Contents

Programming Matter

IN THE EARLY 1700S, the English carpenter and clockmaker John Harrison solved one of the most vexing puzzles that sailors faced at the time: how to calculate longitude while at sea. This challenge was so important for navigation—and had been so confounding up to that point—that the British Parliament offered a substantial cash reward to anyone who could find a practical solution. As trade increased, and ships sailed around the world with increasing regularity, it was critical for the crew to understand where exactly their ship was along the earth's horizontal axis. Disrupted by the challenging conditions at sea, timekeeping and way-finding devices were inconsistent and unreliable. Consequently, navigation at the time was notoriously imprecise and shipwrecks were far too common as a result of ships losing their way.

While scientists and many others looked to astronomy, mathematics, or even magic in their quest to unlock an answer to the riddle, Harrison's solution was amazingly simple and elegant. From wood, metal, and other simple material components, he crafted a "sea clock" that could keep reliable track of the time in relation to a given reference location, which would allow sailors to calculate their position based on the difference from their local time. Earlier attempts at such clocks had been thwarted by the motion of the sea, changes in the environment, and accumulating errors in the mechanical clockwork. But Harrison's design, by accounting for the ways in which materials would expand and contract, enabled his mechanism to adapt naturally to even the most minor fluctuations in temperature, pressure, moisture, and physical movement. As a master craftsman, Harrison understood that the dynamic and adaptive properties of his materials were the keys to a sea clock that could keep perfect time for long intervals, no matter the weather, the conditions of the sea, or the movement of the device.[1]

His invention became known as the marine chronometer, and it revolutionized not only sea navigation but also the way we think about materials and their ability to adapt in intelligent ways. Harrison demonstrated how material properties could be exploited to solve notoriously challenging design and engineering problems. Since that time, similar material-based mechanisms have been applied to a number of novel devices that are abundant in our everyday lives. Thermostats, for example, take advantage of a bimetallic structure to regulate the temperature in our houses or maintain safe operating temperatures in an engine. Orthodontic devices are made from Nitinol, a nickel titanium alloy that can move teeth into precise locations based on a response to body temperature. Lifesaving medical devices like stents use similar bimetallic structures to morph from one shape into another. This behavior has been "preprogrammed" in the material through heating and molding it at high temperatures. When a stent is placed in the body, for example, it is collapsed to fit through small spaces, and then activated by body temperature, allowing it to morph into the memorized shape and open the vessel.

Yet this way of working with materials to craft elegant, simple, and transformative solutions is still largely contained to a few niche applications, and not widely used today. Since Harrison's time, we have moved from a society that produced goods with localized crafts-based knowledge—one in which products and environments were intimately and intrinsically linked with material properties—to a system of industrially standardized mass production. The Industrial Revolution effectively ignored the intimate material knowledge of previous generations. Instead of taking advantage of the inherent material properties within wood or metal, for example, factories started to create standardized components that attempted to limit the amount of heterogeneity and differentiation. We attempted to standardize the trades and create repeatable outputs that did not rely on a single person's skill set or knowledge in the craft—with some good reason: it was much more difficult to make a house out of logs and branches, or a stone wall out of geometrically unique elements, than it is to construct anything with repeatable components like bricks or two-by-fours. Similarly, at an environmental scale, humans shifted from an intimate relationship working with the earth and the natural forces of rain, sun, storms, tidal shifts, or sediment movement to a top-down, brute-force dictation through the use of machines. We could build anywhere, create land, dredge, redirect water flows, and artificially construct nearly any environment. Most of this standardization in manufacturing, construction, and land use was attempting to fight the dynamics of materials, minimizing their movement, and resisting the forces of the environment (gravity, temperature changes, moisture changes, vibration, natural disasters, and so on). The goal was to produce more, and to do it faster, cheaper, and better.

This alienation from materials has only been exacerbated in recent times by the rise of computing and the digital revolution. Digitalization and virtualization have tended to disconnect the average person from materiality and led us to believe that creating something "intelligent" means either a human being or a digital system with software/hardware that simulates human intelligence. But all of our own human and biological intelligence is ultimately built from simple materials, not computer chips or robotic components. We have lost touch with our appreciation for material intelligence.

I often think of Harrison and his marine chronometer and wonder: if society were challenged with the same problem today, would we come up with the same elegantly simple solution? Hundreds of years later, simple devices like this can encourage all of us to take a fresh look at the way we design with materials, even as new research and technologies have us poised to surpass traditional craft-based production methods. The emergence of digital fabrication technologies and the rapid advance of new research in synthetic biology, materials science, and other fields are making it possible not just to tap into, but also to create material properties in a new way, bringing the possibility of a new industrial revolution into view—a materials revolution.

In this book, I offer you a glimpse inside this emerging materials revolution, from my vantage point as founder and codirector of MIT's Self-Assembly Lab.[2] The Self-Assembly Lab is a group of architects, designers, artists, engineers, scientists, computer scientists, and many others who work on a variety of research topics from self-assembly to new material behaviors or new fabrication processes. Through this work, we explore applications in product design, manufacturing, construction, and large-scale environments. Sitting at the intersection of design, science, and engineering, we are an academic research lab that blends creativity with exploration, elegant design aesthetics with technical performance, and the design principles needed to make those ideas reality. At its core, our work is motivated by the conviction that smarter, higher-performing products and sustainable environments don't require complicated, expensive, device-centered solutions to achieve. Instead, we seek to use simple materials and their relationships with environmental forces to design and create a more active, adaptive, lifelike world around us.

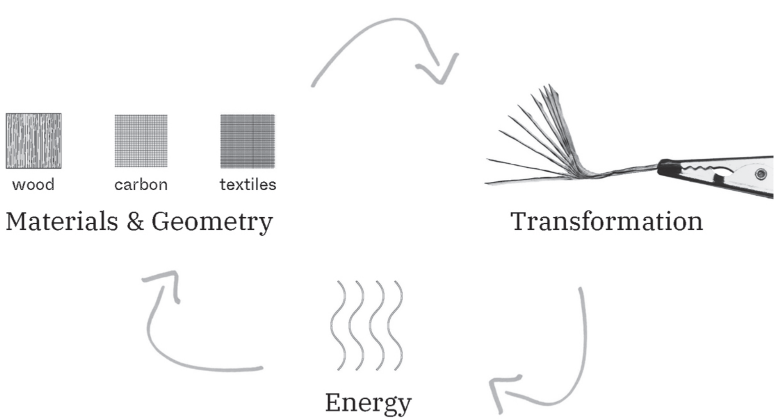
In this work, we are part of a broader community of scientists, engineers, and designers across research and industry who are finding ways to design, create, and program physical materials that can do more than even Harrison could have dreamed. These materials can take in information, perform logical operations, sense, react, and much more. Unique behaviors often seen only in living natural systems—like the ability to correct errors, reconfigure, replicate, assemble themselves, grow, evolve, and so on—can now emerge in innate material objects. At the Self-Assembly Lab, for instance, we have explored phenomena where physical components assemble and self-organize to build structures from objects, furniture, electronic devices, and even land formations. By understanding and utilizing material capabilities, we can give simple materials and environments new functionality—going beyond mass production or even mass customization, into material programmability with behavioral intelligence built into our products.

As we will explore throughout this book, recent material advances are influencing various fields from robotics to apparel, furniture, medical devices, manufacturing, construction, and even coastal engineering. With novel material functions embedded within fibers, we are now creating clothing and textiles that can adapt to temperature or moisture fluctuations and keep you cool or dry on the fly. Furniture and products can transform in size, shape, or function and assemble themselves after being shipped flat. Novel medical devices are emerging that can be quickly multimaterial printed to be customized to the individual's body. When they are inserted, they adapt to the person's internal environment, expanding arteries or air passages without complex behaviors. At the largest of scales, a simple material like sand becomes a medium to promote the self-organization of new islands or coastlines by tapping into the energy of the ocean. These and many other material-driven performances are coming into reality where simple products are becoming more active and static things are becoming more lifelike and playful.

This kind of work ultimately requires a new way of collaborating with materials in our broader environment, new relationships with our products, a different mindset, and a fresh way of looking at the world. This book describes that new mindset through simple design principles that offer new ways to think about traditionally "static" mechanisms, products, and environments—as well as a different definition of what makes a product "smart." The world is crying out for highly intelligent, active, and "smart" products, yet far too often we see smart products that are expensive, complex, battery-powered devices that are prone to failure. The principles in this book point to a different path forward. My hope is that they will make you stop and think, and wonder why some "smart products" might not be quite that smart after all. The aim is to show how we can take advantage of these hidden possibilities inherent in our physical world—and uncover a new relationship with materials, tapping into their built-in intelligence.

What do we mean when we talk about programming materials, and how has this reality emerged? We can start with a general definition: to program something is to create a set of executable instructions that an intended medium can perform or process. This is, obviously, a *very* general definition of programming—I'm using *medium* instead of computer, because, as I will explain, *we can embed a program into any medium.* Any time we perform a set of instructions, we're executing a type of program. When we program materials, we're embedding such instructions into a *physical* material, such that the material can make logical decisions and can sense and respond to its environment.

Thus, we can define a **programmable material** as a physical material structure that is embedded with information and physical capabilities like logic, actuation, or sensing. A related term, **active matter**, is used throughout this book to describe the expanded field of researchers that are programming materials from the smallest to the largest of scales to create highly active structures that can self-assemble or physically transform.[3] I will both describe the ways to program a material and explore the applications of its active behavior. In essence, these emerging material systems are all based on the ability to take simple material components, activate them with energy, and then have them assemble, transform, and create new physical behaviors.



A diagram showing the key ingredients for programmable materials: materials, geometry, and energy to create physical transformations. *Credit:* Self-Assembly Lab, MIT

The idea of matter that can be programmed is a fairly old concept, but our understanding and realization of the idea has changed. People have been dreaming of programming matter since at least the Star Trek Replicator, with a machine that could instantly create anything.[4] There are many early examples from science fiction that dream of infinitely small programmable material units that can be easily fabricated and set free to live, grow, and transform.[5] This dream has a long history of overpromising and underdelivering, however, most likely due to the lack of material and fabrication capabilities, until very recently.

Of course, from another perspective, there is a sense in which matter has always been "programmed." Everything around us is *programmed* to sense something or function based on built-in information. The most obvious examples come from living systems: just think of our DNA, which encodes the instructions to build a human, or how a plant grows toward sunlight. But our everyday life is replete with materials that transform in this manner, according to built-in information. In addition to complex living things, we can also see physical transformation in natural, yet nonbiological materials, or even synthetic materials that sense and respond to the ambient environment. For example, crystals that grow and morph, or chopped wood, which is no longer alive yet will still warp in response to changes in humidity, and plastics that expand or contract based on temperature. All of these materials are nonbiological, coming from both natural and synthetic systems, and all demonstrate lifelike, information-rich behavior.

Craftspeople, master builders, or anyone with an intimate, hands-on relationship to materials like John Harrison are the forerunners of today's "matter programmers," having long taken advantage of the inherent characteristics of materials. For example, craftspeople have used wood's inherent properties when making furniture or building joints, ship hulls, or whiskey barrels, forging tighter and stronger joints by changing the amount of moisture in the environment in which they were made. Metalsmiths often use the expansion and contraction of metal based on temperature to make precise and strong connections. Or engineers design a metal component for an engine to be able to operate uniformly with ever-changing environmental fluctuations. Textile manufacturers often use temperature and moisture to control the contraction of a garment to create finely tuned shapes and sizes.

Today, however, new digital fabrication technologies can produce at speed and scale while also customizing material properties, giving us greater capabilities than ever before. Computing, fabrication, and materials share deep and long-standing links. The Jacquard loom, invented in the 1800s and considered one of the earliest examples of computing, read punch cards as an analog program to create intricate and beautifully complex woven textiles.[6] More recently, not long after the modern computer was born with the invention of the transistor in 1947, scientists at MIT first linked a modern-day computer with a milling machine in 1952.[7] This paved the way for the first computer-aided design (CAD) tool in 1963 and today's computer numerically controlled (CNC) machining with CAD to CAM (computer-aided manufacturing) design workflows. This allowed computers to be programmed to run fabrication equipment that produced material parts.[8] Nearly every manufactured product today is made in some way with this sequence of technology—CAD to CAM to CNC—from electronic devices to cars, clothing, buildings, infrastructure, airplanes, and even children's toys. In the twenty-first century, we have achieved an ever-increasing level of sophistication with digital fabrication capabilities using laser cutters and water jets, 3D printers, milling machines, industrial robot arms, and many other technologies. These are acquainting more and more people with the properties of materials and machines, as well as eroding traditional boundaries between design and fabrication, materials and information.

This development in computing, fabrication, and materials research has led to the growing materials revolution and enabled programmable materials. Not only can we take advantage of the hidden abilities within materials to sense and transform, but we can customize the material with these rapidly advancing fabrication techniques. In the same way that we can alter the "instructions" coded into DNA using principles of synthetic biology and other technological advances like gene editing, we can now customize and produce complex compositions of many different materials, from scratch. We can go beyond the evolutionary mutations that have led to specific genes or material properties to now fabricate embedded material codes. For example, we can now produce synthetic wood that responds to moisture with customized grain patterns that would never be found naturally, complex metal components that adaptively tune engines, high-performance composites that morph for aerodynamics, and multimaterial printed structures for smart medical devices. All of these examples have both geometric complexity and a diversity of material properties, designed according to a set of instructions for tunable and adaptive performance.

This entire progression, from naturally evolved materials to synthetically designed and generated materials toward fully programmable materials, can be seen in the simple example of the continuing evolution of fashion and footwear. We can trace the lineage from traditional natural spun-cotton garments to programmably controlled textile production, and now synthetic fibers and high-performance textile products. More recently, the industry is turning the corner toward smarter garments that have sensors and actuators embedded within the textile to inform and act on our body's every move. These robotlike articles of "smart" clothing are quickly evolving from bulky garments with bulky devices to simple and smarter materials. The Self-Assembly Lab has worked with emerging companies, like Ministry of Supply, to develop highly active garments that can be made from material properties intelligently knit into intricate garments, functioning through materials, rather than complicated devices.[9] Garments can become porous and breathe when the person is hot, or get thicker to insulate them when they get cold. The garment can morph to the person's body shape and create the perfect fit, or change aesthetics for different occasions. Not only are we using novel materials, but we can now fabricate garments and other products in this new way, enabling active performance in everyday clothing.

One might assume that a *programmable* material would be more electronic or robotic, less human, static, and less active—just sitting there waiting to be programmed. But as I hope to show you, today's *digital* capabilities have actually reintroduced the human perspective and the craft of materials. Intimate knowledge of a material's properties brings surprise and intuition back into discovery and invention. Programming materials is more about opening our eyes and designing in collaboration with materials rather than forcing them into place.

The ideas within this book seek to illuminate the surprising, yet still mostly untapped, capabilities of materials through novel approaches to design and fabrication. We will uncover ways to seemingly reverse entropy, create simple material "robots," and program everyday physical objects or environments to come alive. We will challenge the conventional idea that things fall apart: objects can get better with time, and we can program materials to become more active, to adapt, and to evolve on their own. We will question why so many objects and environments are designed to be static and why human-made things typically don't have lifelike properties—for example, why they can't grow, transform, or repair themselves. Why does a "strong" structure usually mean it requires *more* material, *more* rigidity in its composition? Think of a plant or a tree, whose strength usually comes not from bulk or excess material, but from efficient distribution, flexibility, and the ability to adapt to different forces, to error correct, or regrow when needed. We will discuss the reasons why we've become so comfortable with the notion of what a robot or a computer looks like and how it behaves, yet why that is rapidly changing. In this way, we arrive at the new reality of active matter.

These ideas have taken shape after years of play, experimentation, collaboration, failure, and some happy accidents at the Self-Assembly Lab, yet they go far beyond our own work, crossing many academic disciplines and offering surprising applications in many different fields. This emerging field is based on blending rigorous science and engineering with creativity, play, and imagination. Progress requires not only the solution of technical problems but also the freedom to explore creatively and to take big risks, tackle big questions, and propose radical ideas. Accordingly, throughout the book we'll explore both concrete examples of technological advances being made today by talented designers, scientists, and engineers across different fields, as well as near-term thought experiments and possible futures. While this emerging field is rapidly growing and has shown promising advances, it is still early days. We are in just the beginning of this materials revolution, and much of the potential impact or applications have yet to be realized. At this exciting juncture, I am hoping to create purposeful visions for the future to help catalyze these advances, inspire applications and new collaborations, and energize the field of active matter.

Index

Page numbers in italics refer to figures.