed car.[2] There are some 10,000 individual parts in an average car. Every single part and how all the parts work together to function as a car is the result of the work of engineers. This is true for everything around us: computers,[3]

bicycles,[4] everything.

Anyone know what this is?[5] *(It's a typewriter)*.

How about this?[6] *(It's a print film camera)*.

[1] You can go as far as you like, using the immediate physical surroundings – walls, floors, ceilings, electrical systems, halls, gymnasium, sidewalks, parking lots – to emphasize the point that engineering is a major part of our world; alternatively, you can also ask the students to look around the classroom, and share with the rest of the class things they notice that engineers made.

[2] PPT1, slide 1.

[3] PPT1, slide 2.

[4] PPT1, slide 3.

[5] PPT1, slide 4.

[6] PPT1, slide 5.

Just like these objects, all the parts of a city are also designed by engineers, which in that case are called urban planners.[7]

Students take turns reading aloud: So you can see, the technologies that inventors and engineers have developed literally shape our world. And these things also shape our experience of the world, because they also shape our interaction with the world. And so to significant degree, engineering shapes our experience of life itself. On a personal level, engineering matters.

That the influence of technology has an impact on our history is not hard to see. Anyone know who these people are and what they're doing?[8] These people were known as "knocker-uppers" and their job was to go around to people's windows in the morning and wake people up for work. Of course, they were replaced in time by moms and dads,[9] and then replaced by a technology – the alarm clock.[10]

Think of the influence of another piece of engineering on your life: the automobile.[11] Imagine for a moment, if you can, what the world would be like without them. You would walk or maybe ride a horse to school or the grocery store. You might not come to school at all.[12] And just think of the impact of the automobile on the planet we live on. Anyone know how many miles of roads there are on our planet? About 40 million miles of roads (64 million kilometers),[13] enough road placed end-to-end to drive to the planet Venus, by car.

Or think for a minute of the impact of medicine on how we live, like penicillin.[14] The antibiotics derived from penicillium fungi, modified by biotechnology engineers, have saved over a hundred million lives. It's saved many of you. Even if you haven't

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[7] PPT1, slide 6. It may be effective to replace or also include a picture of your own city here.
[8] PPT1, slide 7.
[9] PPT1, slide 8.
[10] PPT1, slide 9. For the less comically inclined, you can just skip the picture of the dad and put up the picture of the alarm clock.
[11] PPT1, slide 10.
[12] If possible, consider going outside with the students at this point in the discussion, and looking out from the school area onto the surrounding landscape. How has engineering, for example through the invention of the automobile, influenced what you see? Consider things like housing density, the existence of roads, etc. You could also use Google Earth to look at the impact of the automobile on the urban design from satellite images of the area surrounding your school and city.
[13] <http://en.wikipedia.org/wiki/List_of_countries_by_road_network_size>
[14] PPT1, slide 11.

needed life-saving antibiotics yourself, some of you in this room probably are here today because one of your direct ancestors did.

Technology matters. And the engineers who invent and design it make this possible. And just imagine what the world was like before the internet![15] Also invented by engineers.

Teacher says: The point is, engineering is a major part of our world. Technology and the engineers who design technology have a huge impact on our world, and our experience in that world. To get a less abstract and more physical sense of what we've been talking about, each of you is going to take apart an example of technology, and examine it.

Activity*: Provide students with examples of technologies (VCR, cell phone, etc. See "What you need" section). Prepare surfaces and provide tools. Instruct students not to break apart anything, in as much as possible, but to carefully take the item apart into its separable components. Students can do this individually or in pairs.*

As students begin, ask them to take a careful look at each component part, and consider how that component part interacts with the larger object. Remind them that every component has been designed and engineered. Tell students to take a close look at the components of their object (shape, texture, weight, connection to other pieces, etc.), and ask students to speculate to themselves and with their partners (if paired) about each component's function, based upon its structure, its relationship to other internal components, and what they think they know about the object itself.

Once students have had 10-20 minutes for this activity, engage the class in a discussion about the activity. What did they think? What did they notice? Did they enjoy it?

*Finally, ask students questions about the object's various materials, the manufacturing process that produces those materials, and what happens to these materials once they are no longer needed. What materials are used in the object? How are these materials created? What happens to the materials at their end-of-use? You can write each material up on the board and the answers the students give to these questions in columns, connected by arrows, or use a table (****Fig. 1****).*

MATERIAL	ORIGIN	DISPOSAL
plastic	fossil fuels, pumped from the Earth	landfill, environment
metal	rock ore, mined from the Earth	landfill, environment
silicon	quartzite sand, mined from the Earth	landfill, environment

Fig. 1. Understanding where the materials we use in human-made technologies come from, and where they go. From the diversity of human-made technologies one examines, clear patterns start to emerge.

[15] PPT1, slide 12.

Now have the class sort the various materials of their deconstructed objects into several piles, depending on the material type and its recyclability. Use knowledge of local opportunities for recycling to determine these piles (e.g., plastics by recycling number, non-recyclable materials). Take photos of each pile (you may choose to use these later in the course).

More Resources

If for some reason you do not want students to take apart real objects, you can have them take apart virtual objects on the computer, e.g., a camera (http://classroom.materials.ac.uk/camera.php) or MP3 player (http://classroom.materials.ac.uk/mp3.php).

2. INTRODUCTION TO ENGINEERING INSPIRED BY NATURE

The conscious emulation of life's genius is a survival strategy for the human race, a path to a sustainable future. The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.

Janine Benyus

Quote from Biomimicry: innovation inspired by nature (1997). Mushroom by Jason Vanderhill.

Summary: This lesson aims to engage and excite students about engineering inspired by Nature and the course through a carefully-prepared mixed-media presentation.

Main ideas: By shaping technology, engineering can improve our lives, but it can also result in unintended consequences. When technologies need improvement, we look to engineers and designers again – this time for innovation. One particularly fascinating and promising source of ideas for technological innovation comes from the natural world around us.

Introduction for teachers: Though we readily think of the concepts "Nature" and "technology" as very distinct (even opposites), it turns out this is a misconception, and like any misconception, this blocks us from understanding the truth. Just like the colors blue and red seem very distinct, they are both still colors. Similarly, even though they are different, the things we make and the things made by the rest of Nature have much more in common than we normally realize, and we can improve our technologies in surprising and even profound ways by learning from the natural world around us. This idea is known as innovation inspired by Nature, or by various terms such as biologically inspired (or just bio-inspired) innovation, biomimetics, biomimicry, and a few other lesser-used terms.

Bio-inspired innovation is not a new idea, but its influence on technological development has become striking in recent years, both in the breadth of different technological areas impacted, and in the kinds of innovations developed. Bio-inspired innovation is now an established part of architecture, urban planning, computer software design, medical technology, mechanical engineering, and many, many more areas of human endeavor. Moreover, many of the technologies inspired by Nature being developed have extremely surprising capabilities. People can now climb glass walls using special gloves, for example, because of studying and emulating the material structure of gecko feet. And like trees, people are now able to make physical materials directly out of thin air.

Bio-inspired innovation is a fascinating topic, but it is also a large and fast-changing field. The purpose of this lesson is to introduce the idea of bio-inspired innovation to students. There are many different ways to do this, different possible examples to use, and so forth, and teachers are encouraged to fine-tune the presentation as needed.

Concepts/skills covered: Humans can improve their technologies in various ways by studying and emulating the rest of the natural world.

What you need: Sizable unpolished rock (e.g., the size of a cantaloupe) and prepared slideshow.

Time required: 1 class period (e.g., 50 minutes).

Teaching approach: This lesson plan features a substantial slide show in order to illustrate several examples of innovation inspired by Nature. Despite being a slide show, it is designed to amaze students as much as possible (your own genuine enthusiasm will help). Guided class discussions also weave through the slide presentation as topics are raised.

There are dozens and dozens of potential examples of bio-inspired innovation for such a presentation. These examples shown here were selected to represent the broad applicability of bio-inspired design, to highlight the sustainability applications of bio-inspired design, and to engage and entertain a high school audience. Other examples can be added or examples removed as desired.

Narrative:

Place a sizable rock next to you as speak, within clear view.

Teacher says: So… we've seen how engineering is all around us, shaping the things we use and the world we live in. Engineering is all around us in another way, too, in a way we sometimes overlook: this body (*referring to yourself*), speaking to you, is an example of that engineering. You all are an example of that engineering. And we are truly extraordinary. Not so long ago, the atoms in our bodies were floating around in the sky, in rivers, or were just stuck in the dirt: carbon, hydrogen, oxygen, nitrogen, the atoms comprising over 96% of our bodies. Life has found a way to organize these building blocks into something that moves…thinks…talks…lives. That's why this rock is here (*gesture to the rock*), to emphasize the contrast. Somehow, though we come from this planet, though we're made *of* this planet, we *live*, we're animated – animated rocks. So with that, let me introduce to the most amazing engineer on this planet: Life.[1]

Engineering is truly all around us – what life makes, and what we, as part of life, make. By creating technology, engineers can improve our lives. However, our engineering can also result in unintended consequences. We saw, for example, how some of the materials we use to make things cannot be recycled. Sometimes our technologies work well in the short term, but don't work well in the long term. So we call these technologies *unsustainable*.

What are some technologies that you would consider unsustainable? (*Write a list of these on the board as students come up with ideas*).

When technologies need improvement, we again look to engineers and designers, this time for innovation.

Students take turns reading aloud: One intriguing source of innovation for new technological inventions and engineering designs comes from the living world around us. Engineering innovations inspired by Nature will be a focus in this course. What exactly is a technological innovation inspired by Nature? There are lots and lots of kinds of examples, so let's look at some of these.

The electricity consumed by a cell phone goes mostly towards… what would you guess? That's right: backlighting, for illuminating the display screen.[2]

[1] PPT2, slide 1.
[2] PPT2, slide 2.

The display screen of this smart watch uses less than half the battery power of other screens.[3] Any idea why? That's right: it doesn't use backlighting. So how is it that we can see the display? Well, to understand that, you have to take a look at organisms like these.[4] Unlike humans, these animals and plants create color without using pigments or dyes or paints. Instead, deep inside their tissues, microscopic structures reflect surrounding sunlight in very carefully controlled ways.

Consider this mountain bluebird:[5] this very blue bird actually has no blue in its feathers at all. The feathers are essentially transparent. Not only that, but if you were to take a feather from this bird and hit it with a hammer –

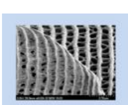
Teacher can interject: Just the feather, mind you, not the whole bird!

Students continue taking turns reading aloud: – the blue color would vanish. That's because the blue color is caused by physical structures deep inside the bird's feathers. Air bubbles trapped in the bird's feathers have the exact diameter of blue wavelengths of light. So sunlight goes in, but only blue light gets reflected back out, while all the other color wavelengths scatter randomly or are absorbed.

Teacher says: This is a very clever approach to getting noticed for a bird (anyone know why?): when it wants to communicate, for example to find a mate or assert its territory, the bird just flies out into the sunshine and lights up, but when it wants to elude predators, it can duck into the shade, and essentially disappear.

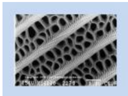
Students continue taking turns reading aloud: Here's an example of these physical structures from the wing of a butterfly, the Blue Morpho from Central and South America.[6] These butterflies can signal to each other from a quarter of a mile apart. With the help of a scanning electron microscope, we can essentially enlarge the wing or shrink ourselves.[7]

Here are the scales on the wing enlarged 600 times.[8]

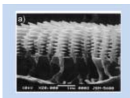


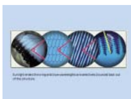
Enlarged 8,000 times.[9]

[3] PPT2, slide 3.
[4] PPT2, slide 4.
[5] PPT2, slide 5.
[6] PPT2, slide 6.
[7] PPT2, slide 7.
[8] PPT2, slide 8.
[9] PPT2, slide 9.



Enlarged 16,000 times, we can see these walls of material rising over the flat lattice of the wing scale.[10]

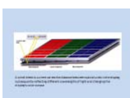




And if we turn these walls sideways, enlarged 20,000 times from what you'd see with the naked eye, you can see these repeating spaces, which turn out to have the exact diameter of a blue wavelength of sunlight.[11] Sunlight enters the wing and while all the other colors are scattered or absorbed, blue wavelengths are selectively bounced back out of the structure.[12]

Give students a moment to absorb this and ask questions.

Teacher says: What do you think would happen if you changed the spacing between these structures in the butterflies' wing scales?



Students continue taking turns reading aloud: Once engineers began to study species like these and understand that you could create color in this way, using *spacing* instead of paints and pigments, they realized this opened the door to dynamic color, color that changes, because spacing can be varied. They have now applied the design idea to electronic displays.[13] A small electric current varies the distance between optical units in the display, subsequently reflecting different wavelengths of light, and changing the display's color output.

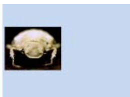
As a consequence, the electronic screen of this watch lights up in the sunlight, just like the butterfly that inspired it.[14] Unlike a conventional display screen, whose backlighting capability is overwhelmed outside, these Nature-inspired electronic display screens get brighter in the sunshine. And since they don't require backlighting, they use much less battery power, around 50% less.

This is an example of technological innovation inspired by nature, the first of many we'll explore in this class.

The idea of structural color learned from other organisms has been applied to a wide variety of human-made things.[15] The surfaces of consumer products, for instance. More interestingly, it also includes things like counterfeiting safeguards on

[10] PPT2, slide 10.
[11] PPT2, slide 11.
[12] PPT2, slide 12.
[13] PPT2, slide 13.
[14] PPT2, slide 14.
[15] PPT2, slide 15.

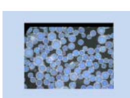
money. The new US $100 bill for example uses structural color to make the “100” turn different colors, depending on the angle you view the bill.[16] The idea of structural color has also been applied to cosmetics.[17] Because the color is created by reflecting light waves rather than potentially unhealthy chemicals, these cosmetics can produce vivid color on skin more safely.



This beetle from Southeast Asia, the *Cyphochilus* beetle, creates a brilliant white using structures in scales that cover the beetle’s backside.[18] The scales are very thin, about half the width of a red blood cell, which makes them 100 times thinner than any whitening or brightening materials invented by humans yet. Mimicking the structure of this beetle’s scales could help us make paper without using dangerous bleach.[19]

Because the color is produced by physical structures, damage to those physical structures can indicate the severity of an impact.[20] This could be used on helmets to quickly indicate the level of head trauma a soldier has experienced, useful for medical support teams, and in sports helmets.[21]

Dyes and pigments are static, they can’t change color, but color from reflective physical structures can. It can be green one second and black the next. So you can tune it, like a dial. A dial in your car for color could mean that in the summer, you could turn your car white to reflect as much sun and heat as possible.[22] In the winter, you turn the dial, and your car becomes black.[23] Want to change the color of your bedroom? Just turn the dial.



Thanks to creatures like bluebirds, this isn’t so far-fetched as it may have once seemed. These plastic spheres recently designed by chemists produce color much the same way as do bluebirds, and they do it with a flick of a switch.[24] That’s innovation inspired by nature.

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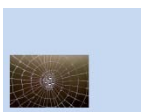
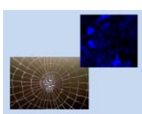
[16] PPT2, slide 16.
[17] PPT2, slide 17.
[18] PPT2, slide 18.
[19] PPT2, slide 19.
[20] PPT2, slide 20.
[21] PPT2, slide 21.
[22] PPT2, slide 22.
[23] PPT2, slide 23.
[24] PPT2, slide 24.

Let me give you another example of inventions inspired by nature. Worldwide, millions of birds perish each year, colliding into the things architects build, because they can't see them.[25] A few years ago, a glass manufacturer heard about something having to do with spider webs that caught his attention.[26]

Now, you might be surprised how much engineers are interested in spider webs. What we're basically looking at is a spider's version of a bullet proof vest. Instead of bullets, this one is designed to catch flies. Ounce-for-ounce, spider web material is actually as strong or even stronger than Kevlar, the material used to make bullet proof vests. So engineers have been interested for a while in what makes spider silk so strong. And also how it's made. After all, to make Kevlar, we have to use fossil fuels and acids. Spider silk is merely made out of the digested flies it catches!

So this glass manufacturer heard an interesting observation, which is that birds rarely collide into spider webs.[27] If you've ever walked into a web, you can see why birds should want to avoid them. And when you think about it, spiders should want to help birds avoid inadvertently destroying their webs, so they don't need to rebuild them every day. So how might this happen? Do spiders somehow communicate with birds to help them see their webs? They do.





It turns out that spiders help birds see their webs, by using a light we can't see, but which birds can see very well.[28] When you shine an ultraviolet light on a spider web, it lights up like a Christmas tree, and that's what birds see as they're flying around.[29] Spiders even add UV reflecting elements to their webs, just to make sure birds don't overlook them.

The glass manufacturer borrowed this clever idea from spiders, and began manufacturing their windows with a coating that reflects UV light.[30] Birds can see it, but humans can't. In paired tests with conventional glass, this spider-web inspired glass reduces the amount birds collide into glass by 75%.

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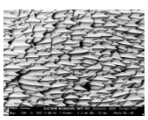
25 PPT2, slide 25.
26 PPT2, slide 26.
27 PPT2, slide 27.
28 PPT2, slide 28.
29 PPT2, slide 29.
30 PPT2, slide 30. The company is called Arnold Glas; the product is called Ornilux.

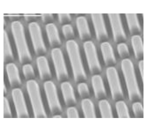
That's an example about protecting our feathered planet-mates; this is an example of innovation inspired by Nature even closer to home. Every year, about 100,000 people die from getting infected by this strain of bacteria, *Staphylococcus aureus*.[31] What's especially troubling about this situation is that we inadvertently bred this strain of dangerous bacteria, by accident, through the use of antibiotics. Antibiotics are biocidal: they kill off all the bacteria except those individuals resistant to it.[32] The result is a bacteria now known as MRSA, which stands for Methicillin-resistant *Staphylococcus aureus*. Antibiotic resistant bacteria, sometimes called superbugs, are a growing problem ever since we discovered penicillin and other antibiotics just 70 years ago. As long as we fight bacteria by killing them, we are locked in an arms race that produces ever-more dangerous pathogens.

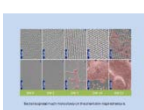
A way out of this dilemma has presented itself, thanks to this organism, the Galapagos shark.[33] A few years ago a scientist started paying attention to the fact that sharks have very clean skin. This isn't due to sharks being fast swimmers, because most of the time they're swimming relatively slowly, cruising through the ocean. And most slow-moving creatures in the ocean have lots of things attached their skin – barnacles and so on. But not sharks. It turns out this is true at the microscopic level as well. Sharks have virtually no bacteria on their skin. How do they achieve this? Well, sharks fight bacteria not with chemicals, but with texture.



This is what their skin looks like under a scanning electron microscope – it's not smooth.[34] The scales of this predatory fish have lateral ridges and valleys running across them. And this is the key to their success, because it turns out bacteria have great difficulty sticking to this surface. One end of a bacterium is clinging to a thin mountain ridge, while the other end tries to gain purchase in the valley below, where water is flowing, accelerated through the narrowed channel. For a bacterium, this is energetically expensive, and they evidently don't persist on this kind of surface.

Teacher says: Can anyone see how this might help us fight unwanted bacteria? *Give students a chance to respond.* What if we mimicked this shark skin texture in a plastic film? How would bacteria behave on such a surface? That's exactly what you're looking at, magnified to a few tens of microns in length.[35]





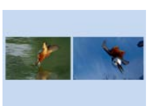
Students continue taking turns reading aloud: With bacteria on it, colored pink, you can start to see what happens on an artificial shark skin textured surface.[36] Now bacteria can grow very quickly. They divide every 20 minutes, so one single bacterium can become more than 8 million bacteria cells in less than a day.

[31] PPT2, slide 31.
[32] PPT2, slide 32.
[33] PPT2, slide 33.
[34] PPT2, slide 34.
[35] PPT2, slide 35.
[36] PPT2, slide 36.

Compared to the spread of Staph on the smooth control surface on the bottom row, the shark skin inspired surface is much more effective at slowing the spread of bacteria. No chemicals, no antibiotics required, just surface texture.

And when you employ this plastic film in a hospital, it means you no longer have to use biocidal chemicals to clean surfaces every few hours, just soap and water.[37] The approach has applicability on just about on any surface where bacteria is a concern: high touch surfaces like bed rails and doors, and also medical implants. And the magic part is, because the textured surface doesn't kill bacteria in order to stop it, it doesn't breed resistance, it doesn't create superbugs. That's why it's worked for sharks for 450 million years, bacteria getting none the wiser. And now, thanks to people learning from sharks, this technology is beginning to work for humans.

Innovation inspired by Nature can help us innovate in many fields, in medicine, in architecture, in electronics, and in transportation. This is the original Shikansen Bullet Train, for example, one of the fastest trains in the world.[38] When it first was introduced, the train had a problem: it created a great deal of noise, specifically when it emerged from a tunnel. In a tunnel, air built up on the nose of the train, increasing in pressure, until the dense air was pushed out of the tunnel, where it suddenly expanded.[39] The outrushing air created a sonic boom, like a suddenly popped balloon.[40] Residents of Tokyo began to complain, and the train company's chief engineer was asked to come up with a solution to quiet the train.



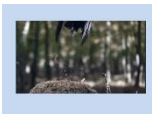
The train engineer happened to be an avid bird water, and it occurred to him that a particular kind of bird might hold an answer for him. Any idea what kind of bird? Anyone one know what kind of bird this is?[41] *Give students a chance to respond*. A kingfisher. Many species of kingfisher dive for fish. As soon as their beaks pierce the surface of the water, a pressure wave is transmitted down into the water, which can alert fish. In order to catch a fish before it swims away, therefore, kingfishers have to enter the water as smoothly as possible.

So kingfishers go from one less-dense medium, air,[42] to a more dense medium, water,[43] and they do so with very little splash. The train engineer recognized that this was similar to his challenge, in which trains must go from one medium, the air before the tunnel, to a denser medium, the air within the tunnel, and exit without creating a build-up of air pressure.

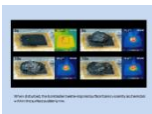
The engineer went back to his lab and began testing long projectiles with different

[37] PPT2, slide 37. The company making this surface is called Sharklet Technologies.
[38] PPT2, slide 38.
[39] PPT2, slide 39.
[40] PPT2, slide 40.
[41] PPT2, slide 41.
[42] PPT2, slide 42.
[43] PPT2, slide 43.

nose shapes traveling through cylinders.[44] And he found that as the shape of the projectiles became more and more like the shape of a kingfisher's bill, they traveled more quietly. The result is the modern Shinkansen Bullet Train, which travels more quietly, more quickly, and yet uses less electricity, than the original train.[45]



Technological ideas reside throughout the natural world. Consider for instance the bombardier beetle.[46] *Play short video.*



Inventors recently created a surface that, like the bombardier beetle, creates a caustic liquid reaction when it's disturbed.[47] The surface begins foaming less than 5 seconds after impact.

Teacher says: And here's one application of the invention.[48] *Play short video.*

Teacher continues through the end of the lesson: Whether from bluebirds, or spider webs, sharks or bombardier beetles, the natural world is full of technological ideas. Technology inspired by Nature isn't a new idea. Famous inventors like Leonardo da Vinci and others have pointed to the value of Nature to human innovation for a long time.[49] But what is new is the *extent* to which inventors today regularly borrow insight from the natural world in order to come up with brand new approaches to design and engineering.[50] Traffic engineers, material scientists, chemists, fashion designers, in nearly every field of human endeavor, technology innovators today are exploring the natural world for fresh ideas.

Why would the biological world be of interest to people in engineering-related careers? Anyone have any thoughts as to why? Why would engineers be looking to the natural world for innovation? *Give students a chance to consider why Nature would be of interest to people doing engineering-related work.*

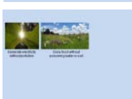
Well, engineers solve challenges. And Nature, in its four billion year old journey on Earth, has also had to solve challenges. So the natural world has had a lot of time to create solutions, and a lot of opportunity to experiment with different kinds of approaches. The result is a world full of original, often brilliant ideas humans might never have thought of themselves. Sometimes we overlook some of the most basic

[44] PPT2, slide 44.
[45] PPT2, slide 45.
[46] PPT2, slide 46.
[47] PPT2, slide 47. From Halter, J. G., Cohrs, N. H., Hild, N., Paunescu, D., Grass, R. N., & Stark, W. J. (2014). Self-defending anti-vandalism surfaces based on mechanically triggered mixing of reactants in polymer foils. *Journal of Materials Chemistry A*.
[48] PPT2, slide 48.
[49] PPT2, slide 49.
[50] PPT2, slide 50.

but extraordinary things Nature can do. For example, Nature can grow houses,[51] create stunning color,[52] withstand hurricanes,[53]

stick without glue,[54] stop bullets,[55] stay clean without chemicals,[56]

generate electricity without pollution,[57] grow food without poisoning water or soil,[58] clean contaminated water,[59]



[51] PPT2, slide 51.
[52] PPT2, slide 52.
[53] PPT2, slide 53.
[54] PPT2, slide 54.
[55] PPT2, slide 55.
[56] PPT2, slide 56.
[57] PPT2, slide 57.
[58] PPT2, slide 58.
[59] PPT2, slide 59.

capture carbon dioxide,[60] decompose when done,[61] and turn back into itself forever.[62] That's a pretty impressive resume. These are all things humans would dearly love to be able to do as well. And the point is, there is no reason we can't, because Nature's example tells us it's possible.

Once we can see the rest of the natural world for everything it is – not only something beautiful, and interesting to learn about, but as a *technological* guide – then we can begin to emulate its successful designs in our own engineering practice, and develop a world we can all thrive in.[63]

And that's the focus of this course: how engineers and designers and inventors of all kinds look to the natural world for innovative ideas, and, how to invent new technological ideas ourselves with Nature's help. In this class, every student will be developing his or her own technological concepts inspired by models in the natural world.

To wrap up, guide the class in a discussion, first by asking if there are any questions about what you've talked about. Are any of the students aware of existing technologies that were inspired by Nature? Airplanes and Velcro are probably the most well-known of these – see below for more background information on these. Also discuss the various terms that refer to innovation inspired by Nature: biomimetics, bio-inspired, biomimicry, etc. Make sure students understand that, though the use of these terms sometimes differs depending on the context, they all are essentially synonyms and mean innovation inspired by Nature.

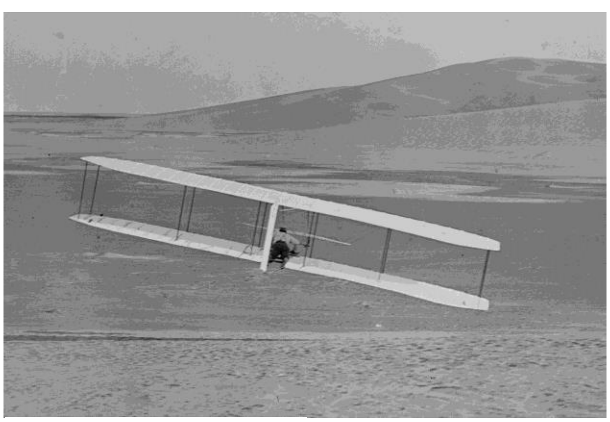
[60] PPT2, slide 60.
[61] PPT2, slide 61.
[62] PPT2, slide 62.
[63] PPT2, slide 63.

Airplanes and Velcro

Two of the most well-known bio-inspired technologies are airplanes and Velcro, although many people do not know the basic stories about how these technologies were developed, or are aware these technologies were fundamentally inspired by Nature in the first place.

The concept of a hook-and-loop fastener was invented by a Swiss electrical engineer named George de Mestral, in 1941. Mestral came up with idea after going on a two week hunting trip with his dog. While removing the many seeds stuck perniciously to his dog's fur, he became curious how they worked. Looking at one of these burdock seeds more closely, he saw that the seed coat was covered in dozens of projections that ended in tiny hooks which snagged the fur of his dog. Mestrel realized such a design would make a novel fastener, if he could only mimic the hook-and-loop principle. First used by astronauts to get in and out of spacesuits, and store food pouches on spaceship walls, Velcro went on to become a much more broadly applied invention generating millions of dollars. Mestrel once said, "If any of your employees ask for a two-week holiday to go hunting, say yes."

For over a thousand years of recorded history, birds spawned in humans the aspiration to fly. For centuries, people tried to accomplish this feat by flapping wing-like appendages strapped to their bodies, inevitably falling to their death or suffering serious injuries. Then, starting around 1799, an Englishman named George Cayley began to document his observations of bird flight and to develop a theoretical framework of flight that underlies modern human aviation today. Drawing from Cayley's theories and their own observations of bird flight, Wilbur and Orville Wright developed the first successful engine-powered fixed wing airplane in the early 1900s, establishing human aviation technology.



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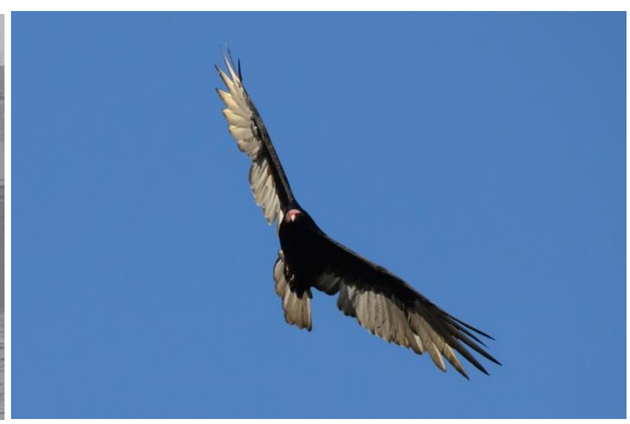


DON ENDICOTT

Wilbur Wright flying in a the glider he and his brother Orville designed, October 24, 1902. Wilbur is able to make a controlled turn utilizing "wing warping", the origin of modern-day ailerons that allow today's airplanes to bank. The wing warping concept was a key breakthrough enabling the Wright brothers success, and occurred to the Wrights after observing the behavior first in turkey vultures (*Cathartes aura).*

What Do You Call Innovation Inspired by Nature?

Many different terms are used to refer to innovation inspired by Nature today. Which terms should you use? This short discussion may help you decide.

Innovation inspired by Nature is known by at least three common terms: bio-inspired (sometimes biologically inspired, bio inspired, bioinspired), biomimetic, and biomimicry. A recent search for each term on Google and Google Scholar produced the following number of results per term:

Term	**Number of search results produced (Google/Google Scholar)**
Bio-inspired	16,000,000/500,000
Biomimetic	1,750,000/227,000
Biomimicry	640,000/ 12,800

Biomimetic is probably more commonly used in Europe, bio-inspired more common in the United States. Biomimicry tends to be more common in discussions of sustainable technology. Biomimesis and bionic are also sometimes used, particularly in Europe. But all of these terms refer to innovation inspired by Nature.

Which term you decide to use is naturally up to you, but it's good for students to understand the breadth of terms and their largely equivalent meaning. For doing research, it's essential to be familiar with all of these terms.

"Bio-inspired" is used most frequently in this curriculum, because it is the most self-evident term using the plainest language, assumes the least amount of prior familiarity with terms to understand its meaning, and appears most commonly used in general searches and academia.

More Resources:

White beetle: http://sciencenetlinks.com/science-news/science-updates/ultra-white-beetle/

Tumbleweeds and tumbleweed inspired innovation:

https://www.youtube.com/watch?v=didO-DHpnAE

https://www.youtube.com/watch?v=rNVcSIZyBuE

Frank Vassen

Giant leaf-tailed gecko, Madagascar.

Geckos use the enormous surface area of their nanoscopically-textured feet to fuse temporarily with the atoms of the surface they're walking on.

Climbing a glass building using gecko-based adhesion

Eric Eason, Biomimetic and Dexterous Manipulation Lab

Biomimicry is a powerful approach to innovation, because it is based on a very accomplished world.

7. BRAINY CORAL

More and more one comes to see that it is the everyday things which are interesting, important and intellectually difficult… the materials which we use for everyday purposes influence our whole culture, economy and politics far more deeply than we are inclined to admit; this is, indeed, recognized by the archaeologists when they talk about the 'stone age', the 'bronze age' and the 'iron age'.

James Gordon

Summary: In this hands-on, inquiry-based chemistry lesson plan, students create the raw material for cement out of seawater and car exhaust, mimicking a physiological process used by corals that is inspiring more sustainable concrete manufacturing in the real world.

Quote from New Science of Strong Materials, p. 254. Coral image by Malcolm Browne.

Main ideas: The goal of this activity is threefold: to provide students with a different perspective on chemistry and manufacturing than normally conveyed through conventional chemistry lessons; to encourage students to think critically about the relationship between humans, technology, and the environment; and, to provide students with a hopeful approach to creating chemical and manufacturing processes with a net neutral or positive impact upon our world, by drawing inspiration from chemical processes in the rest of Nature.

Introduction for teachers:

The last several lesson plans have covered the structure, function, and design of materials. This lesson plan explores how we acquire these materials in the first place, and what we can learn from the rest of the natural world to extract materials for manufacturing in a more benign and even environmentally beneficial way.

> **Chemical engineering** is a branch of engineering that applies the natural (or experimental) sciences (e.g. chemistry and physics) and life sciences (e.g. biology, microbiology and biochemistry) together with mathematics and economics to produce, transform, transport, and properly use chemicals, materials and energy. It essentially deals with the engineering of chemicals, energy and the processes that create and/or convert them. Modern chemical engineers are concerned with processes that convert raw-materials or (cheap) chemicals into more useful or valuable forms. In addition, they are also concerned with pioneering valuable materials and related techniques – which are often essential to related fields such as nanotechnology, fuel cells and bioengineering.
>
> *Source: Wikipedia*

Generally, we think of there being two categories of sources for materials: virgin and recycled. This dichotomy presents a limited future from the standpoint of sustainability, because with limited recycling and a large and growing human population, the destructive impact of harvesting virgin resources seems inescapable. Humans extract hundreds of billions of tons of rocks and minerals from the Earth's crust every year, farm the majority of the world's arable land, and have already harvested most of the readily accessible petroleum and more than half of the world's rainforests. We are mining our way into a transformed planet and future of narrowed options. Is there a way to envision escaping the downward spiral of resource extraction and environmental degradation? Is there another way to think of sourcing raw material for manufacturing? There is, and it comes from looking at how other species on Earth acquire raw materials for manufacturing.

We think of humans as being the only species on Earth that manufacturers materials, but in fact we are not unique in that regard: every species makes materials. From the wood of trees to the chitin of lobster claws and silk of spiders, Nature is a prolific manufacturer of an enormous variety of materials. In fact, the rest of Nature marshals larger amounts of raw materials that even we do, producing biologically manufactured materials far exceeding the entire input of resources into human industry worldwide. From this perspective, raw material extraction is not inherently damaging to the Earth. In fact, it is precisely *because* the rest of Nature is so industrious, so prodigiously extracts and processes resources into biological materials, that our world appears as abundantly productive and habitable as it does.

Engineering inspired by Nature seeks to emulate the processes which allow Nature to simultaneously make prodigious extraction and sustainable productivity possible. In Engineering inspired by Nature, there emerges an unexpected and exciting third category of raw materials. This source of raw materials suggests a way in which we might break free of the constraints of the conventional dichotomy of virgin and recycled materials, and build a more sustainable and abundant future for all people. Exploring this completely unexpected third source of raw materials is the subject of this lesson.

Processing raw materials for manufacturing is both a physical and chemical process. The way students presently explore chemistry tends to reinforce unsustainable manufacturing models: school chemistry labs regularly begin with materials mined from the earth and mixtures of hazardous chemicals, processed by Bunsen burners to facilitate reactions (i.e., fossil fuels), the products of which are vented into the air, dumped in the garbage, or poured down the drain at the end of each class. The underlying message of these types of labs may be a faithful microcosm of real world manufacturing, but, they in no way suggest a way towards a sustainable future.

Consider one material, and the focus of this lesson plan: cement. The way we manufacture cement is to mine calcium carbonate from the Earth's crust and cook the limestone at 2642° Fahrenheit (1400° Celsius) using fossil fuels; the process removes 39 billion tons of rock per year from open pit mines, the cooking puts 6% of our annual carbon emissions into the atmosphere. We are not the only species to make cement, however. Stony corals (Scleractinia) have been making the exact same substance – calcium carbonate – for millions of years. In the wake of their manufacturing efforts we do not have a scarred planetary surface and a destabilized climate. On the contrary, in the process of building their calcium carbonate exoskeletons, stony corals create one of the most biodiverse habitats on Earth and lock-up what otherwise would be billions of tons of atmospheric carbon.

What is the secret to the coral's manufacturing process that leads to such counter-intuitive results? A key to corals' success is the way in which they extract and process the raw materials for their calcium carbonate tissues. Instead of bulk mining limestone from the Earth's crust, corals pull calcium and carbon and oxygen atoms out of the surrounding seawater. And instead of combining these ions through bulk heating, corals create the chemical conditions in which calcium carbonate molecules assemble themselves, at ambient ocean temperatures: no quarries or greenhouse gas emissions required.

Several companies[1] have taken inspiration from corals and other organisms to create manufacturing processes that seem to do the impossible, creating cement out of carbon dioxide emitted from coal-fired power plants, for example, or plastics from thin air. Just like the organisms they emulate, these companies are demonstrating that a whole new way of creating materials is possible, and that we are not locked into a downward spiral of resource scarcity and environmental

[1] See for example, Calera (www.calera.com) or Newlight Technologies (www.newlight.com).

degradation. Industry that emulates Nature's dominant manufacturing paradigm can truly improve the environment from which it borrows, while generating ample productivity.

In this science lesson plan for upper elementary to high school students, students mimic an example of Nature's sustainable chemical processes by creating cement out of a waste substance (car exhaust) and seawater. In the process, students experience first-hand a cutting-edge manufacturing technology with the promise of transforming conventional concrete manufacturing into a more sustainable industry, and learn that the prevailing manufacturing model on planet Earth, practiced by millions of other species, is actually one in which raw materials for manufacturing are acquired benignly from the environment. Moreover, students learn that there is a universe of biological models around us to serve as inspiration for sustainable chemical methods and other kinds of innovation. The lab is safe, meets national and state educational standards, can be conducted within one-to-two 50 minute periods without specialized scientific knowledge or equipment, and uses inexpensive, readily available materials.

Concepts/skills covered:

1. Convey to students that manufacturing and consumption do not necessitate harm to the environment, and in fact, such a consequence is an anomaly in the living world. The prevailing manufacturing model on planet Earth, practiced by millions of species, is actually one in which raw materials are acquired benignly from the environment.
2. Demonstrate through a hands-on activity that, by emulating manufacturing processes widespread in the rest of the natural world, humans can transform their production methods to be more benign, and even beneficial to the environment of which humans are part.
3. Impart critical thinking skills about the environmental impact of human technology.
4. Impart to students skills in discovering means of improving technology by drawing inspiration from natural models.
5. Illustrate that chemistry relates to topics of interest to students, including biology and sustainable technology.

What you need:

- A piece of wood, preferably something that hasn't been milled, so that you can still readily tell that it's part of a tree.
- Cup of water
- Sea shell of any kind
- A source of carbon dioxide, ideally collected from a waste stream such as car exhaust (~15% CO2; see procedure below). An alternative source of carbon dioxide is dry ice (100%

CO_2). Many grocery stores carry dry ice. Cost: $3.00 (enough for 5 groups of 4 students each). Carbon dioxide can also be collected from exhaled air (~5%). Uncollected ambient carbon dioxide in the atmosphere can also be used (~0.04%).

- A source of seawater or seawater analog. Actual seawater can be used, if available. Alternatively, a seawater mix found at any pet store for aquariums can be used. Cost: ~$4.00 (enough for 5 groups of 4 students each). A solution of calcium chloride will also work well.
- Aquarium bubbler (optional but recommended), which can be found at any pet store for aquariums. Cost: ~$.57 each (http://gobstock.com/_015561109659-Hagen-Aqua-Fizzzz-Air-Stone-Round-1); total $3.00.
- A source of sodium hydroxide (NaOH), such as household 100% lye drain opener, which can be found in grocery or hardware stores. Cost: ~ $4.00 (enough for 5 groups of 4 students each). Must be clear and non-viscous.
- Glass containers, rubber tubing, and connectors (see procedure below). These can be chemistry lab grade or recycled glass food jars. Rubber tubing can be found at any chemistry supply outlet (e.g., http://www.hometrainingtools.com/glass-rubber-tubing/c/130/). Tubing cost: ~$1.30 for 2 feet (enough for 2 groups of 4 students each); total $4.00
- Filter paper, which can be ordered on-line (e.g., at Amazon.com). Cost: ~ $1.99 (enough for 5 groups of 4 students each).
- Small bag of cement (e.g., Quikrete). Cost ~ $8.00 (enough for 5 groups of 4 students each).
- Vinegar (optional). Cost: ~$3.00 (enough for 5 groups of 4 students each).
- Red cabbage (optional). Cost: ~1.00 (enough for 5 groups of 4 students each).

Safety: Dry ice and cement should be handled with a skin-barrier (e.g., gloves). Sodium hydroxide is caustic; avoid skin or eye contact or inhaling vapors.

Time required: 1-2 class periods (e.g., 50-100 minutes)

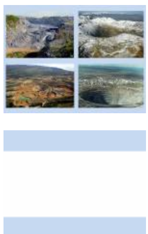
Teaching approach: Lecture, discussion, hands-on activity, slide presentation

Narrative:

Engage your students interest by asking them a series of questions that will also serve to contextualize the lab activity:[2]

[2] There are many ways to engage students and contextualize this lesson, other than what is presented here. The essential element is to get students to think about how humans acquire most of their raw materials (through

Teacher says: Who can tell me where the metal from this ruler comes from? How about the plastic used in your chairs? How about the material in this chalk? *(You can also use the photographs you took of the object deconstruction activity in Lesson Plan 1).*



It seems like almost everything humans make starts with material dug out of the ground. Do you think there are any problems that might come from digging things out of the ground? Have any of you seen a mine?[3] In the upper left that's a quartzite sand mine in Wisconsin, used for making glass; in the upper right is a copper mine in Utah; in the lower left a gold mine in the middle of the Peruvian Amazon; and in the lower right another copper mine, in South Africa. That's just four, but there are nearly three thousand large scale mines in operation around the world today.[4]

Is there another way we can make things that does not require us to dig materials out of the Earth? *Recycling may come up, to which you can appropriately respond, yes, that is one important approach. But your focus today is the original material, before it gets recycled.*

Let's explore potential answers to this question. We've talked a lot about wood. Who can tell me where this wood comes from? *Hold up a large chunk of wood; convey its solidity by tapping it on a table*. Where do you think the tree gets the material that makes up this wood? *Some students may answer that it comes from materials that come out of the ground. You can ask them the follow-up question:* How come there isn't a sunken pit around each tree, as so much material is pulled out of the dirt and put into the tree? *Give students a chance to come to the conclusion that the tree's bulk must come from somewhere else other than the soil.*

Explain that trees do pull a very small amount of essential nutrients out of the soil,[5] but this makes up very little of the physical material or weight of the tree. So where does most of the bulk come from? *Some students may propose water (e.g., from rain); explain that living trees do contain a great deal of water, but that the chunk of wood you are holding is mostly dry. Give students a chance to guess the air. Explain that yes, it seems surprising, but much of the bulk of a tree comes from air,[6] specifically, from the element carbon, from the atmospheric compound carbon dioxide, which animals and fungi exhale, and plants take up. Explain that they all are familiar with carbon – it is what remains after you make a fire for example. You might show a piece of charcoal at this point.*

Here is a very solid and useful thing, wood, and trees manufacture it without practically any material out of the soil. Instead, the raw materials or building blocks for making wood come

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environmentally destructive means) in contrast to how many other species acquire theirs. The lesson is organized according to the 5E Instructional Model (Bybee et al. 1989).

[3] PPT7, slide 1.

[4] PPT7, slide 2. Katja Freitag, Operations Manager at www.EduMine.com, personal communication.

[5] Less than 5%, composed of minerals and nitrogen. The nitrogen is essential for proteins, which the tree depends on soil organisms to get out of the air and into a form the tree can use.

[6] Flemish physician and chemist Johann van Helmont conducted an interesting experiment in the 1600s that demonstrated that much of the bulk of trees come from air (e.g., see Hershey 2003).

primarily from a gas (carbon dioxide out of the air) and from a liquid (rain). In other words, Nature can make things – big, hard, useful things – without mining, without degrading or destroying the surface of the Earth. In fact, when Nature makes trees, it *creates* habitat for other species. In other words, Nature's factory, running all day and night, is actually good for the environment. *Repeat the question:* So do you think there is another way *we* can make things that does not require us to dig materials out of the ground and damage the Earth's surface?

Well, it certainly must be possible, right? Because other species around us are doing it all the time. If they can do it, it must be *possible*. Right? If they can do it, it must be possible. *Let this sink in.* The challenge for us is to figure out *how* other species accomplish these impressive things, and to explore how we might copy or emulate the key aspects of their processes to innovate our own ways of doing things.

Hold up a bag of cement. Does anyone know what this is? It is cement, and we make it to use in concrete. *Pour or spoon some out into a clear plastic cup, so students can see it is a powder.* What kinds of things do we use concrete for? *Give students time to come up with things like skyscrapers, sidewalks, bridges, etc.* That's right: we use it for all sorts of things, and we use a lot of it. Concrete is one of the most widely used materials manufactured by people.[7] Its main component is a molecule called calcium carbonate, which can be represented as "$CaCO_3$," (*write it on the board*) meaning a compound of calcium carbonate contains one atom of the element calcium (an element found in our bones and teeth), one atom of carbon, and three atoms of oxygen. Does anyone know where we get the calcium carbonate we use in concrete? Well, lots of organisms make calcium carbonate, especially aquatic organisms, for example plankton, mollusks (clams, etc.), and corals. When these organisms die, over thousands of years their hard calcium carbonate shells and skeletons pile up and form large solid deposits in the earth's crust.[8] To make the cement that goes into concrete, humans dig up these deposits, creating open-pit mines or quarries.[9,10]

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[7] PPT7, slide 3.

[8] PPT7, slide 4.

[9] PPT7, slide 5. Approximately 13 billion metric tons of limestone are quarried out of the Earth's crust every year (http://geology.com/usgs/limestone/).

[10] The material is then heated to approximately 2642 degrees Fahrenheit (1400 degrees Celsius), which results in approximately 6% of humanity's annual greenhouse gas emissions. The heating changes the crystalline structure of deposited calcium carbonate (i.e., calcite or limestone) to a reactive form (e.g., vaterite), so that when water is added to it, a chemical reaction occurs that makes the calcium carbonate harden again. This allows concrete to be formed into a wide variety of desired shapes. In this particular lesson plan, less emphasis is placed on the polluting aspects of conventional concrete manufacturing, to focus instead on how we can learn from other organisms (in this case, corals) processes of acquiring raw materials without damaging the surface of the Earth. However, the opportunity also exists to contrast non-target manufacturing outputs (net increase of CO_2 in the case of humans, net decrease in the case of corals), as well as the fact that non-human manufacturing processes characteristically

Do you think there might be another way to make concrete that does not cause so much damage to the surface of the Earth? *Give students some time to consider this*. Well, are there other organisms on this planet that make cement, or a cement-like material? *Give students some time to consider this*. What about corals? How do organisms like corals make *their* calcium carbonate? I mean, humans are just digging up the calcium carbonate made by other species, but how do these other species create these materials for themselves? It turns out corals use a different process that does not require digging open-pit mines. Instead, corals acquire calcium, carbon, and oxygen atoms out of seawater. Seawater has a lot of calcium in it, and the carbon and oxygen atoms come from carbon dioxide from the atmosphere, which get absorbed into the seawater. Corals put these atoms together next to their bodies to create a protective outer skeleton.

It's sort of a magical thing. *Place a glass of water on the table.* Do you think you could make something hard and solid come out of *water*? *Place a marine shell in the water.* Organisms like mollusks and corals do it every day, all day long. And, in the process, organisms like corals make a fantastic habitat that other species thrive in: the coral reef.[11]

What if people could make calcium carbonate like corals do, instead of digging it up? What if we learned how to copy this special power corals have? That would be pretty neat, wouldn't it? Well, what would we need in order to copy what corals do? What do corals use to make calcium carbonate? *Give the students time to think this out. Then point at the "CaCO3" on the board.*

The next part requires basic ad-lib coaching to get the students to come up with the answers themselves. OK, so we need a calcium source, a carbon source, and an oxygen source, right? Where can we get our calcium from? Do you think we could get it from the same place corals get it from – the sea? Ok, and what about our carbon and oxygen source? Where do corals get their carbon and oxygen from? Carbon dioxide from the atmosphere, right. And if we want a lot of carbon dioxide, where else might we get carbon dioxide from? What are some other sources of carbon dioxide? What about, say, car exhaust?

Activity:

*The following lab elaborates on the previous discussion through a hands-on activity (**Fig. 1**). You may want to describe the reaction formula and the role of pH in the process corals use.[12] Consider coaching students to come up with a way to manipulate pH themselves, before suggesting a NaOH source. The lab involves the following four reactions: First, bubbling carbon dioxide through water causes the*

occur at ambient temperatures, in contrast to most human manufacturing processes, which often rely on raising heat (or pressure) above ambient conditions (generally by using fossil fuels).

[11] PPT7, slide 6.

[12] For reference, the reaction formula of the lab activity is as follows: CO2 + H2O --> H2CO3; add the base: H2CO3 + NaOH --> NaHCO3 + H2O; and NaHCO3 + NaOH --> Na2CO3 + H2O. This step needs to occur to allow: Na2CO3 + CaCl2 --> CaCO3 + 2NaCl.

formation of carbonic acid: $CO_2 + H_2O \rightarrow H_2CO_3$. Second, the addition of the base causes the formation of sodium hydrogen carbonate: $H_2CO_3 + NaOH \rightarrow NaHCO_3 + H_2O$. Third, the addition of even more base results in the formation of sodium carbonate: $NaHCO_3 + NaOH \rightarrow Na_2CO_3 + H_2O$. Finally, the sodium carbonate reacts with the aqueous calcium chloride (seawater) to form the calcium carbonate that will be used in the production of cement for concrete: $Na_2CO_3 + CaCl_2 \rightarrow CaCO_3 + 2NaCl$.

Dry ice is the simplest source of carbon and oxygen, but a preferred source from a pedagogical perspective is to take students outside and collect the carbon dioxide gas products from a car exhaust pipe. This better emphasizes the promising sequestration of waste carbon products in this technology. Car exhaust should be collected from a car that has recently been turned on (before heat builds up in the exhaust pipe), using a mylar balloon (latex is semi-permeable) attached to the pipe through a funnel or plastic bottle sawn in half, all connected together by O-clamps and duct tape. Two or three minutes are adequate to obtain enough gas in the balloon. If students are to run the lab themselves (next step), collect car exhaust in several mylar balloons.

Fig. 1. The lab set-up mimicking how corals make calcium carbonate, using household equipment and readily obtainable materials. Dry ice in the plastic bottle supplies carbon dioxide through the straw into the glass jar of ocean water surrogate bought from a pet store. Clear sodium hydroxide (e.g., Liquid Plumber) raises the pH of the solution and speeds the formation of calcium carbonate (white cloudy material).

Back in the classroom, you have the option of demonstrating the lab for the class, or having them perform it themselves. To have the students do the lab themselves, form them into small groups (2-4 people) and explain the procedure to them, the materials involved, and safety considerations. Assign tasks to different students within each group, so each child has a tangible role to play in the process.

Use seawater or create a seawater analog mix, either from a seawater mix from a pet store, or by providing students with a pre-mixed solution, or having them create a solution of 0.1 M $CaCl_2$ *(i.e. 1.47 g in 100 ml). Encourage students to explain what role the seawater or seawater analog plays in the final product, i.e., that the solution is like the seawater that corals use, and contains calcium atoms that will become part of the calcium carbonate compound they are creating.*

Prepare a 1M solution of NaOH (i.e. 3.99 g in 100 ml). Household lye can serve as a source of NaOH (if clear and non-viscous). Students should wear goggles and gloves when handling this material. Explain to students that corals get calcium to bind with carbon and oxygen by controlling the solution in which the atoms are placed, increasing the concentration of some atoms and reducing the concentration of others using special biological pumps. The sodium hydroxide acts to help do this without the special pumps used by corals.[13]

Attach the mylar balloon full of car exhaust to tubing using duct tape. Or, if using dry ice, place a piece of dry ice in a glass jar or side arm flask with gloves and enclose with a screw-top lid or stopper through which the tubing passes.[14]

Attach aquarium bubbler to the other end of the tubing.[15]

Add several drops of the NaOH solution to the seawater solution. While precipitate forms, continue adding NaOH as desired or needed.[16] *A pH of around 9 will produce the best results.*

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[13] In corals, calcium carbonate formation occurs in a space between the coral's soft tissue and its existing exoskeleton. CaCO3 formation also occurs in oceans without corals, but slowly. Corals speed up the process 100x. They do this by actively increasing the concentration of calcium ions and CO2, and removing hydrogen ions from the solution (using ion pumps). The increase in pH results in a supersaturated solution in which calcium and carbonate react and precipitate rapidly, forming calcium carbonate (Cohen and Mcconnaughey 2003). Here, in place of a biological ion pump, NaOH functions to raise the pH of the solution and facilitate precipitation.

[14] A reused glass jar with a screw-top lid works well. Simply drill an appropriately sized hole in the lid for the tubing.

[15] The bubbler, though not essential, reduces the size of the carbon dioxide bubbles to increase the effective surface area and increase the product. It also produces a vibrant sound in what otherwise would be a silent reaction.

[16] Corals raise the pH of the solution in which precipitation of CaCO3 occurs above ambient ocean pH, to around 9. Precipitation will occur rapidly with any increase in pH, so precise pH control or measurement is not necessary. However, as an option, students can monitor the pH of the solution using a pH Electrode or pH paper, and attempt to keep the pH at around 9. Low-cost pH paper can be created by pouring boiling water over chopped red cabbage, letting it sit for 30 minutes then either using the pigmented water directly or running the cabbage and water through a blender to extract more pigment followed by straining the fluid. The resulting solution is used to

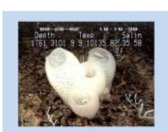
Insert bubbler into the container of seawater solution. If using car exhaust, exert gentle pressure to the mylar balloon. White, cloudy precipitate should form immediately, falling slowly to the bottom of the container. To produce enough precipitate, run the reaction for at least 3-5 minutes (longer with car exhaust).

Remove the tubing from the seawater solution and let the solution sit for a few minutes. You will see the solution clearing up at the top as the precipitate falls to the bottom. Have students write their *initials on the filter paper, and then slowly pour the solution through the filter paper to collect the precipitate.*[17]

Debrief the lab activity with the students. Emphasize to the students that they just made the starter material for making cement, which is normally mined out of the Earth's crust, but they did it with some car exhaust, seawater, and Liquid Plumber! The idea for the chemical process came straight from corals.

Students take turns reading aloud: People have made cement this way now on a large scale.[18] One approach scientists and chemical engineers have used is to take the carbon dioxide not from tailpipes, but from smoke stacks from coal-fired power plants, bubbling the gas through seawater, which contains the calcium atoms. The process removes the carbon dioxide from smoke stacks – before it gets into the atmosphere – adds calcium from seawater, and down comes powdered cement, tons of it, without making any more open-pit mines or quarries. That's essentially what you all just did in this lab.

So cement is one of the materials humans manufacture a lot of. What other large, solid materials do we make? *Let students come up with a list. It's surprisingly short: glass, plastic, metals, ceramics, and not much else.*



It turns out we are not the only organisms to be making these materials. This, for instance, is a marine sponge, called the Venus flower basket.[19] It's body is made of glass. Whereas we mine quartzite sand from the Earth's surface and cook it at 2,732° Fahrenheit (1,500° Celsius), the Venus flower basket extracts silica and oxygen ions out of seawater, precipitating glass at ambient ocean temperatures, no mining or fossil fuels required.

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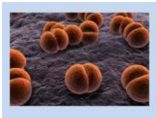
saturate filter paper strips that are allowed to dry. The pH of the now light blue paper will be around 7 (depending on the pH of the boiled water used), and will turn greenish-yellow as pH increases (see http://www.erowid.org/archive/rhodium/chemistry/equipment/ph-indicator.html)

[17] Filtration by gravity works fine. Placing the filter paper in a *büchner* funnel using a vacuum filtration system will also work.

[18] PPT7, slide 7. See www.calera.com

[19] PPT7, slide 8; see e.g., Kröger et al. 2002.



This is the bacteria *Neisseria meningitides*.[20] It is an expert at extracting iron from blood hemoglobin, which it does using specialized proteins. We mine iron of course in order to make steel, not with proteins but with dynamite and bulldozers. A company that mimicked Neisseria's proteins has been able to extract commercial quantities of various metals out of mine tailing waste water, no additional mining required.

And this of course is what we use to make plastic,[21] well, what's under this: hydrocarbons or oil, the mining for which turns places like this, into this.[22]

Trees also make a plastic-like material, cellulose, but they get the carbon for making these long molecular chains of carbon not from mining the Earth, but out of the air.

The result, in addition to removing carbon dioxide and stabilizing the Earth's climate, looks like this.[23]

A company inspired by trees' ability to make plastic-like molecules out of atmospheric carbon dioxide is now able to make biodegradable plastics, like these items you see here, without a drop of oil.[24] Instead, their plastics are made of 100% greenhouse gases, rendered inert and harmless in these useful items.

*Place the filter paper on a window ledge to dry overnight, or place in a drying oven (if available) for approximately 20 minutes. Once dry, allow students to rub the powdered calcium carbonate between their fingers. The product may contain other compounds in addition to CaCO3, depending especially on the seawater mixture. X-ray crystallography analysis of product created with this lab procedure using dry ice and a calcium chloride solution yielded 100% CaCO3 (**Fig. 2**).*

[20] PPT7, slide 9; see e.g., DeVoe et al. 1991. The company was called MR3 Systems.

[21] PPT7, slide 10.

[22] PPT7, slide 11.

[23] PPT7, slide 12.

[24] PPT7, slide 13; see e.g., Greenemeier 2007. The company is Newlight Technologies.

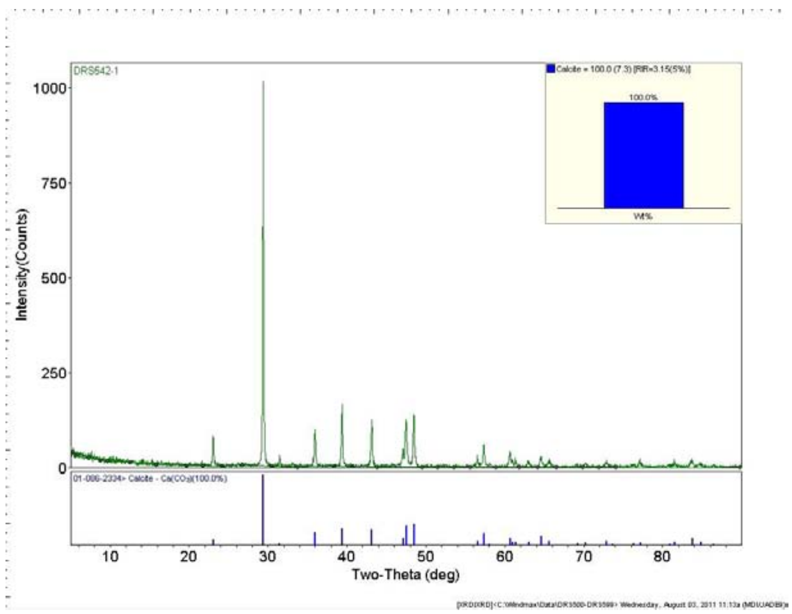


Fig. 2. X-ray diffraction analysis of the material created in this lab: 100% calcite (a form of calcium carbonate). Analysis and image complements of Calera.

(Optional) Place a few drops of vinegar on the precipitate to help illustrate to students the presence of carbon dioxide, once sequestered in the calcium carbonate, and now returning to the atmosphere.

Evaluation:

In order to evaluate the effectiveness of the lesson, the following questions are suggested:

1. How would you describe what you learned from this activity?
2. Because the Earth's natural resources are limited, how would you describe what will happen as humans continue to consume them?
3. What is an important difference between how humans typically acquire raw materials for cement manufacturing, and how corals do it, explored in this activity?
4. What other materials do humans make and how do we make them? Give at least one example. What impact on the environment does each process have?
5. For each material you mentioned in #4, try to identify an organism that makes a similar material. What impact on the environment does each organism's process have?

Extensions:

Select a material manufactured both by humans and other organisms, and prepare a 3-5 page research report with bibliography answering the following questions:

1. What is the material and what is the human process for its manufacture? Note especially how the raw material is acquired, the type and amount of energy required in the manufacturing process, hazardous chemicals used or produced (e.g., as by-products) in the manufacturing process, and any environmental issues related to the material's use and disposal. Quantify the information as much as possible.
2. Which other organisms produce the material, what is their process for the material's assembly? Note especially how the raw material is acquired, the type and amount of energy required in the manufacturing process, hazardous chemicals used or produced (e.g., as by-products) in the manufacturing process, and any environmental issues related to the material's use and disposal. Quantify the information as much as possible.
3. Have people investigated the way other organisms produce the material? Describe the mechanism(s) in detail. Have people attempted to emulate the way other organisms produce the material? Describe the process and status of these attempts.
4. If you were going to emulate the way other organisms produce the material, how would you go about it? Break your thinking down and explain and justify each step.

Acknowledgements:

Many individuals and organizations enabled the continued development of this lesson plan. A special thank you to Dona Boggs for helping adapt the basic chemical process based on the 2003 paper by Cohen and McConnaughey, (see references), and Dave Jones of Big Sky High School for helping test the lab process. Thank you also to the Calera Corporation for their generous technical advice and lab analysis. Finally, thank you to coral, an organism among many that continues to show our species the path towards an enduring and thriving way of life.

Other Standards

This activity can be used to address chemistry education standards. The list below, which is not exhaustive, is drawn from the current version of Benchmarks for Science Literary (Standard D: The Structure of Matter), which incorporates standards also from Science for all Americans (1991), and the National Science Education Standards (1996).

High school

- Atoms often join with one another in various combinations in distinct molecules or in repeating three-dimensional crystal patterns.
- An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.
- The rate of reactions among atoms and molecules depends on how often they encounter one another, which is affected by the concentration, pressure, and temperature of the reacting materials.

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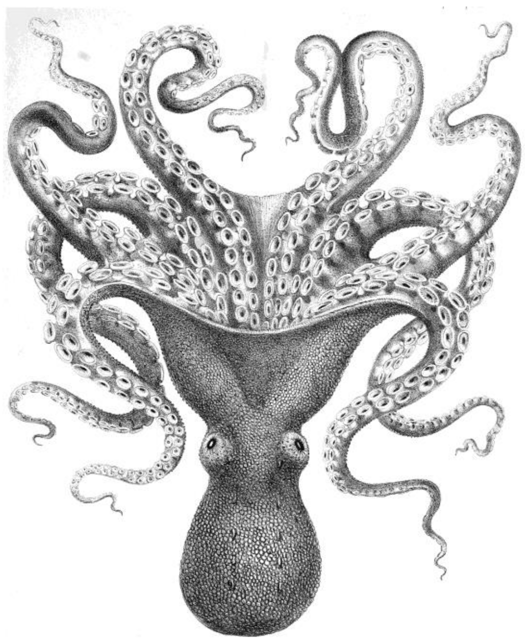
Octopus image by A. Pollock, 1886.




8. THE LARGESS OF LEAVES

Even after all this time
the sun never says to the earth,
"You owe me."
Look what happens with a love like that…

Hafiz (c. 1320-1389)

MIKE NORTON

Summary: In this lesson, you will be sharing inspiring biomimetic energy-related technologies with students, and guide students in making their own working leaf-inspired solar cell.

Main ideas: We power our technology (manufacturing, transportation, electrical, etc.) with polluting heat; the rest of Nature powers its technologies at ambient temperatures using a wide variety of non-polluting strategies. These clever approaches to using clean, enduring sources of energy can help us innovate ways in which we power our own technological activities for a better world.

Introduction for teachers: We live in a busy world. With the rest of the universe edging inexorably towards more and more chaos – entropy, in the parlance of physicists – our planet is quite improbably full of just the opposite: zebras, Norway maples, and amoebas. In short, shockingly organized things.

But it gets more amazing still, because of how Nature goes about making these things. Humans have also learned to fabricate all sorts of our own highly organized things – automobiles and computers and toaster ovens (even file cabinets and closet organizers, as though to flaunt our ability to organize amidst an entropic universe). But while we like the rest of Nature are enormously industrious in creating things, there are some differences as we've seen. For one, all the manufacturing we do is generally carried out by igniting fossil fuels, our energy of choice. As a limited source of energy whose by-products have become pollutants, it seems clear this is not a winning strategy.

So what is? Well, the rest of Nature's approach to doing work certainly should earn our attention. To begin with, its production facilities are in their straight 3.8 billionth year. And if GDP were our measure, well then, the natural world can't be beat for the amount of product that rolls off its assembly lines every day. But perhaps the most extraordinary thing of it all is that none of this abundance is powered by a whiff of gasoline, drop of petroleum, or chunk of coal. What ways Nature has found to power itself have never destabilized the climate, polluted water, soiled soil, or even so much as suffered a brownout. Though possibly the best argument of all for ruminating on how Nature captures and uses energy is the sheer creative genius displayed therein. Something which can fabricate a forest of 400-foot tall redwood trees all at ambient temperatures, powered with light from a star millions of miles distant, is something deserving of our careful consideration.

Indeed, some of the most hopeful new energy technologies today are inspired by the natural world around us: hydrogen power created by an "artificial leaf", for instance; highly efficient wind turbines inspired by the flippers of humpback whales; and leaf-inspired solar panels (the subject of the following lab) as well as many others. Slowly it seems we're catching on: a sustainable world can be just as productive and industrious as the current one, but like the rest of Nature, it must be powered by clean and enduring sources of energy.

Concepts/skills covered: This activity addresses the following key educational themes:

1) To provide students with a concrete example and hands-on activity illustrating a Nature-inspired technology highly relevant to today's technological challenges.
2) Students will understand differences between silicon-based and dye-sensitized solar cells.
3) Students will see first-hand how solar energy can be converted into electrical energy using solar cells.
4) Students will feel empowered to construct their own dye-sensitized cells out of basic materials.

What you need:

- Conductive (tin dioxide coated) transparent slide glass
- Colloidal titanium dioxide powder
- Iodide electrolyte solution
- Soft graphite pencil
- Binder clips
- Surfactant (e.g., clear dish detergent)
- Deionized water
- Ethanol
- Organic dye (e.g., blackberries, raspberries, green citrus leaves, fresh or frozen)
- Volt meter
- Hookup wires (black and red)
- Pipettes
- Mortar and pestle
- Transparent tape

Note: the first 5 items are included in a kit from the Institute for Chemical Education called "Nanocrystalline Solar Cell Kit" (Cost ~ $45.00): http://ice.chem.wisc.edu/Catalog/SciKits.html

Safety: Safety goggles and gloves should be worn when handling materials. Powdered titanium dioxide should be ground in a ventilated hood. Hands should be washed thoroughly after using TiO2.

Class preparation:

1. Order the nanocrystalline solar cell kit from the Institute for Chemical Education (http://ice.chem.wisc.edu/Catalog/SciKits.html).
2. Review how a dye sensitized solar cell works, e.g., at <http://community.nsee.us/concepts_apps/dssc/DSSC.html>
3. Prepare the titanium dioxide solution according to kit instructions.
4. Assemble the other materials for the lab.

Time required: Approximately two 50-minute sessions, longer if desired.[1]

Teaching approach: Guided discussion and lab.

Narrative:

So when we begin to think about the things engineers make as a process, that process begins with the physical material engineers use, material that can be acquired in environmentally destructive ways, or, as we've seen, by mimicking how the rest of Nature acquires raw materials, in ways that can be environmentally benign or even beneficial. Cement manufactured by mimicking coral's chemical processes, for example, doesn't require mining, doesn't emit greenhouse gases, and even

[1] The present lesson plan is based on two consecutive 50-minute classes. If these are to run on separate days, it is likely the lab portion will span across both hours.

more impressively, pull greenhouse gases *out* of the atmosphere and locks them up in the cement, just as do the corals that serve as a model for this chemical engineering innovation.[2]

If extracting raw material is the beginning of the manufacturing process, what do you think the next step is? That's right: processing those materials. Whether that means transforming calcium carbonate into cement, or quartzite sand into glass, or iron ore into steel, the processing of raw materials requires the use of energy. Changing a raw material's form into a processed material is work, and to do work, we need to use a form of energy. Humans use a lot of energy, generally fossil fuels, whether that's igniting gasoline for transportation, burning coal to generate electricity for running electrical devices, or combusting oil to drive the manufacturing of materials and products in factories.[3]

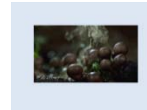
But remember, we aren't the only ones manufacturing stuff.[4] The rest of Nature processes more material than even we do, massively more, to fabricate everything from forests of 400-foot tree trunks, to billions of pounds of grass, bacteria, ants, and elephants.

Just one example of Nature's industriousness. Like humans, the rest of the natural world is constantly manufacturing massive amounts of material.
PUBLIC DOMAIN IMAGE

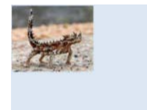
Just look outside: the trees, the grass, everything you see that Nature is manufacturing is not being made with fossil fuels, it's not being processed at high temperatures, it's being made at low temperatures, in fact it's being made without changing the temperature at all.[5] How does Nature do so much manufacturing at ambient temperatures? Because that's an extraordinary thing: Nature makes all this stuff without so much as lighting a match, without burning a drop of oil, without combusting a single hydrocarbon. Where does Nature get its energy from? And how does Nature run all this manufacturing without relying on energy that, like ours, causes pollution?

The general answer is that, instead of drilling through the Earth's crust and pumping billions of gallons of oil up and setting it on fire, Nature is expert at doing work with the energy resources immediately at hand. Let me show you some examples of what I mean.

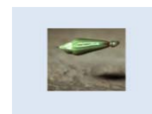
[2] With this lesson, you are well into the subject of the materials economy. For an entertaining overview, you might consider showing the 21-minute video, "The Story of Stuff" (https://www.youtube.com/watch?v=9GorqroigqM).
[3] LP8, slide 1.
[4] LP8, slide 2.
[5] If you can take students briefly outside to make this point, consider doing so.



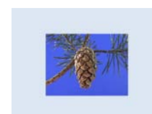
You may have seen this kind of fungi while walking around in the woods outside.[6] They're white or brown and usually the size of a golf ball. They get the energy to eject their spores from the rain; the impact of a droplet on their outer pliable membrane compresses their interior volume (like squeezing a water balloon), and the narrow aperture at their top accelerates the cloud of tiny particles skyward into the air, like water through a skinny hose.



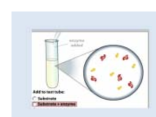
This is the thorny lizard.[7] It lives in the arid deserts of central Australia, where water is scarce. Fortunately, because of the structure of its skin, it can drink water simply by putting its foot in moist sand.[8] With red dye you see how the liquid spreads. Water rises through the lizard's skin against gravity and without a pump, because the hydrogen atoms in the polar water molecules are slightly attracted to the sides of the narrow channels between the scales of the lizard's skin.[9]



The seed pods of the Himalayan balsam plant build up energy as they ripen, increasing in tension as they mature until the slightest impact splits the pod along designed edges of weakness and the recoiling tissue shoots seeds up to 22 feet away.[10] Probably where this group of species got its name: *Impatiens*.



Or consider the pine cone.[11] These open without any electricity or motor. In fact, they'll open even if they are detached from a tree. How does this movement occur? Cleverly, the scales are not homogenous from one side to the other. They're designed so that their outside portion shrinks more on a dry, sunny day than their inside portion. So the scales are simply peeled away from the cone when the time is right to release seeds.



These are things we can see with our own eyes, if we're paying attention. But Nature accomplishes a great deal of work we generally can't see, inside our bodies. Just for you to be alive right now, each cell in your body must perform more than 10 million chemical reactions every second. In order for this extraordinary amount of work to happen so quickly, Nature employs one of its cleverest inventions, enzymes, little tools customized for each chemical reaction that select the desired reactants out of a soup of billions of other molecules, and physically joins or separates them.[12] The dynamic, 3-dimensional enzymes speed chemical reactions by millions of times per second, and reduce the total amount of energy required for chemical reactions to occur. Without them, your life, and life on Earth, would not be possible.

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[6] PPT8, slide 3.
[7] PPT8, slide 4.
[8] PPT8, slide 5.
[9] PPT8, slide 6. This is an animated image. Hover over slide to play.
[10] PPT8, slide 7. This is an animated image. Hover over slide to play.
[11] PPT8, slide 8. This is an animated image. Hover slide to play.
[12] PPT8, slide 9. This is an animated image. Hover slide to play.

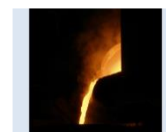
And finally, that Nature has figured out a way to use the light of a star 93 million miles away in order to fabricate things like this,[13]

and this,[14]

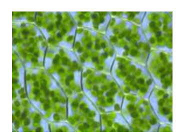
and this,[15]

is really hard to keep a grasp of. But there it is. You can make very substantial things from sunshine.

Photosynthesis is a very good example of how Nature has learned to do work with the energy resources readily available.[16] We have our own version of this, but it has a few obvious drawbacks.[17] For one, our solar panels are made of silicon, which we manufacture by mining and cooking the silicon dioxide to produce silicon purified to better conduct electrons. We purify the silicon using extreme heat generated from fossil fuels, so that a silicon solar panel spends the first 3 to 5 years of its life undoing the carbon dioxide put into the atmosphere just to manufacture it.[18]



This solar panel factory runs on the solar energy its panels generate, no fossil fuels required.[19] And its solar panels are not made of silicon, they are made of carbon from the atmosphere – the very pollutant we are trying to get rid of in the first place. Brilliantly, it uses this unwanted substance as its primary building material.

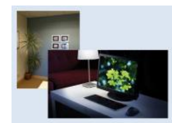


It turns out leaves have inspired a different kind of human-made solar panel, and we're going to make one in this class. Instead of capturing photons of light with silicon, these solar panels capture photons using dyes, just like the chloroplasts in leaves do, which you can see here.[20] In fact, they're called dye sensitized solar panels for this reason.

[13] PPT8, slide 10.
[14] PPT8, slide 11.
[15] PPT8, slide 12.
[16] PPT8, slide 13.
[17] PPT8, slide 14.
[18] PPT 18, slide 15. Less well known are the toxic chemicals resulting from the manufacture of silicon-based solar panels. E.g., see <http://www.solarindustrymag.com/issues/SI1309/FEAT_05_Hazardous_Materials_Used_In_Silicon_PV_Cell_Production_A_Primer.html>
[19] PPT8, slide 16.
[20] PPT8, slide 17.

Because they use dyes to capture photons instead of silicon, dye sensitized solar panels can be made using a wide variety of materials, even recycled plastic.[21] So they don't rely on purified silicon, and can start producing carbon dioxide-free electricity the day they're installed. Also, because they use dyes, they can be made to be semi-transparent or even transparent, so they can be integrated into architectural applications.[22]

This inventor mimicked English Ivy in another kind of architectural application of dye-sensitized solar panels. Like ivy, these can be placed just about anywhere to maximize solar collection.[23]



Another interesting feature of dye sensitized solar cells is that, like an office plant, they can operate with very low solar input. This solar powered wireless keyboard, for instance, runs off the light of the computer monitor.[24]

Today, you'll all be making your own dye-sensitized solar cell in class. This kind of solar cell was inspired by photosynthesis and simulates the process in a very abstract form.[25] In a leaf, photons strike a heavily folded structure called the thylakoid, which resides within chloroplast organelles inside the cells of a leaf. These structures contain chlorophyll, a pigment, and their folded structure gives them a very large surface area. The force of photons striking these structures release electrons from the chlorophyll, and start a chain reaction of work that alters chemicals sequentially and results in the fabrication of plant tissues and food. As we will see, dye-sensitized solar cells emulate key pieces of this solar energy architecture.

> "Our cell is different in the sense that it is close to what photosynthesis does in green leaves. The charges are generated by dye molecules and other constituents take care of the conduction. That separation was achieved for the first time by our cells – except for photosynthesis, which has been working for 3.5 billion years!"
>
> - Michael Grätzel

Activity procedure:

1. Form the students into small groups (2-4 people) and explain the procedure to them, the materials involved, and safety considerations. Assign tasks to different students within each group, so each child has a tangible role to play in the process.
2. Clean two glass conductive slides using ethanol.[26]

[21] PPT8, slide 18.
[22] PPT8, slide 19. This is an animated image. Hover slide to play.
[23] PPT8, slide 20.
[24] PPT8, slide 21.
[25] PPT8, slide 22.
[26] It would be interesting to do this lab using conducting plastic instead of glass. Conducting plastic, such as tin oxide coated plastic, is available. It might even be possible to learn how to make plastic conductive oneself, in which case one might be able to simply use locally-sourced recycled plastic.

3. Determine which side of the slides is conductive using the voltmeter (set to ohms).
4. Orient one glass slide conductive side up. Apply pieces of tape to the slide to mask the outer 1 mm edge of the slide with the tape. Apply a third piece of tape along the top of the slide to mask the outer 4-5 mm. The three pieces of tape should extend from the edge of the glass to the table to keep the slide stable.
5. Coat the glass uniformly with the TiO2 suspension so it is fully, evenly, but thinly coated, and allow it to dry. At this stage, point at that the titanium oxide suspension consists of nanoscopic particles of titanium dioxide. These particles conduct electricity, and their nanoscopic size was a major breakthrough in dye sensitized solar technology. Like the folded thylakoid in a chloroplast, the use of nanoscopic titanium dioxide particles creates a very large surface area for electrons to flow, greatly boosting the overall electrical output of the solar cell.
6. Place the slide TiO2 side down in a tray with the crushed blackberries, so that the slide becomes coated completely with the juice. The pigment from the blackberries serves to capture photons of light, much like the chlorophyll they simulate.
7. Allow the slide to air dry.[27]
8. Wash the slide in water, then ethanol, and gently blot dry.
9. Obtain another slide and apply a light carbon film to the entire conductive side of the slide (this can be done concurrently with step 6).
10. You are now ready to assemble the cell. Place the slide with TiO2 (face up) and place the other (graphite covered) slide on top of it, graphite surface down.
11. Offset the two slides so that the uncoated 4-5 mm strip of the TiO2 slide is exposed. Place two binder clips on the other edges to hold the slides together.
12. Place one or two drops of the iodide electrolyte solution at one edge of the slides and alternatively open and close each side of the cell by releasing the binder clips, so that the liquid is drawn into the space between the slides. The entire TiO2 surface should get covered. The electrolyte solute serves to re-supply electrons to the dye (crushed blackberries) as they conduct.
13. Clean and dry the unmasked surfaces of any electrolyte solution.
14. Fasten alligator clips to the two exposed sides of the cell and attach these to the wires of the voltmeter.
15. Bring the assembly outside on a sunny day and turn on the voltmeter.

Discussion questions

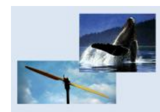
1. Were your surprised you could use blackberry juice to create a solar cell?
2. This assembly uses glass slides. Could you use an alternative material? What materials could you use and how might these improve the overall sustainability of the solar cell?
3. What is different about this way of creating solar energy from a silicon-base solar cell? What are the potential advantages of this approach?
4. What other challenges and opportunities can you discern with this technological set-up? How might the energy output or environmental performance of the dye sensitized solar cell be

[27] Many protocols will have students anneal the TiO2 to the slide using a heat source, e.g., a hotplate. However, we have found this step is unnecessary: the cell will work without annealing. We recommend removing the annealing step because it introduces potential confusion about using high temperatures in the dye sensitized solar cell process.

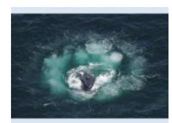
improved? If you were to try and generate design approaches to address these challenges and opportunities, what biological organisms might you turn to for ideas, and why?

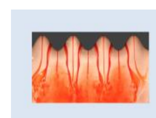
To wrap up, consider showing the students a few more slides of energy-related bio-inspired technologies.

Leaves have also inspired another major energy technology, which is the production of hydrogen, from which engines can be made to run automobiles, for instance, whose only by-product would be water vapor. In order to create hydrogen currently, we use fossil fuels to essentially cook water molecules into the constituent atomic parts. Leaves accomplish this however without any fossil fuels, using enzyme catalysts. Inspired by this process, scientists have recently developed catalysts that can do the same thing.[28] Drop the device in a glass of water in sunlight, and bubbles of hydrogen begin forming.

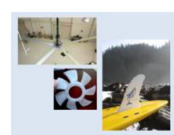


These wind turbine blades which mimic the shape of humpback whale flippers are 20% more efficient than conventional straight-edged wind turbine blades.[29] Now why would humpback whale flippers have anything to teach us about wind turbine blade design? The answer comes from how humpback whales catch fish. They do it much the same way humans often do: they use nets. Only humpback whales make their nets out of air. When they find a school of fish, they begin blowing bubbles which surround and corral the school into a tighter and tighter space.[30] To do this, humpbacks turn in circles at ever smaller radii, closing the fish school in. Then, they open their mouths and come up through the center, swallowing a huge mouthful of fish. It's their flippers that give them the ability to turn in such tight radii. The bumps on their flippers speed up the water flow, keeping the flow smooth and steady over their flippers as they rotate.[31] Without the bumps, they would lose their grip on the water and be unable to complete tight turns. Likewise, a wind turbine that employs these bumps on their blades turns more rapidly in the same breeze than a straight-edged blade. And it's quieter and more stable too.

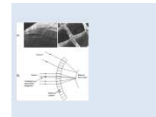


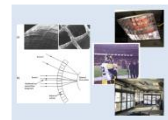


The biological mechanism has been applied to industrial ceiling fans (also 20% more efficient), computer fans, and even the skeg of surfboards, which makes for much greater control while riding a wave.[32]

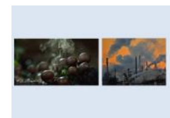


[28] PPT8, slide 23. This is an animated image. Hover over slide to play.
[29] PPT8, slide 24.
[30] PPT8, slide 25.
[31] PPT8, slide 26.
[32] PPT8, slide 27.





One of the biggest uses of energy is to heat homes and buildings. An idea for an innovative approach to heating comes from this guy, the lobster.[33] Lobsters inhabit much of the world's ocean habitats, from the tropics to murkier temperate waters. Lobster vision is exceptional, largely due to the unique structure of their eyes.[34] Their square compound eyes reflect light with great precision onto their retinae. The architecture of this reflecting lens has been applied to spot heaters.[35] These heaters are extremely efficient: they can raise the temperature of a target area by 20 degrees (Fahrenheit) in moments. This has led to the idea that instead of heating an entire building or home, as we do now, it would be possible to only heat the people *in* the buildings, using wall-mounted spot heaters which rotate and can track people as they move.



So the take home message is that energy is a fundamental part of our world.[36] It literally runs everything an engineer might design. Paying attention to how the rest of Nature runs itself so creatively, so effectively, and so sustainably, can lead to important insights and innovations in how we run ourselves.

Extensions:

Try to calculate how much material is processed by Nature worldwide per time (day or year). Hint: research "net primary productivity." Compare this with how much material is processed by humans over the same time period.

Standards:

This activity can be used to address chemistry education standards. The list below, which is not exhaustive, is drawn from the current version of Benchmarks for Science Literary (Standard 8: The Designed World; B: Materials and Manufacturing, C: Energy Sources and Use), which incorporates standards also from Science for all Americans (1991), and the National Science Education Standards (1996).

B. Materials and manufacturing

[33] PPT8, slide 28.
[34] PPT8, slide 29.
[35] PPT8, slide 30.
[36] PPT8, slide 31. This is an animated image. Hover over slide to play.

- Manufacturing processes have been changed by improved tools and techniques based on more thorough scientific understanding, increases in the forces that can be applied and the temperatures that can be reached, and the availability of electronic controls that make operations occur more rapidly and consistently.

- Increased knowledge of the properties of particular molecular structures helps in the design and synthesis of new materials for special purposes.

- Groups of atoms and molecules can form structures that can be measured in billionths of a meter. The properties of structures at this scale (known as the nanoscale) and materials composed of such structures, can be very different than the properties at the macroscopic scale because of the increase in the ratio of surface area to volume and changes in the relative strengths of different forces at different scales. Increased knowledge of the properties of materials at the nanoscale provides a basis for the development of new materials and new uses of existing materials.

C. Energy sources and use

- When selecting fuels, it is important to consider the relative advantages and disadvantages of each fuel.

- Industrialization brings an increased demand for and use of energy. Such usage contributes to having many more goods and services in the industrially developing nations but also leads to more rapid depletion of the earth's energy resources and to environmental risks associated with some energy resources.

- The useful energy output of a device—that is, what energy is available for further change—is always less than the energy input, with the difference usually appearing as thermal energy. One goal in the design of such devices is to make them as efficient as possible—that is, to maximize the useful output for a given input.

- Sunlight is the ultimate source of most of the energy we use. The energy in fossil fuels such as oil and coal comes from energy that plants captured from the sun long ago.

More Resources:

Smestad, G.P., and M. Grätzel. 1998. Demonstrating electron transfer and nanotechnology: a natural dye-sensitized nanocrystalline energy converter. *Journal of chemical education* 75, no. 6: 752.

Interview with Michael Grätzel: http://www.theguardian.com/technology/2010/jul/04/michael-gratzel-bright-idea-energy

Michael Grätzel's review of dye-sensitived solar cell technology:
http://sciencesupply.com.au/research/gratzel4.pdf

Sportswear reallocates sweat inspired by the thorny devil

http://www.innovationintextiles.com/new-trick-from-xbionic/

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