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WHY A NATURE-INSPIRED APPROACH?

I think the biggest innovations of the twenty-first century will be at the intersection of biology and technology.

–Steve Jobs

How should we teach engineering to young people?

This question is more relevant today than ever. If there were a movie theater devoted to K-12 education, this is the question that likely would light up the marquee much of the year. To begin with, new education standards include engineering for public schools for the first time in U.S. history. Similar standards requiring the same now exist in many other countries. Meanwhile, the maker movement continues to grow in popularity, and teachers find themselves in need of learning activities that incorporate basic principles of engineering design. Since entirely new subjects rarely join long-time staples of public education (such as reading, writing, math, and more recently science), the somewhat abrupt prescription to teach engineering with large-scale K-12 educational standards has rightfully pushed the question of *how* to the front of contemporary education discussions.

Fortunately for us, this question has an uncommonly stellar answer.

This is a book about teaching engineering to young people using a Nature-inspired approach. *Nature-inspired engineering* means addressing design questions and opportunities by looking to the living world for ideas. Known by a number of terms (such as biologically inspired engineering, biomimicry, and biomimetics), Nature-inspired engineering today is at the cutting edge of professional engineering practice. It is responsible for many of the biggest technological advances in the daily news, as well as many existing technologies that define the modern world. Nature-inspired engineering is also the educational approach taken by many of the most prestigious engineering colleges and university programs around the world, producing engineers with the kinds of backgrounds today's most successful companies seek. At a time when parents are increasingly concerned about their children's connection to the natural world, it is also an exceptionally powerful way to reconnect students with the living world of which we are part, even when they can venture no farther than the classroom or schoolyard each day. Nature-inspired approaches to engineering education have a demonstrated record of success for educators who have already adopted it, engaging young people from all backgrounds, rural to inner city, Memphis to Mumbai. Last but not least, Nature-inspired engineering is an exciting and inspiring approach for teachers to learn about, reinvigorating their classroom practice and reminding them why they chose teaching as a profession in the first place. For these many reasons, Nature-inspired engineering continues to spread and to attract advocates and practitioners. It deserves to be in your educational tool belt too.

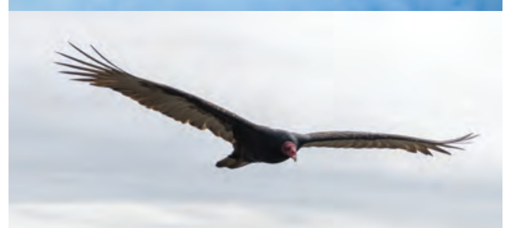
At first blush, a Nature-inspired approach to engineering education may seem surprising, if not downright strange. After all, some would say, isn't engineering and technology what distinguishes humans from the rest of Nature? From that perspective, Nature-inspired engineering seems like an oxymoron. But it's easy to forget just how similar the practice of engineering is to the functions of biology. To begin with, both use design to address opportunity. Ever since our ancestors shaped their first stick or chipped away at their first rock to make tools, humans have been designing things to make our lives better. That's what engineers do: they strive to generate effective solutions to design challenges. The rest of Nature has been doing something very similar, for several billion years. Who can look at a seagull soaring above the planet and fail to see a superb solution to the hassle of getting around? Or at a spindly vine and not be impressed by its resourcefulness in using other plants to reach the light? Or at your own hands, holding this book, and not see a masterly tool for manipulating objects? Engineers use cognitive processes to solve design challenges; engineering in the rest of Nature is accomplished through the ever creative, ever optimizing, ever restless process of evolution. The means differ, but the result is the same: the production of effective solutions to the struggles and possibilities of Life. And Nature is full of answers to unnoticed

ONE OF THE BEST-KNOWN ENGINEERS OF THE WESTERN WORLD, Leonardo da Vinci (1452–1519) was a great observer of Nature, borrowing ideas from the living world for many of his designs. He is also a superlative example of someone who successfully integrated science with art.

questions. The breathtaking ability of an octopus to camouflage the texture of its skin to mimic surrounding coral, even the housefly in your kitchen doing stunts a jetfighter pilot would envy, shows that we already live in an exceptionally well-engineered world. And that's a world human engineers can learn from.

No wonder, then, that so many of our world's most famous engineers, architects, and creators throughout history have drawn inspiration for their work from the living world. Leonardo da Vinci, the best-known engineer in the Western hemisphere, astutely observed Nature and reflected what he saw in his inventions as well as his art. His anatomical drawings of the human heart educate and inspire surgeons and medical students to this day. And his famous fifteenth-century sketches of flying contraptions based on the wings of birds and bats are considered some of the earliest clear examples of bio-inspired engineering we have.

The practice of looking to Nature for design inspiration continued to pick up steam in the 1800s, when Alexander Graham Bell, fascinated by the structure and function of the human ear, had an epiphany that changed modern communication as we know it. In 1874, while experimenting with an ear from a cadaver, Bell began conceiving the fundamental architecture of the modern telephone. Observing the way the tympanic membrane mechanically activated the middle ear bones, he wrote: "It occurred to me that if a membrane as thin as tissue paper could control the vibration of bones that were, compared to it, of immense size and weight, why should not a larger and thicker membrane be able to vibrate a piece of iron in front of an electro-magnet?" Here was the mechanical blueprint of the modern telephone laid out for the first time, inspired by the structure of the human ear he so admired. Certain he was now on the right track, Bell scribbled in his notebook: "Make transmitting instrument after the model of the human ear. . . . Follow out the analogy of nature." The diaphragms and connected magnets in today's cell phones, which make the speakers and microphones generate working electric currents, are the direct result of Bell appreciating and understanding the architecture and mechanisms of the mammalian ear. He translated what he observed and abstracted what he understood into the metal, wire, and other materials of human industry. Your cell phone works, fundamentally, because it contains an abstract model of the mammalian middle ear in it. Engineering inspired by Nature is right in our pockets.



Every time we soar around the planet on an airplane, we're also enjoying the fruits of Nature-inspired engineering. For a thousand years or more, people strapped feathered appendages to their limbs and jumped to their deaths, flapping in futile mimicry of birds in the hopes of flying. Then, in the 1800s, an English baron named George Cayley figured out that, while flapping like birds wasn't the answer to human flight, soaring like them was. The Wright brothers built on Cayley's work and from watching birds discovered the secret to controlling roll in aircraft, the last obstacle to building workable airplanes. Turkey vultures, for example, control roll by twisting their wings, which the Wright brothers copied faithfully through their "wing warping" technique. On modern aircraft, rolling is controlled by the same principle using ailerons, small movable flaps at the ends of wings. Birds first planted the very aspiration of flight in our imagination and then showed us how to achieve it.

The computers that run an aircraft's navigational systems and help you book a flight through the Internet are also products of Nature-inspired engineering. The heart of the machine, the central processing unit (CPU), is as much a biological model as the critical parts of a cell phone. In the 1930s Claude Shannon, a Michigan graduate student, had the epiphany that relay switches (the precursors of today's silicon transistor switches) could be arranged in sequences that modeled human logical reasoning. This single, wildly creative idea, which Shannon detailed in his graduate thesis (widely considered the most influential master's research project of all time), opened the door to the kind of sophisticated automated "thinking" that computers do on a routine basis, from figuring out whether it will be raining six days from now to enabling me to write this book using a word processing computer program. Shannon's flash of genius is why the electrical wiring in a computer's CPU is known, literally, as a logic circuit. Computers can perform the logical operations that make them work because the mind of a university student drew an improbable analogy between how humans reason and the design of electrical circuitry.

Another monumentally consequential example of Nature-inspired engineering comes from the origin of modern antibiotics, which Alexander Fleming discovered in 1928. The story of Fleming's discovery is legend: he returned from holiday to a messy lab to find mold growing on the petri dishes of the cultured bacteria he studied. But noticing unwanted mold growing on his research project was not what earned Fleming a knighthood or a Nobel Prize (I discover as much whenever I venture into the recesses of my own refrigerator). Fleming is celebrated because he saw the relevance of the fact that the mold on one of his petri dishes appeared to be stopping the bacteria he studied from spreading. From there the world's first human-made antibiotic, penicillin, was engineered, a medical revolution that has saved millions of lives. Many of you reading this book owe your lives to this one Nature-inspired innovation, either from taking life-saving antibiotics yourself at some point or because your direct ancestors did.

These are standout historical examples, of course, but Nature-inspired innovations are anything but a thing of the past. Many of the technologies filling today's headlines are the result of engineering inspired by Nature. These include ongoing breakthroughs in genetic engineering, inspired by a virus's ability to alter host DNA; the current revolution in artificial intelligence, a.k.a. machine learning or "neural networks," modeled on the processing architecture of human neurons; and the burgeoning field of robotics, whose mechanics, sensors, and control systems draw heavily from biological models as varied as elephants, vines, geckos, and locusts. Lesser known technologies also important to society today are inspired by the natural world as well. These include programs for computer-assisted design, or CAD, a principal tool used by professional designers and engineers to model their ideas, which incorporate algorithms inspired by how bones grow. This software allows engineers to minimize the material required to design everything from airplanes to skateboards without sacrificing safety. Redesigning everyday products using bone-inspired lightweighting software is estimated to save millions of dollars for companies, as well as over one billion pounds of material each year, reducing annual carbon dioxide emissions by nearly one million tons in the aerospace sector alone (see Chapter 4).

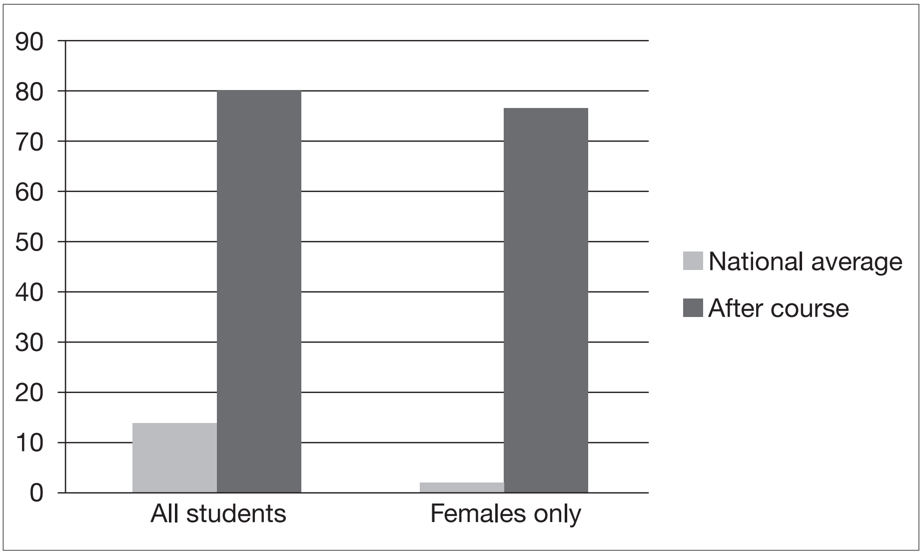
INNOVATORS EVERYWHERE LOOK TO THE NATURAL WORLD FOR INSPIRATION, which informs both their technological research and their teaching. *Top left*: For Dr. Frank Fish (Dept. of Biology, West Chester University), studies of marine life have resulted in a completely new kind of energy-efficient rotary blade, based on the hydrodynamics of humpback whales. *Top right*: Dr. Paula Hammond (Dept. of Chemical Engineering, MIT) develops ways to fight cancer inspired by the microbiology of the human cell. *Left, second image down*: Dr. Zhenan Bao (Dept. of Chemical Engineering, Stanford University) develops electronics that can biodegrade. *Middle right*: Dr. John Dabiri (Dept. of Mechanical Engineering, Stanford University) discovered that, by arranging wind turbines together, he could boost their overall efficiency, much like the schools of fish that inspired the idea. *Left, third image down*: Dutch designer Lilian van Daal designs recyclable furniture inspired by the versatility of cellulose. *Bottom*: Inspired by the byssus threads that enable marine mussels to adhere to rocks in pounding surf, Dr. Kaichang Li (College of Engineering, Oregon State University) developed a toxin-free adhesive now used in plywood.

Because companies and organizations like Airbus, General Motors, Verizon, Apple, Facebook, Google, the New York Stock Exchange, and NASA are all relying on Nature-inspired technology to operate, it should come as little surprise that colleges and universities everywhere are following this trend as well as helping shape it. In the last few decades, dozens of prestigious postsecondary educational institutions have established Nature-inspired approaches to train their engineering, architecture, and design undergraduate and graduate students. This includes Harvard's Wyss Institute for Biologically Inspired Engineering, Georgia Tech's Center for Biologically Inspired Design, and the Imperial College of London's Centre of Bio-Inspired Technology, to name a few. Every state in the union today has one or more colleges or universities that employ Nature-inspired innovation as a component of teaching, research, or both. Whether at a public state school or an expensive private university, Nature-inspired engineering is how today's college students and tomorrow's professionals are being trained, coast to coast and around the world.

Such approaches to engineering and design are so historically important, so contemporarily relevant, and now so widespread across colleges and universities that using this approach in K-12 schooling will undoubtedly help prepare students for college and careers. One economic impact study projected nearly two million jobs resulting from bio-inspired innovation in the United States alone and the addition of $1 trillion in gross domestic product. In fact, so firmly established is Nature-inspired innovation that it's probably easier to make the case that *not* teaching engineering through a Nature-inspired approach is likely to leave students ill-prepared for the future.

AN APPROACH WITH THE POWER TO ENGAGE STUDENTS AND TEACHERS

None of this would matter much if students didn't find Nature-inspired engineering fascinating. But they do. Educators using Nature-inspired approaches to teach engineering have known this for years. Just one example comes from a pilot study of students at a public high school in California, who were asked about their interest in the field of engineering after completing a Nature-inspired engineering course. Nationally, only about 14 percent of high school students in the United States report an inter-



PERCENTAGES OF HIGH SCHOOL STUDENTS REPORTING AN INTEREST IN ENGINEERING: nationally (light gray) and among students who took a Nature-inspired engineering course (dark gray).

est in engineering, and just 2 percent of female students. But among students who took a Nature-inspired engineering course, 80 percent reported greater interest in engineering afterward—five times the national average. For female students, this rate was even more dramatic: 77 percent—*over 38 times* the national average.

More impressive than the numbers are what students say after experiencing Nature-inspired engineering. Here's just one typical example out of dozens, from Ashlynn, a high school junior:

> *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. The lessons were so unbelievably fascinating! I loved getting to learn about so many amazing, remarkable creatures and learning how certain things work. I've noticed that I'm more aware of the products and technologies we use and the way things, human-made and in nature, function. Overall, I enjoyed the class immensely and took so much away from it.*

How often do high school students speak so enthusiastically about their classes?

From a teacher's perspective, Nature-inspired engineering can serve as a unifying, integrating, and authentic context for STEM/STEAM education. This is an important consideration given the value and importance of interdisciplinary education, as well as practical time constraints. As I detail throughout this book, engineering inspired by Nature brings in the life sciences, of course, which underpins the entire approach. It also relates to chemistry and physics, the sciences that help us understand the biological abilities of organisms, while math is the language often used to describe and explore all of these branches of science. Engineering also relates directly to technology. And one need go no further than Leonardo da Vinci to see how engineering and art go hand in hand. The upshot is, no other approach to a school subject comes remotely close to Nature-inspired engineering as a way to unify and integrate all of STEM/STEAM learning.

> I cannot tell you how excited I am to integrate this curriculum into my classes. . . . This curriculum ticks so many boxes for me: critical thinking skills, project-based learning, engineering design, creativity, interdisciplinary, STEM/STEAM, environmental sustainability, prototyping, and so on. This curriculum is a perfect example of twenty-first-century education.
>
> –Mr. Brian Hoover, Technical Design,
> Hellgate High School, Missoula, Montana

A Source of Fascination and Hope

At least two features of Nature-inspired engineering make it so engaging to students and teachers alike. First, Nature-inspired engineering is a unique blend of natural history and compelling technological advances. Every Nature-inspired technology—from materials inspired by geckos that enable people to scale sheer glass walls (see below) to plastics inspired by trees, made of atmospheric carbon dioxide (see Chapter 6)—joins a fascinating natural history story with a story about human creativity that results in a brilliant technological fusion of natural and human design. That's a package that is hard to beat.

Second, these technologies are hopeful. Many of the scenarios we imagine about the world's future are not very optimistic—just consider movies like *Terminator* and *The Matrix* and the dystopic novels so popular with young people today. Many of the trends we all sense in modern society seem to lead to an unpleasant logical conclusion; perhaps art helps us process our complex feelings about the matter. Nature-inspired engineering is a powerful countercurrent to these subterranean concerns. What other approach to technology shows us, for example, ways of creating carbon-negative cement you can make out of car exhaust (inspired by coral reefs; see Chapter 6), productive and sustainable farming systems like permaculture (inspired by how natural plant communities function), or ways for billions of humans to live on Earth while actually *increasing* biodiversity and access to Nature, through urban planning strategies inspired by ants (see Chapter 6)? While human society can seem hopelessly destined to increasing misery and self-destruction, we are yet surrounded by a world with millions of flourishing populations of creatures, full of light and color, billions of years old, and noticeably absent of pollution and waste.

By drawing inspiration from such a world, by reimagining and recreating our technologies through Nature's mentorship, we can start to glimpse a human-built world that works as well as the rest of Nature, a world without toxins, blight, or poverty. The truth is, the future is not at all predetermined: it can be as terrible as we often imagine, or more extraordinary than we ever dreamed. All that's certain is that, to a very large extent, which future we'll end up with has to do with which future we pursue. Right now too many young people don't believe they or this world has much of a chance. A recent, large-scale study of one million students across the United States found that less than half of these young souls feel hopeful about the future. Giving young people a vision of a future worth inventing can make all the difference in what they think is possible, all the difference to their aspirations, and, ultimately, all the difference in what they achieve with their lives. Nature-inspired engineering can be that hopeful, solution-oriented vision of the future we all sorely want and need.

A Connection to the Natural World

There is an additional way in which Nature-inspired engineering can be transformative for students: through nurturing a bond with the living world around us. Many young people today never form such a connection. A recent study—this is no joke—actually found incarcerated *prisoners* spend more time outside today than do our children. How can our children enjoy the full experience of what it means to be alive while living a Nature-less existence? Not only does this lack of connection profoundly wither the full experience of being alive for young people, but it also severely limits the choices they will make over their lifetimes, including what products to buy or not buy, what political leaders to elect, and what activities to pursue in their lives. Since at the heart of Nature-inspired engineering is a greater awareness and appreciation for the myriad, superlative abilities of Life around us, greater admiration and love for the natural world readily results from a deep engagement with Nature-inspired engineering.

Getting kids outdoors is a laudable goal but challenging to achieve. Some children don't have much of an outdoors nearby to experience: most U.S. children today now live in urban areas, and the trend is growing worldwide. Can we labor to get more children outside more often and to green our schools and cities? Yes, we can, even if progress is slow and expensive. But in the meantime, a readily achievable strategy for reconnecting most of the world's children with Nature already has the funding and necessary infrastructure in place: schools. Millions of children go to school for over seven hours each day, for over a decade of time during the most formative period of their lives. All that's missing is a Nature-oriented curriculum and teachers ready to implement it. Engineering can be the perfect subject with which to start this process of healing the rift between children and Nature and instilling hopefulness about the future.

AN APPROACH THAT MEETS CURRENT STANDARDS

Does a Nature-inspired approach to engineering education work with new educational standards that require engineering be taught in the first place? To begin answering this question, let's take a look at these standards, at least those in the United States. Table 1.1 summarizes what U.S. K–12 students are expected to be able to do to demonstrate their engineering competence, according to the Next Generation Science Standards (NGSS). In the parlance of the NGSS, these are the "Performance Expectations," that is, the end-point metrics used to assess student learning in engineering, not the foundational practices, core disciplinary ideas, and crosscutting concepts that underlie them.

TABLE 1.1.
NGSS engineering performance expectations for K–12

Grades K–2
Ask questions, make observations, and gather information about a situation people want to change to define a simple problem that can be solved through the development of a new or improved object or tool.
Develop a simple sketch, drawing, or physical model to illustrate how the shape of an object helps it function as needed to solve a given problem.
Analyze data from tests of two objects designed to solve the same problem to compare the strengths and weaknesses of how each performs.
Grades 3–5
Define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost.
Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem.
Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.
Middle School
Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.
Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.
High School
Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.
Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.
Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.
Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

What Do the Standards Say Students Should Be Able to Do?

Whew! Table 1.1 is a lot to read, and even more to do, but remember, it's something students are supposed to learn how to accomplish over a thirteen-year period. Let's break it down a bit. Fortunately, some themes are quickly evident, so we might be able to boil things down to their essence and (mostly) ignore the rest. Looking across the standards, you might notice the following motifs:

- Some form of **defining design challenges** is part of every grade band's standards. K-2 students "gather information about a situation people want to change." Upper elementary students "define a simple design problem reflecting a need or a want." Middle school students must understand a design problem in order to "define its criteria and constraints." And high school students "analyze a major global challenge." All these variations reflect a theme, involving *clearly identifying and describing a challenge* that one is attempting to address through engineering.
- **Generating and representing solutions** is also a part of every grade band's standards. Whether it's illustrating how a solution functions (K-2), generating and comparing solutions (3–5), developing models of solutions (middle school), or designing and evaluating solutions (high school), the idea that students *create something solution oriented* runs throughout the standards.
- Finally, **testing potential solutions** is part of every grade band's standards. In K-2 and middle school, that means "analyzing data from tests"; in grades 3–5, "planning and carrying out fair tests"; and in high school, testing potential solutions by simulating their effects using a computer.

The small number and continuity of these motifs across K-12 are noteworthy. I return to these motifs on occasion, because they are the skeleton running through the NGSS engineering standards. You can think of these as the raisons d'être, evidently, for the NGSS engineering standards to exist. They represent the skill set students are to learn. This summary of the performance expectations at each level of schooling can help translate the potentially overwhelming verbiage of the NGSS into something more concise, capturing their essence.

What Do the Standards Not Say?

Something else useful is also highlighted in Table 1.1 or, rather, not highlighted. That's because what is *absent* from these performance expectations is also important and instructive—perhaps even more so. Notice that there is no mention whatsoever of any content knowledge for specific types of engineering in these standards, no mention of concepts particular to mechanical or electrical engineering, for example, or architecture or computer science. That doesn't mean one shouldn't bring specific engineering content knowledge into the classroom curricula once fully manifested (more on this later), simply that it is not mandated by the standards. No particular type of engineering is preferred above any other.

Second, there is no mention of domain-specific mathematical or physics knowledge, what we normally think of when we think of pre-engineering curricula. The NGSS engineering standards are not standards for a pre-engineering education. The emphasis, instead, on defining problems, creating solutions, and testing ideas adds up to a set of standards with a much greater emphasis on *design process*. Engineers do many things, and the NGSS can't cover it all. In fact, these standards are not even actually called engineering standards. Instead, they're referred to in the NGSS specifically as engineering *design* standards. A careful read of what's in and what's not in the standards makes why abundantly clear: kids are supposed to understand problems, make things to fix them, and test what they make. The NGSS are design-oriented engineering standards, full stop.

That makes good sense, when you think about it. There are just too many engineering subdisciplines to address in educational standards, as mentioned, but the aspects addressed here—defining challenges, generating solutions, and testing them—are things pretty much all engineers in every subdiscipline do. So the standards demonstrate great wisdom here, to their credit. If you're going to address engineering in K-12, you want students to come away with what is essential across as many of the engineering fields as possible. It's not that Young's Modulus of Elasticity isn't an important concept in materials engineering; it's just that not every kind of engineering-related curriculum needs to cover it. But figuring out what you're trying to fix, coming up with solutions for fixing it, and testing whether your solutions are any good *are* relevant to every form of engineering, irrespective of engineering subdiscipline. These standards, then, have succeeded in the difficult and vital task of being relevant, irrespective of what kind of engineer a student might become. They capture engineering's essence.

AN APPROACH WITH RELEVANCE FOR ALL STUDENTS

Of course—and this is key—some students might not become engineers at all. In fact, *most* won't. Do the engineering standards still need to be relevant to them? *Of course they do!* This is a mistake many K-12 engineering curricula make: they are designed on the assumption that students will (or should) become engineers. Thus, they are developed based on the implicit question, what should every engineer know? And, adapted to the K-12 context, they become something like a pre-engineering curriculum.

But this makes no sense: we don't teach math to students because we think they should all become mathematicians, or art because we think all students should become artists. We teach these subjects to young people because we think there is something valuable about them *no matter what* students do with their lives. Identifying problems, coming up with solutions to them, and testing solutions are not just central to what engineers do; they are worthwhile abilities for *all* people to have. And the process of acquiring these abilities is a valuable educational opportunity to explore and learn all manner of topics.

Here's how Sonia Dhingra, a wise high school sophomore, put it in a recent article in *Scientific American*:

> *A lot of people in my age group ask, why do engineering activities if you don't think you will be an engineer? . . . I love painting, but my motivation is not to become a professional artist. Similarly, I do not play the piano because I think I am going to grow up to be a concert pianist. I do these things because they are both enjoyable and help me unwind; they relax and carry me to a place where my mind can try different things without judgement. So why not engineering? Engineering is also creating.*

This imperative, that K-12 engineering standards be relevant to *all* students, no matter what careers they end up pursuing, is a profoundly wise K-12 educational philosophy, evinced in the NGSS's language. And when we consider the most important reason teachers select a specific curricular approach to engineering education, the importance of relevance understandably comes up again. An engineering curriculum—or any curriculum, for that matter—that fails to be relevant to students will simply not be successful. That's because student engagement is the number one prerequisite for a successful curriculum of any kind. The positive connections among student engagement, intrinsic interest, learning, and achievement (not to mention student satisfaction and happiness) are not only self-evident but also have been confirmed through extensive educational research. Strong student engagement is an essential feature of any successful curriculum. It's got to feel relevant to students—not to mention teachers, too.

Unfortunately, the track record thus far for K-12 engineering education, at least in terms of generating interest, leaves a lot to be desired. Based on surveys of schools with existing K-12 engineering programs (one prominent program has been operating since the 1990s), student interest in engineering is not high. Moreover, it generally declines over time. That means the longer students learn engineering in these programs, the less they become interested in it! In one study, for example, interest in engineering plummeted from a high of 63 percent in elementary school to 20 percent by the end of high school. As mentioned above, nationwide student interest in engineering averages a measly 14 percent overall at the end of high school, and a scarce 2 percent for girls. Weak interest in engineering continues into college and careers, especially for certain groups. Only 14 percent of the professional engineering workforce in the United States is made up of women, for example, despite women making up half the population.

What gives? Is engineering just inherently boring? That's unlikely, to say the least: humans have been making things ever since we became human, if not before. Making stuff is part of who we are, and that inclination has led us to where we are today. I've yet to meet a young child uninterested in how things work or in making stuff, and you probably haven't either. The truth is, the process of making things can be utterly fascinating, both in and of itself and as a window on many topics of equal interest: explorations into human creativity, stories of invention, how things are manufactured, the impact of technology upon ourselves and the environment, and the reaches of human possibility itself.

Advocates for K-12 engineering education often point to the need to prime the workforce pipeline and keep our competitiveness up with other countries. But that preoccupation may be shortsighted, and counter-

MAKING THINGS IS PART OF WHO WE ARE. From this masterfully shaped spear point to this extraordinary telecommunications and pocket computer tool, some 73,000 years of nearly nonstop human ingenuity and engineering have addressed human needs and wants.

productive besides. Perhaps we should focus less on turning young people into future engineers and more on how engineering education can turn young people onto the world around them—more attentive, that is, to the benefits engineering education can provide students regardless of their eventual professions. In K-12, we err when thinking engineering education is primarily vocationally motivated; it isn't, and shouldn't be, for it offers much more valuable benefits still.

The real question is, how can engineering education be a means of enriching the lives of young people and, in the process, society overall? The potential benefits to young people of an engineering education are enormous, potentially the largest of any STEM subject. In part that's because we largely live in a human-built world: an engineering education is an opportunity to better understand, appreciate, and participate in the world in which we live. Why are the things we make designed the way they are? Where do the materials we make stuff out of come from? How are these materials processed? What happens to these things when they're disposed of? How do the things we make have an impact on us and on the environment we depend on? How were the things that define our human-built world invented in the first place? How can we improve on what we make, innovate and optimize their design? These are the kinds of questions from which a great engineering education is shaped.

Undeniably, the need to produce young people interested in these questions, as well as these pursuits, is more important than ever. Every aspect of human technological development today has been put into question by our current circumstances. Humankind's current technological practices strain Earth's resources, strain the quality and functionality of the environment, and strain our personal health and well-being. This pressure worsens on a daily basis at an exponential rate, making a vibrant and engaging engineering education of appropriate scope and scale for all children an imperative for our continued and ideally improving way of life.

A Nature-inspired approach to engineering provides this vibrant and engaging education, and it has much greater educational and social value than more myopic concepts of K-12 engineering education. Since most children will not grow up to become engineers, even in the best K-12 engineering program possible, an engineering curriculum has to have value that extends beyond a vocational orientation toward college and career. A Nature-inspired approach to engineering, with its propensity to reconnect children with Nature and its capacity to raise their hopes, skills, and aspirations to invent a better human-built world, has the kind of enhanced value educators should seek for the diversity of children we serve. And a Nature-inspired approach to engineering education also can provide the fundamentals needed for preparing students for life beyond graduation, in the most pragmatic sense.

ORGANIZATION OF THIS BOOK

A Nature-inspired approach to engineering education also offers ample opportunities to not only teach engineering but also meet the NGSS engineering requirements and other standards (such as the Common Core math standards) and generally support and integrate learning across all STEM/STEAM subjects. This book explores this approach in detail. The sequence of Chapters 2–8 correspond to sequential steps in an engineering program: introducing students to engineering inspired by Nature (Chapter 2), exploring a variety of engineering topics (Chapters 3–7), culminating in student-led projects where students employ Nature-inspired design processes for innovation and problem solving using their own ideas and skills (Chapter 8). And while kindergarten students are very different from seniors in high school, the chapters explore these topics in a cohesive way applicable to all grade bands, so as to be interesting and relevant to all teachers, across primary and secondary education.

Each chapter is not intended to provide the material for an entire curriculum. Could you do an entire course on Nature-inspired computer science or Nature-inspired product design? Of course, and it would be cool! But I'm not trying to squeeze all of that into any single chapter within this book. This is intentionally a broad, moderately deep, survey-like introduction to K-12 engineering education using a Nature-inspired approach. While what follows is structured differently than a series of lesson plans, nonetheless a goal of this book is to provide you with a practical understanding of Nature-inspired engineering education and its implementation, with a range of student activities clearly identified throughout. If I can show you some concrete examples of how to use Nature-inspired approaches to engineering topics, then perhaps you'll want to take your teaching to the next level and start to seek or work out an actual curriculum. This book is not that curriculum itself but its ambassador.

Finally, a note of humility: Nature-inspired engineering is not new, but teaching engineering using a Nature-inspired approach is. These are still early days in the practice of Nature-inspired engineering education in K-12. I'm not claiming this is the only way to approach Nature-inspired engineering education, or that this is the best way to do it. But we definitely can get started with what we have now, and we shouldn't wait. We'll figure out more as we go along. There are more people who still have a lot to contribute to this field. So, while I want to provide you with state-of-the-art content, I know we're just getting this party started. In my writing this book, and in your reading it, we're doing something new together. It's a beginning.

Additional Resources

Video introductions to innovation inspired by Nature

Michael Palwyn's TED talk, "Using Nature's Genius in Architecture": https://www.ted.com/talks/michael_pawlyn_using_nature_s_genius_in_architecture?language=en

Janine Benyus's TED talk, "Biomimicry's Surprising Lessons From Nature's Engineers": https://www.ted.com/talks/janine_benyus_shares_nature_s_designs

Books on Nature-inspired engineering

Benyus, J. M. 1997. *Biomimicry: Innovation inspired by nature.* Harper Perennial.

Forbes, P. 2005. *The gecko's foot.* Fourth Estate.

Harman, J. 2013. *The shark's paintbrush: Biomimicry and how nature is inspiring innovation.* Nicholas Brealey.

Khan, A. 2017. *Adapt: How humans are tapping into nature's secrets to design and build a better future*. St. Martin's Press.

Excellent online magazine about Nature-inspired design

Zygote Quarterly: https://zqjournal.org/

K-12 curricula on Nature-inspired engineering

The Center for Learning with Nature: www.LearningWithNature.org.

Good introduction to the subject of biology

Hoagland, M. B., and Dodson, B. 1998. *The way life works: The science lover's illustrated guide to how life grows, develops, reproduces, and gets along.* Three Rivers Press.