

Contents

<i>Acknowledgments</i>	IX
Programming Matter	1
Computing Is Physical	15
Order from Chaos	41
Less Is Smart	57
Robots without Robots	77
Build from the Bottom Up	97
Design from the Bottom Up	117
Reverse, Reuse, Recycle	135
The Future of Matter Is Evolving	155
<i>Notes</i>	175
<i>References</i>	181
<i>Index</i>	193
<i>Image Credits</i>	211

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 so-

ciety 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

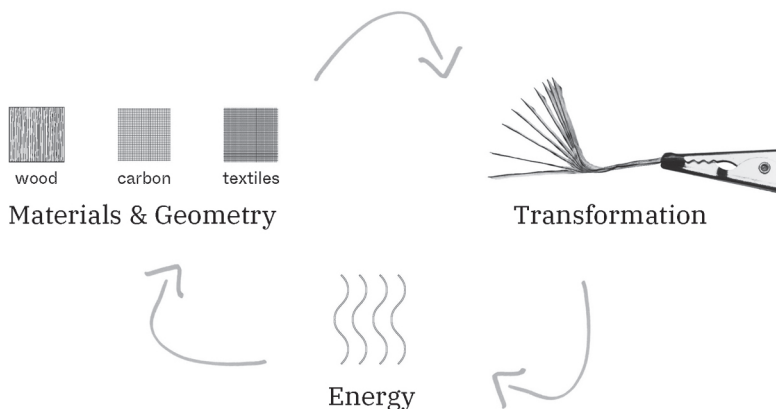
the individual's body. When they are inserted, they adapt to the person's internal environment, expanding arteries or air passages without complex behaviors. At the largest of scales, a simple material like sand becomes a medium to promote the self-organization of new islands or coastlines by tapping 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.

- 3D printing, 10; active products and, 69, 72–73; computing and, 15, 18; customization and, 138–40; error correction and, 140; gravity and, 138–39; limitations of, 138; liquid metal, 141, *142*; multi-material, 73, 80; rapid liquid printing (RLP) and, 138–41; robots and, 80, 82; textiles and, 69; wood and, *123*
- 4D printing, 79–85, 143
- activation energy: disassembly and, 149; Goldilocks principle and, 48; order and, 46, 48; pressure and, 46, 145, 161; vibration and, 46
- active matter: advances in, 162; education for designers of, 158; order and, 42; periodic table for, 161; programming matter and, 7, 12–13, 42, 57, 158, 161–62
- Active Matter Summit, 175n3
- active products: 3D printing and, 69, 72–73; adaptability and, 66, 70–75; biomaterial and, 74–75; bottom-up assembly and, 130; common platform and, 160–65; complexity and, 67–69, 73; contraction and, *71*, 73; control and, 70; efficiency and, 72; error correction and, 58–61; fabrication and, 66, 69, 74; flexibility and, 67, *68*; functionality and, 70; geometry and, 67–69; manufacturing and, 67–73, 75; material properties and, 57, 70, 73, 75; moisture and, *71*, 72–73; nature and, 69, 73; Self-Assembly Lab and, 66, *68*, *71*, 74; sensors and, 74; static products and, 66–67, 69, 75; synthetics and, 75; textiles and, 66–75; wood and, 66
- actuators, 11, 32, 74, 77, 85–87, 92, 117
- adaptability: 3D printing and, 82; 4D printing and, 84–85; active products and, 66, 70–75; bottom-up assembly and, 98–103, 105, 109, *111*, 114; bottom-up design and,

- adaptability (*continued*)
 - 118–19, 127–33; complexity and, 57–58; computing and, 25–27; customization and, 137–38, 141; disassembly and, 148; environment and, 78; error correction and, 59–60; future issues and, 155–56, 164, 169–73; growth and, 150, 153; inflatable materials and, 93; order and, 42; programming matter and, 2, 5–6, 10, 12; redundancy and, 61; robots and, 92–95; robustness and, 26, 57–61, 66, 86; sustainability and, 135
- adhesives, 51, 63, 146
- Advanced Functional Fabrics of American (AFFOA), 71–72
- air bubbles, 27–28
- algorithms, 36, 103
- alloys, 2, 82
- Apple, 159
- Arduino, 15
- artificial intelligence (AI), 155, 158; bottom-up assembly and, 132; common platforms and, 162–64; computing and, 26, 35; material AI and, 87, 89, 170–73
- asphalt, 145
- astronomy, 1, 172
- Atoms to Products (A2P), 168
- automation, 34–35, 164
- Avogadro's number, 167
- bacteria, 25
- balloons, 49, 140
- Bell Labs, 18, 159
- Benjamin, David, 101, 151
- bimetal, 2, 86, 172
- bioLogic, 74
- biology: active products and, 74; bacteria and, 25; bottom-up design and, 131–32; computing and, 18, 23–27, 36–37; efficiency of, 167; future issues and, 158; growth and, 151; mass speciation and, 16–19; material AI and, 171–72; modularity and, 144; mutations and, 23; order and, 42, 44, 46; polymorphism and, 36, 169; robots and, 85; self-replication and, 165–68; synthetics and, 4, 8, 10, 18, 23, 25, 27, 85, 131–32, 151, 155, 170, 172
- biomaterial, 24–27, 44, 74
- Bletchley Park, 17
- blockchain, 163
- bonding strength, 48
- Boolean logic, 30, 31
- bottom-up assembly: active products and, 130; adaptability and, 98–103, 105, 109, 111, 114; artificial intelligence (AI) and, 132; chaos theory and, 126, 128; chemistry and, 105; collaboration and, 98, 101–2, 110, 112, 114–15; communication and, 99, 100; complexity and, 97–99, 103, 105–6, 109–10, 114–15; computing and, 118–20; control and, 99, 103–9; decision-making and, 117, 121, 126, 128; design as adaptation and, 127–29;

- design as optimization and, 127; design by chaos and, 126; design by committee and, 126; destruction and, 109–15; DNA and, 110; efficiency and, 106; fabrication and, 106, 110; functionality and, 97, 105, 109, 114; generative adversarial networks (GANs) and, 121–22; genius designers and, 126, 128; geometry and, 106–7, 111, 112–14; manufacturing and, 103–4, 106, 109; material properties and, 112; moisture and, 122–24; nature and, 97–98, 105, 110, 112, 115; order and, 46; pre-process execution and, 120; robots and, 97, 99–103, 106; self-assembly and, 106; self-organization and, 110–15, 127; sequence and, 102–4; synthetics and, 105; wave tank experiments and, 112, 113–14
- bottom-up design: active products and, 74–75; adaptability and, 118–19, 127–33; biology and, 131–32; collaboration and, 117–24, 128–33; communication and, 117; complexity and, 119, 125, 131–32; control and, 131, 133; decision-making and, 117; DNA and, 132, 167; efficiency and, 122, 124; fabrication and, 118, 124–25, 127, 129, 132; flexibility and, 140; functionality and, 118, 128–32; geometry and, 123, 125; gravity and, 122, 124; hardware and, 130; manufacturing and, 117; material properties and, 117–18, 132; metal and, 118; morphing and, 119, 124; nature and, 118, 122–25, 131–32; reconfigurability and, 128; robots and, 117; self-assembly and, 117; self-organization and, 127; software and, 126, 129; static products and, 117, 127; synthetics and, 122, 131–32; textiles and, 124; wood and, 118, 122, 122–24
- British Parliament, 1
- Brownian motion, 47
- Bush, Vannevar, 16
- Carbitex LLC, 87, 88, 89
- carbon dioxide, 145
- carbon fiber, 87, 88–89
- carbon forms, 169
- Carnegie Mellon, 159
- cassette tapes, 24
- CDs, 24
- cell phones, 53, 106, 143, 145
- cellular automata, 38
- cellulose, 85, 151, 152
- Center for Bits and Atoms (CBA), 79, 90
- chains, 79, 122, 124–25
- chaos theory: bottom-up assembly and, 126, 128; cellular automata and, 38; computing and, 38–39; entropy and, 11, 41–43; order and, 46, 55
- checks and balances, 17, 163
- Cheerios Effect, 54

- chemistry: active matter and, 42; blending disciplines and, 158; bottom-up assembly and, 105; communication and, 32; computing and, 32, 37; curing processes and, 139, 141; customization and, 139; error correction and, 59; insects and, 98; modularity and, 143–44; morphogenesis and, 37; polymorphism and, 169; printed multimerials and, 91–92; self-assembly and, 44, 168; self-repair and, 145, 149; self-replication and, 165
- Chiodo, Joseph, 146
- chronometers, 1–2, 4, 86
- Church, George, 23–24
- Coelho, Marcelo, 101–2
- collaboration: bacteria and, 25; bottom-up assembly and, 98, 101–2, 110, 112, 114–15; bottom-up design and, 117–24, 128–33; common platforms and, 164–65; computing and, 25, 32; customization and, 138; design as adaptation and, 127–28; growth and, 153; mass speciation and, 169; material AI and, 172–73; order and, 46; programming matter and, 6, 11–13, 118–19, 155–57; research and, 46, 61, 69–71, 87–88, 91; self-replication and, 165
- Colossus, 17
- common platforms, 160–65
- communication: antennas and, 33; bottom-up assembly and, 99, 100; bottom-up design and, 117; common platform and, 160–65; computing and, 15, 17–18, 29–34, 33; material AI and, 172
- complexity: active products and, 67–69, 73; adaptability and, 57–58; blending disciplines and, 158; bottom-up assembly and, 97–99, 103, 105–6, 109–10, 114–15; bottom-up design and, 119, 125, 131–32; computing and, 19, 21, 33, 37–38; customization and, 140–41; DNA and, 167–68; error correction and, 61; nature and, 167; order and, 41–42, 44, 55; programming matter and, 6–10, 16, 171; redundancy and, 61; robots and, 80, 82, 83, 88, 90, 92, 94–95
- Computational Fabrication Group, 138
- computer-aided design (CAD), 9
- computer-aided manufacturing (CAM), 9
- computer numerically controlled (CNC) machining, 9, 18
- computing: 3D printing and, 15, 18; adaptability and, 25–27; artificial intelligence (AI) and, 26, 35, 170–73; bacteria and, 25; biology and, 18, 23–27, 36–37; biomaterial and, 24–27; bottom-up assembly and, 118–20; bugs

- and, 16; cellular automata and, 38; chaos theory and, 38–39; chemistry and, 32, 37; code and, 15, 17–19, 21, 23–24, 31, 33, 35–36, 38; collaboration and, 25, 32; communication and, 15, 17–18, 29–34; complexity and, 19, 21, 33, 37–38; digital material and, 18–19, 171; DNA and, 18, 23–24, 26, 35; efficiency and, 26, 31, 34–39, 95; error correction and, 17, 21, 24; fabrication and, 15, 18; flexibility and, 26; functionality and, 23–25, 32–33; geometry and, 19, 21–22, 30, 31, 33, 37; gravity and, 21–22; haptic interfaces and, 15, 74, 92; hard drives and, 23–24, 26, 31, 35; hardware and, 15, 18, 21; historical perspective on, 15–20; human-computer interfaces (HCI) and, 15; logical operations and, 5, 15, 27–31, 37; machine learning and, 25, 35, 121, 132, 138; materials and, 18–29, 34, 37, 170–73; metal and, 27–28; moisture and, 16, 28, 31–32, 36–37; morphing and, 21–22, 33, 36–37; motors and, 15, 21; nature and, 24–25, 27, 32, 39; plastics and, 27; polymers and, 68, 70, 73; robots and, 21–22; robustness and, 26, 57–61, 66, 86; sensors and, 32; Shannon on, 17–18; silicon and, 15, 17, 19, 22, 35; software and, 15, 21–22, 35; synthetics and, 18, 23, 25, 27; temperature and, 16, 28, 31, 33; trajectory of, 170–71; Turing and, 17, 22, 37; universal, 22–23, 26, 28, 31; vibration and, 33–34; without efficiency, 34–39; zip drives and, 24
- concrete, 12, 42, 59, 66, 124, 140, 144–45
- contraction: 3D printing and, 82; active products and, 71, 73; error correction and, 60; metal and, 9, 86; moisture and, 16; temperature and, 2, 8–9, 16, 60, 73, 86, 145; textiles and, 9, 71
- control: active products and, 70; aviation and, 88–90; bottom-up assembly and, 99, 103–9; bottom-up design and, 131, 133; CNC machining and, 9; common platforms and, 162; communication and, 33; microfluidic logic and, 92; modularity and, 144; nature and, 156; pneumatic, 93; randomness and, 37–39, 43, 46, 51, 104–5, 125–26; redundancy and, 66; self-replication and, 168; textiles and, 9–10
- Cooper, Muriel, 35
- cotton, 10
- COVID-19 pandemic, 20
- CRISPR technologies, 132
- crystals, 8, 41, 44, 173

- customization: 3D printing and, 138–40; adaptability and, 137–38, 141; collaboration and, 138; complexity and, 140–41; functionality and, 136–37, 143; gravity and, 139, 141; manufacturing and, 138, 143; material properties and, 137–38, 143; metal and, 141; morphing and, 137, 140–41; plastics and, 139, 140; rapid liquid printing (RLP) and, 138–41; recyclability and, 136–43; robots and, 140–43, 171, 173
- Danino, Tal, 24–25
- Darwin, Charles, 122
- decision-making: bottom-up assembly and, 117, 121, 126, 128; genius designers and, 126; material logic and, 86–90, 171; programming matter and, 7, 157; spatial search and, 171
- Defense Advanced Research Projects Agency (DARPA), 79–85
- design as adaptation, 127–29
- design as optimization, 127
- design by chaos, 126
- design by committee, 126
- diamond, 169
- Dickey, Michael, 141
- Dierich, Karola, 148
- Differential Analyzer, 16
- digitalization, 3–4
- digital material, 18–19, 171
- disassembly: activation energies and, 149; adaptability and, 148; destruction and, 109–15; functionality and, 148; geometry and, 149; moisture and, 146; plastics and, 149; recyclability and, 136, 146–50; robots and, 147; sensors and, 147; temperature and, 146; vibration and, 146
- disintegration, 75, 147–49
- Distributed Robotics Lab, 91
- DNA: base-pair sequences and, 23, 45; bottom-up assembly and, 110; bottom-up design and, 132, 167; complexity of, 167–68; computing and, 18, 23–24, 26, 35; CRISPR technologies and, 132; error correction and, 59, 167; manufacturing and, 167, 169; order and, 44–45, 48, 53, 55; programming matter and, 8, 10; robots and, 85; self-assembly and, 18, 44–45, 169
- Dole, Sarah, 110
- drones, 99–100, 101, 112
- efficiency, 58, 159; active products and, 72; biology and, 167; bottom-up assembly and, 106; bottom-up design and, 122, 124; computing and, 26, 31, 34–39, 95; elegant code and, 95; future issues and, 167, 171; plane components and, 87–88, 90; programming matter and, 12; redundancy and, 61, 64; robots and, 77
- ENIAC (Electronic Numerical Integrator and Computer), 17
- Eno, Brian, 36, 119

- entropy, 11, 41–43
- equilibrium: entropy and, 11, 41–43; error correction and, 60; order and, 42–44, 46, 48; temperature and, 42
- error correction: 3D printing and, 140; adaptability and, 59–60; built-in, 168; checks and balances, 17, 163; chemistry and, 59; complexity and, 61; computing and, 17, 21, 24; contraction and, 60; DNA and, 59, 167; equilibrium and, 60; expansion and, 60; fabrication and, 60; feedback loops and, 38, 92, 119, 128–29, 138, 161, 163; flexibility and, 60–61; functionality and, 59; growth and, 60; manufacturing and, 59–60; moisture and, 60; nature and, 59–60; order and, 51–53, 55; sketching and, 35; static products and, 59
- ETH Zurich, 62, 63, 99, 101, 148
- Evolutionary Architecture, An* (Frazer), 122
- expansion: 3D printing and, 82, 83; adhesives and, 146; error correction and, 60; Harrison's sea clock and, 2; manufacturing and, 156; medical devices and, 6; moisture and, 80; robots and, 82, 92; silicone and, 140; temperature and, 2, 8–9, 16, 60, 73, 86, 145
- fabrication: active products and, 66, 69, 74; blending disciplines and, 158–59; bottom-up assembly and, 106, 110; bottom-up design and, 118, 124–25, 127, 129, 132; checks and balances, 17, 163; common platform for, 160–65; computing and, 15, 18; customization and, 137–43; error correction and, 60; growth and, 151–53; mass speciation and, 169; material AI and, 170–73; order and, 55; programming matter and, 4, 8–11; robots and, 82–85, 91–92; waste and, 58, 135–37, 141, 144, 147, 150–52
- feedback, 38, 92, 119, 128–29, 138, 161, 163
- fiberglass, 49
- flexibility: active products and, 67, 68; bottom-up design and, 140; computing and, 26; error correction and, 60–61; mass speciation and, 168; programming matter and, 12; redundancy and, 61; robots and, 85, 87, 88, 90, 92, 164; spheres and, 166
- Fluid Assembly Chair, 52, 53
- fluidic logic, 27–28
- Flyknits, 69
- Frazer, John, 122
- Fry, Ben, 35, 119, 120
- functionality: active products and, 70; bottom-up assembly and, 97, 105, 109, 114; bottom-up design and, 118, 128–32; computing and, 23–25, 32–33; customization and, 136; disassembly

- functionality (*continued*)
 - and, 148; error correction and, 59; future issues and, 158–59, 170, 173; macro-scale, 168; material AI and, 170, 173; order and, 44; programming matter and, 5; robots and, 90, 95
- furniture, 5, 9, 59, 135, 138
- fused deposition modeling (FDM), 139–40
- future issues: active products and, 155–56; adaptability and, 155–56, 164, 169–73; artificial intelligence (AI) and, 155, 158, 162–64, 170–73; blending disciplines and, 158–60; changing landscape and, 155–57; common platforms and, 160–65; communication and, 160, 164, 172; efficiency and, 167, 171; functionality and, 158–59, 170, 173; manufacturing and, 156, 164, 167–70, 173; mass speciation and, 168–69; material properties and, 161, 164, 169–72; plastics and, 160, 166; reconfigurability and, 163, 171; robots and, 157, 162–73; self-replication and, 165–68; static products and, 156; synthetics and, 155–56, 170, 172
- Gaudi, Antoni, 122
- generative adversarial networks (GANs), 121–22
- genius designers, 126, 128
- geometry: 4D printing and, 80–85; active products and, 67–69; bottom-up assembly and, 106–7, 111, 112–14; bottom-up design and, 123, 125; carbon fiber and, 87, 89; computing and, 19, 21–22, 30, 31, 33, 37; customization and, 140; disassembly and, 149; order and, 45–46, 48, 50, 52, 53, 55; programming matter and, 3, 7, 10; redundancy and, 61; self-repair and, 145; self-replication and, 166
- glass, 46, 145
- Goldberg, Rube, 43
- Google, 35, 64, 136, 159, 162
- Gramazio Kohler Research, 61–63, 99–100, 101, 148
- granular convection, 50
- granular jamming, 62, 63–65, 85, 148
- graphene, 169
- graphite, 169
- gravity: 3D printing and, 138–39; bottom-up design and, 122, 124; computing and, 21–22; customization and, 139, 141; programming matter and, 3; robots and, 77
- growth: adaptability and, 150, 153; biology and, 151; cellular, 167; collaboration and, 153; error correction and, 60; fabrication and, 151–53; manufacturing and, 151–52; nature and, 60, 151; recy-

- clability and, 136, 150–53;
- sustainability and, 150; syn-
- thetics and, 151
- Gruber, David, 92
- Guburan, Christophe, 68, 69, 87,
123, 124, 138, 139
- haptic interfaces, 15, 74, 92
- hard drives, 23–24, 26, 31, 35
- hardware: bottom-up design
and, 130; computing and,
15, 18, 21; impact of, 155,
161; programming matter
and, 4; upgrades and, 135
- Harrison, John, 1–2, 4–5, 8, 86,
172
- Harvard University, 16, 44,
92, 99
- human-computer interfaces
(HCI), 15
- humidity: 8, 32, 122, 8, 32, 122
- hydrogels, 80, 145
- hyperbolic surfaces, 67
- IBM, 159
- Industrial Revolution, 3
- inflatable devices, 74, 91, 93,
140–41, 143
- infrared (IR) light, 33–34
- Inkbit, 138
- Institute for Computational
Design (ICD), 122, 124
- Ishii, Hiroshi, 74
- Jacquard loom, 9, 16
- Jaeger, Heinrich, 148
- Kernizan, Schendy, 175n2
- Kilobots, 97, 99, 100
- Kudless, Andrew, 124
- language, 23, 32–33, 35, 160–
61, 163
- laser cutters, 9, 18, 69, 91
- Laucks, Jared, 175n2
- Lee, Suzanne, 151
- Lego, 18, 44, 144
- Lewis, Jennifer, 91
- LeWitt, Sol, 36, 119
- LG, 136
- Little Bits, 15
- logical operations, 5, 15, 27–28,
30, 31, 37
- Logic Matter, 31
- longitude, 1
- Lovelace, Ada, 16
- Lycra, 66
- machine learning, 25, 35, 121,
132, 138
- Maeda, John, 35
- magnetism, 51, 53–55, 166, 172
- Makey Makey, 15
- Maldives, 109–15, 127
- Maniku, Hassan, 110
- manufacturing: active products
and, 67–73, 75; bottom-up
assembly and, 103–4, 106,
109; bottom-up design and,
117; common platform and,
160–65; computer-aided
(CAM), 9; control and, 103–9;
customization and, 138,
143; DNA and, 167, 169;
error correction and, 59–
60; future issues and, 156,
164, 167–70, 173; growth
and, 151–52; localized
fabrication and, 136; modu-
larity and, 21, 136, 143–44,
156; order and, 46, 55;

- manufacturing (*continued*)
 - programming matter and, 3–5, 9; robots and, 77, 88, 94–95; standardization and, 3, 136; transportation and, 136–37
- Mark II, 16–17
- mass speciation, 168–70
- material AI: collaboration and, 172–73; computing and, 170–73; decision-making and, 87, 89, 171; fabrication and, 170–73
- material logic, 86–90
- material properties: active products and, 57, 70, 73, 75; alloys and, 2, 82; bonding strength and, 48; bottom-up assembly and, 112; bottom-up design and, 117–18, 132; common platform and, 160–65; computing and, 18–29, 34, 37; creating new, 4; customization and, 137–38, 143; enhanced, 164; environment and, 3, 9, 12, 37, 75, 80, 82, 117, 132, 169, 172; future issues and, 161, 164, 169–72; Harrison and, 2; ideal platform for, 161; maker fairs and, 18; metals and, 2–3, 9–10, 27, 48, 118, 171–72; public education of, 10; redundancy and, 65; reversible, 65; robots and, 80–84; self-assembly and, 47; textiles and, 11, 70, 73
- mathematics, 1, 82, 95, 159, 165, 172
- Matusik, Wojciech, 138
- Maxwell, James Clerk, 42
- Mechanics of Self-Reproduction* (Penrose), 165–66
- Media Lab, 74
- Mediated Matter, 153
- medical devices, 2, 5–6, 10, 26, 74, 84, 130, 140, 147
- Menges, Achim, 148
- metal: bimetals and, 2, 86, 172; bottom-up design and, 118; common platform and, 160; computing and, 27–28; contraction and, 9, 86; customization and, 141; Harrison's sea clock and, 1; liquid, 141, 142; moisture and, 9–10; programming matter and, 2–3, 9–10; properties of, 2–3, 9–10, 27, 48, 118, 171, 172; robots and, 92; self-replication and, 166; shape memory, 2, 82; temperature and, 2, 9, 86, 141, 172
- Microsoft, 159
- milling machines, 9–10, 18
- Ministry of Supply, 11
- modularity: biology and, 144; chemistry and, 143–44; control and, 144; manufacturing and, 21, 136, 143–44, 156; nature and, 1; reconfigurability and, 144; recyclability and, 136, 143–44; robots and, 143–44
- moisture: active products and, 71, 72–73; bottom-up assembly and, 122–24; computing and, 16, 28, 31–32, 36–37; contraction and, 16; disassembly and, 146; error correction and, 60; expansion and, 80; humidity and,

- 8, 32, 122; ideal experimental platforms and, 161; manufacturing standardization and, 3; metals and, 9–10; robots and, 77–78, 80, 81, 83, 85, 88–89, 94; sea clock and, 2; self-healing and, 145; temperature and, 2–3, 5, 9, 16, 28, 31, 57, 60, 73, 77–78, 88–89, 145–46, 151; textiles and, 5, 9, 71, 72–73; wood and, 9–10, 32, 85, 122–24
- Molecular Foundry, 168
- morphing: applied loads and, 58; bottom-up design and, 119, 124; computing and, 21–22, 33, 36–37; customization and, 137, 140–41; granular jamming and, 64, 65; inflatable materials and, 93; plane components and, 87–88, 90; polymorphism and, 36, 169; programming matter and, 2, 8, 10–11; smart products and, 10, 58, 90, 94
- Morse code, 33
- motors, 15, 21, 47, 78, 86, 88, 94
- multimaterial printing, 5, 10, 73, 80, 81, 91, 138, 140–41, 143, 158
- Museum of Modern Art (MoMA), 151
- mycelium, 151
- Nagpal, Radhika, 99
- NASA, 16, 90
- National Geographic, 92
- nature: active products and, 69, 73; bottom-up assembly and, 97–98, 105, 110, 112, 115; bottom-up design and, 118, 122–25, 131–32; chemistry and, 98; complexity of, 167; computing and, 24–25, 27, 32, 39; controlling, 156; energy sources of, 94; environmental change and, 155–56; error correction and, 59–60; forces of, 3, 78, 110–12, 115, 122, 125; growth and, 60, 151; living systems and, 5; modularity and, 1; order and, 41, 43, 46, 55; self-replication and, 168; smart materials and, 85; synthetics and, 8 (*see also* synthetics); transformers and, 3, 78, 110–12, 115, 122, 125
- navigation, 1–2
- New Kind of Science*, A (Wolfram), 38
- Nike, 69
- Nitinol, 2
- nylon, 67
- Octobot, 76, 91–92
- Olson, Arthur, 46
- Omenetto, Fiorenzo, 74–75, 147
- On Growth and Form* (Thomson), 122
- optimal design, 34–35, 107–8, 126–28, 171
- order: activation energies and, 46, 48; active matter and, 42; adaptability and, 42; biology and, 42, 44, 46; chaos theory and, 46, 55; collaboration and, 46; complexity and, 41–42, 44, 55; DNA and, 44–45, 48, 53, 55;

- order (*continued*)
 - entropy and, 11, 41–43;
 - equilibrium and, 42–44, 46, 48; error correction and, 51–53, 55; fabrication and, 55; functionality and, 44;
 - geometry and, 45–46, 48, 50, 52, 53, 55; manufacturing and, 46, 55; Maxwell's demon and, 42; nature and, 41, 43, 46, 55; polarity and, 53–55; polymers and, 42; reconfigurability and, 55; second law of thermodynamics and, 41–43; self-assembly and, 44–48, 49, 52, 53–55; self-healing and, 41–42, 59, 145–46; self-organization and, 41, 44, 54; smart products and, 55; static products and, 42, 53
- Origin of Species* (Darwin), 122
- Otto, Frei, 122
- Oxman, Neri, 153
- packaging, 136, 151
- pandemics, 20, 160
- Papert, Seymour, 35
- Patagonia, 137
- Penrose, Lionel, 165–66
- personal computers, 34–35
- plane wings, 78, 87–90
- plants, 8, 12, 32, 46, 47, 59, 97, 105, 145, 171–72
- plastics: computing and, 27;
 - customization and, 139, 140; disassembly and, 149;
 - future issues and, 160, 166; self-assembly and, 46; self-repair and, 145; temperature and, 8
- polarity, 53–55
- poliovirus, 46, 47
- polymers: active products and, 68, 70, 73; carbon fibers and, 87, 88–89; order and, 42; robots and, 80, 82, 87, 88–89; self-repair and, 145; textiles and, 68
- polymorphism, 36, 169
- potential energy, 43
- Prakash, Manu, 27–28
- preprocess execution, 120
- pressure: activation energies and, 46, 145, 161; air, 78, 89–90, 93; carbon fiber and, 88; differential, 89; disassembly and, 146; environmental effects and, 31, 93; sea clock and, 2; self-assembly and, 46; self-repair and, 145
- Programmable Matter program, 79, 80, 85
- programming matter: active matter and, 7, 12–13, 42, 57, 158, 161–62; adaptability and, 2, 5–6, 10, 12; bacteria and, 25; collaboration and, 6, 11–13, 118–19, 155–57; complexity and, 6–10, 16, 171; concepts of, 6–13; decision-making and, 7, 157; digital material and, 18–19, 171; DNA and, 8, 10; efficiency and, 12; fabrication and, 4, 8–11; flexibility and, 12; functionality and, 5; geometry and, 3, 7, 10; gravity and, 3; hardware and, 4; living natural systems and, 5; manufacturing

- and, 3–5, 9; metal and, 2–3, 9–10; morphing and, 2, 8, 10–11; reconfigurability and, 5; robots and, 11–12; Self-Assembly Lab and, 7, 11–12; self-organization and, 5–6; smart products and, 5–6, 10–11; software and, 4; static products and, 6, 11–12, 20–21; synthetics and, 4, 8, 10; textiles and, 9–11
- randomness, 37–39, 43, 46, 51, 104–5, 125–26
- rapid liquid printing (RLP), 138–41
- Reas, Casey, 35, 119, 120
- reconfigurability: bottom-up design and, 128; computing and, 21; future issues and, 163, 171; making products and, 57–58, 137; modularity and, 144; order and, 55; programming matter and, 5; robots and, 79–80, 82
- recyclability: customization and, 136–43; disassembly and, 136, 146–50; modularity and, 136, 143–44; packaging and, 136, 151; reusability and, 135, 137, 143–44, 146, 150; self-repair and, 12, 24, 26, 41–42, 78, 129, 136–37, 144–46, 153, 156; waste and, 135–37, 141, 144, 147, 150–52
- redundancy, 61–65
- Resnick, Mitch, 35
- reusability, 135, 137, 143–44, 146, 150
- reversibility, 64, 138, 141, 143
- Rio 2016 Paralympics, 102, 103
- RNA, 23
- robots: 3D printing and, 80, 82; adaptability and, 92–95; biology and, 85; bottom-up assembly and, 97, 99–103, 106; bottom-up design and, 117; common platforms and, 162–65; complexity and, 80, 82, 83, 88, 90, 92, 94–95; computing and, 21–22; customization and, 140–43; disassembly and, 147; DNA and, 85; efficiency and, 77; electromechanical, 77–79, 82, 84–85, 88–92; expansion and, 82, 92; fabrication and, 82–85, 91–92; flexibility and, 85, 87, 88, 90, 92, 164; functionality and, 90, 95; future issues and, 157, 162–73; gravity and, 77; manufacturing and, 77, 88, 94–95; mass speciation and, 169; material logic and, 86–90, 171, 173; material properties and, 80–84; metal and, 92; modularity and, 143–44; moisture and, 77–78, 80, 81, 83, 85, 88–89, 94; motors and, 78, 86, 88, 94; plane wings and, 78, 87–90; polymers and, 80, 82, 87, 88–89; printable, 90–92; programming matter and, 11–12, 79, 80, 85; reconfigurability and, 79–80, 82; redundancy and, 63, 65; self-assembly and, 90; self-replication and, 165–67;

- robots (*continued*)
 - sensors and, 78, 85–88, 94;
 - silicon and, 91; soft, 79, 85, 91, 92–93, 140–41, 143, 164;
 - static products and, 78, 82, 84–85; synthetics and, 85;
 - temperature and, 77–78, 82, 84, 86–89; textiles and, 95; transformers and, 3, 78, 110–12, 115, 122, 125;
 - vibration and, 77–78; wearables and, 11, 74, 93–95;
 - wood and, 85
- robustness, 26, 57–61, 66, 86
- Rus, Daniela, 91
- sand: ripple patterns and, 44, 114–15; self-organization and, 6, 110–15, 127; wave tank experiments and, 112, 113–14
- scalability, 80, 85, 111, 157, 167–68
- sea clock, 1–2, 4, 86
- second law of thermodynamics, 41–43
- self-assembly, 4; biomaterial and, 44; bottom-up, 106, 117; Cheerios Effect and, 54; chemical, 168; chemistry and, 44, 168; disassembly and, 146–50; DNA and, 18, 44–45, 169; fabrication platforms and, 156; Fluid Assembly Chair and, 52, 53; order and, 44–48, 49, 52, 53–55; phenomenon of, 44; plastics and, 46, 145; polymers and, 145; pressure and, 46, 145; robots and, 90; self-organizing sand and, 109–15; spheres and, 166; temperature and, 46, 145
- Self-Assembly Lab: 3D printing and, 123; 4D printing and, 80–85, 143; active products and, 66, 68, 71, 74; air chamber assembly and, 108; balloon structures and, 49; carbon fiber and, 87, 89; founding of, 175n2; granular jamming and, 62, 64, 148; inflatable materials and, 93; Kernizan and, 175n2; Laucks and, 175n2; liquid metal and, 142; liquid printing and, 139; Ministry of Supply and, 11; Olson and, 46; order and, 46; programming matter and, 7, 11–12; role of, 4–5; self-organizing sand and, 109–15; slip-forming methods and, 64; sphere oscillation and, 167; water tank assembly and, 52, 54
- self-healing, 41–42, 59, 145–46
- self-organization: bottom-up assembly and, 110–15, 127; bottom-up design and, 127; order and, 41, 44, 54; programming matter and, 5–6; sand and, 110–15, 127
- self-repair: adaptability and, 144; chemistry and, 145; composites and, 144–45; recyclability and, 12, 24, 26, 41–42, 78, 129, 136–37, 144–46, 153, 156

- self-replication: biology and, 165–68; collaboration and, 165; control and, 168; metal and, 166; offspring code and, 165; Penrose on, 165–66; robots and, 165–67
- self-similar units, 54, 108
- sensors, 117; active products and, 74; computing and, 32; disassembly and, 147; robots and, 78, 85–88, 94; textiles and, 11, 74
- Shannon, Claude, 17–18
- shoes, 57, 66–70, 94, 106
- silicon: computing and, 15, 17, 19, 22, 35; inflatable structures and, 91, 93; robots and, 91
- silicone rubber, 140–41
- Silicon Valley, 160
- Silk Lab, 74–75, 147
- silkworms, 153
- simulations, 112, 126
- sketching, 35
- smart clothing, 11, 57, 74, 93–95
- smart products: active products and, 66–75; adaptability and, 57; error correction and, 58–61; morphing and, 10, 58, 90, 94; order and, 55; programming matter and, 5–6, 10–11; redundancy and, 61–66; robots and, 82–86, 90–92; static products and, 6; wearables and, 93–95
- software: bottom-up design and, 126, 129; computing and, 15, 21–22, 35; impact of, 155, 159–61, 165, 170; programming matter and, 4; upgrades and, 135
- spheres, 166–67
- standardization, 3, 57, 136
- Stanford University, 27
- static products: active products and, 66–67, 69, 75; bottom-up design and, 117, 127; error correction and, 59; future issues and, 156; making, 57–58; order and, 42, 53; programming matter and, 6, 11–12, 20–21; robots and, 78, 82, 84–85
- STEAM (science, technology, engineering, arts, and math), 158
- Steelcase, 138
- stereolithography apparatus (SLA), 140
- Styrofoam, 151
- Summer Pavilion, 151
- sustainability, 5, 115, 135, 143–44, 150
- synthetics: active products and, 75; biological materials and, 4, 8, 10, 18, 23, 25, 27, 85, 131–32, 151, 155, 170, 172; bottom-up assembly and, 105; bottom-up design and, 122, 131–32; computing and, 18, 23, 25, 27; future issues and, 155–56, 170, 172; growth and, 151; programming matter and, 4, 8, 10; wood and, 10
- Tangible Media Group, 74
- temperature: bimetallic structures and, 2, 86, 172; body,

- temperature (*continued*)
 - 2, 73; computing and, 16,
 - 28, 31, 33; digital inputs
 - and, 161; disassembly and,
 - 146; entropy and, 42; envi-
 - ronmental forces and, 3, 57;
 - equilibrium, 42; expansion/
 - contraction and, 2, 8–9, 16,
 - 60, 73, 86, 145; Harrison's
 - sea clock and, 2; metal and,
 - 2, 9, 86, 141, 172; moisture
 - and, 2–3, 5, 9, 16, 28, 31,
 - 57, 60, 73, 77–78, 88–89,
 - 145–46, 151; Nitinol and, 2;
 - plastics and, 8; robots and,
 - 77–78, 82, 84, 86–89; sec-
 - ond law of thermodynamics
 - and, 41–43; self-assembly
 - and, 46, 145; textiles and, 5,
 - 9, 11, 71, 73–74; thermostats
 - and, 2, 57, 86
- textiles: 3D printing and, 69,
- 72–73; active products and,
- 66–75; bottom-up design
- and, 124; cellulose and, 151,
- 152; clothing and, 5, 9, 11,
- 41, 57, 94, 137; contraction
- and, 9, 71; control and,
- 9–10; Jacquard loom and, 9,
- 16; material properties and,
- 11, 70, 73; moisture and,
- 5, 9, 71, 72–73; mycelium
- and, 151; polymers and,
- 68; programming matter
- and, 9–11; robots and, 95;
- sensors and, 11, 74; smart,
- 11, 57, 93–95; stretchable,
- 66–70, 124; temperature
- and, 5, 9, 11, 71, 73–74
- thermodynamics, 41–43
- thermostats, 2, 57, 86
- Thompson, D'Arcy, 122
- tobacco plants, 46, 47
- transformers, 3, 78, 110–12,
- 115, 122, 125
- transistors, 9, 15, 17–19, 28, 87
- Tufts University, 74
- Turing, Alan, 17, 22, 37
- University of California, Berke-
- ley, 159
- University of Chicago, 148
- UV light, 139
- VHS, 24
- vibration, 3, 33–34, 46, 57,
- 77–78, 146
- virtualization, 3–4
- von Neumann, John, 17
- waste, 58, 135–37, 141, 144,
- 147, 150–52
- water jets, 10, 18
- wave tanks, 112, 113–14
- wearables, 11, 74, 93–95
- West, Mark, 124
- Whitesides, George, 91
- Wolfram, Stephen, 38
- wood: 3D printing and, 123,
- 124; active products and,
- 66; bottom-up design and,
- 118, 122–24; chopped, 8;
- common platform and,
- 160; moisture and, 9–10,
- 32, 85, 122–24; Penrose
- and, 165; properties of, 3,
- 9, 118; robots and, 85; sea
- clock and, 1; smart, 85, 171;
- synthetic, 10; veneers and,
- 122

Wood, Rob, 91–92

wool, 73

worms, 153

Worn Wear, 137

Wyss Institute, 44

Xerox, 159

Yin, Peng, 44

zip drives, 24