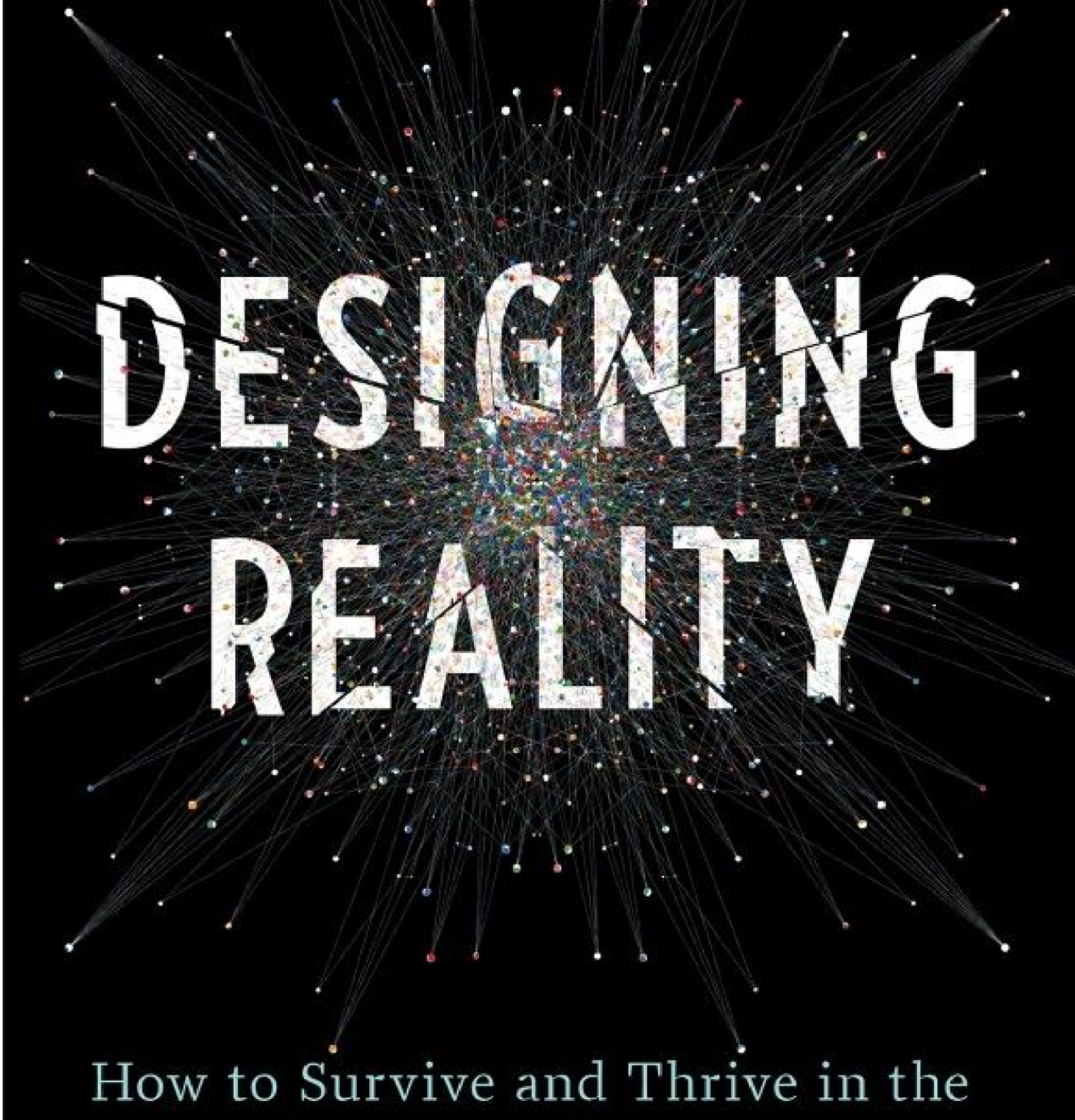
Neil Gershenfeld
Alan Gershenfeld
Joel Cutcher-Gershenfeld



DESIGNING REALITY

How to Survive and Thrive in the Third Digital Revolution

CONTENTS

Cover

Title Page

Copyright

Dedication

N A J Introduction

N Chapter 1: How to Make (almost) Anything

- Fabrication
- Education
- Application
- Implication
- Organization

A J Chapter 2: How to (almost) Make Anything

- Fab Access
- Fab Literacy
- Enabling Ecosystems
- Mitigating Risk
- Grand Challenges

N Chapter 3: The Science

- From Moore's Law to Lass' Law
- Communication, Computation, Fabrication
- Four Billion Years of Digitization
- Intelligent Design

A J Chapter 4: The Social Science

Moore’s Law Versus Lass’ Law
Reactive Versus Proactive Social Science
Rates of Change
Ecosystems
Propagate Versus Scale

N Chapter 5: The Roadmap

Community Fabrication: 1 to 1,000
Personal Fabrication: 1,000 to 1,000,000
Universal Fabrication: 1,000,000 to 1,000,000,000
Ubiquitous Fabrication: 1,000,000,000 to 1,000,000,000,000

A J Chapter 6: The Opportunity

How to Envision (almost) Anything
Predictive Transformation
Assembling Assemblers and Pancake Breakfasts

N A J Conclusion

Goals and Recommendations

N A J Epilogue

Acknowledgments

About The Authors

Also by Neil Gershenfeld

More Praise For Designing Reality

Resources

Index

For our parents, Gladys and Walter, who designed our reality

Introduction

Imagine: The year is 1965. Gas is thirty-one cents per gallon. The Beatles have just released the album *Help!* The Watts riots are raging in Los Angeles. *The Sound of Music* is leading at the box office. Digital Equipment Corporation introduces the PDP-8, the first computer to use integrated circuit technology, for eighteen thousand dollars.

You're sitting in a packed coffee shop in San Jose drinking a cup of joe (venti half-sweet no-foam caramel macchiatos have yet to be invented). The only open seats are at your table. A group enters, talking animatedly. They're all holding the latest issue of *Electronics* magazine and are clearly bubbling over with excitement. One of them asks if they can sit at your table. Sure, you say.

You listen in as the group—researchers, it turns out, at a nearby semiconductor company—talk excitedly about an article in the magazine. What they're saying seems completely far-fetched. They're talking about how, one day, computers will be small enough to fit in a pocket or be worn like a watch. How these "personal" computers will be as powerful as a mainframe computer. How, in the near future, all these computers will be connected, enabling anyone, anywhere, to access, manipulate, and share information with anyone, anywhere.

The more they go on, the more their vision of the future sounds fantastical. After all, computers are enormous machines filling entire rooms and run by leading research institutions and big companies. They're expensive and require highly trained operators. The idea that computers could fit in a pocket or be connected seems like something out of Arthur C. Clarke or *Dick Tracy* or *The Jetsons* and not any near-term reality that you need to pay attention to. You can't help but express your skepticism to your tablemates.

The researchers pause and nod as if they've heard this skepticism before. What has made them so excited isn't just that computer technologies are increasing in performance, but that they're doing so at an exponential rate. That kind of change, they explain, can be hard to see in the early phase, before the change becomes so explosive that it is obvious to everyone. And yet, they argue, all the signs of accelerating computing performance are there—if you know where to look. And they insist they know where to look. They're brimming with confidence. You're both skeptical and intrigued. Fine, you say. Where, exactly, should you look?

Encouraged, the researchers begin to explain. First, they say, look at the very nature of digital technology—specifically, what enables digital technologies, unlike most everyday technology, to accelerate at an exponential rate. They compare digital computers to another recent invention, the Xerox machine. Unlike a computer, they explain, a Xerox machine employs an analog process. If, for example, you wanted to make an exponential number of Xerox copies of a document, you'd feed the first copy into the machine and make a copy. You'd then feed the two copies back into the machine to make four copies, then eight, then sixteen, and so on. By the time you get to thousands of copies, let alone a million or a billion of them, most of the copies would be nothing more than a garbled mess because of the accumulated imperfections in the copying process—the information they contained would be lost.

This is not the case with digital technologies, they explain. Digital messages are converted into symbols (ones and zeros). By adding an ongoing process of error correction to the system, a digital machine can double the number of these messages repeatedly without losing any information. This, the researchers explain, is the essence of digital. It enables billions of digital messages to be manipulated and shared with no loss of clarity. Further, the error correction is so cheap that the messages have almost no marginal cost of reproduction. This basic science, they argue, will drive revolutionary changes throughout society.

One of the researchers then opens a copy of *Electronics* magazine and shows you the article they are all excited about. It is written by a man named Gordon Moore, head of research and development at Fairchild Semiconductor, where they work. You're amused at the article's wonderfully direct title: "Cramming More Components onto Integrated Circuits." In the article, Moore makes the case that the number of components on an integrated circuit has been doubling annually and that he expects the trend to continue for at least ten years. The researchers are excited because this trend is essential to computers' ability to become smaller, cheaper, and faster—and it's happening at an accelerating pace. If Moore's prediction is right—if computing performance does continue to double during the next ten years, then by 1975, computers will be a *thousand* times faster. Considering this trend, Moore predicts the development of "such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment." He goes on in the article: "The electronic wristwatch needs only a display to be feasible today." You were right to think of Dick Tracy and the Jetsons; that is exactly what Moore is predicting.

The researchers continue to explain. The increasing power of computers makes other digital technologies possible and more powerful as well. For example, one of the researchers is working on a contract from the Department of Defense's Advanced Research Projects Agency to show how computers can communicate over long-distance data networks. Another researcher points out that they are developing computers that will eventually be able to defeat humans at difficult games like chess. These developments, along with many others like them, will intersect and build on each other, laying the foundation for enormous change across every sector of the economy, as well as for culture and society in general.

As your tablemates continue, you become convinced that this is indeed something you need to pay attention to. The exact timing may be unclear, but you realize that you may have just been given a truly unique opportunity to see around the corner into a radically different future. Now you just have to decide what to do with this knowledge.

If you are an entrepreneur, you will probably begin thinking about the potential for new, disruptive business opportunities. If you are the leader of an existing business organization, you are likely to try to use the technologies to gain competitive advantage and to shed or transform parts of your business destined to become obsolete. If you are a leader of a public institution, you might begin to assess how these powerful technologies will reach everyone, not just the fortunate few—how they might be leveraged to enhance the public good and mitigate potential harm. Regardless of who you are, you will consider how these new technologies will have an impact on your personal and professional life. At the very least, it is clear: a digital revolution is coming.

MISSED OPPORTUNITIES

In fact, over the last half century, two digital revolutions have come to pass, more spectacularly than Moore himself predicted. The first digital revolution was in communication, taking us from analog phones to the Internet. The second digital revolution was in computation, bringing us personal computers and smartphones. Together they have fundamentally changed the world.

As early as 1965, the signs of the coming digital revolutions were there for anyone to see. And yet most of the world missed them. As a result, few were prepared for the deep economic, social, and cultural impacts of the first two digital revolutions. Moore's prediction, now known as Moore's Law, didn't just last for the ten years he first projected; it has held for fifty years. And computers are now approximately a *billion* times as powerful as they were in 1965, and they do fit in your pocket and on your wrist.

The technology has continued to advance at an exponential pace, but individuals, organizations, and institutions have largely been playing catch-up, struggling to keep pace. The struggle is at all levels of society —individuals whose lives are increasingly mediated by digital technologies; organizations whose operating models are constantly being disrupted by accelerating technologies; and institutions, such as government, education, and law, that are struggling to maintain stability amid constant change.

The deeper these technologies penetrate society, the greater the struggle for society to keep pace. The best time to shape the destiny of transformative, accelerating technologies is early, before changes have become both widespread and entrenched. This is when the embedded assumptions in the technology and the initial market instantiations are in the early stages of formation and still negotiable. The revolutions in digital communication and computation have enabled unprecedented productivity, generated enormous wealth, and catalyzed remarkable changes in everyday life. But a great many people have also been left behind.

Today, more than a half century after the publication of Gordon Moore's paper, over half the planet still has no Internet access altogether, while billions more have limited or unreliable access. In much of the world, a combination of growing income and wealth inequality, thechnological unemployment, and social polarization, driven by digital echo chambers and “always-on” social media, are ripping at the very fabric of society. Many people feel a deep-seated longing for a simpler, more meaningful and less turbulent future.

The negative aspects of the first two digital revolutions are not simply accidents. Nor were they driven by some unseen hand. Decisions made (and not made) and priorities set (and not set) early on, as the technologies were being developed and introduced to the market, have had lasting effects. We built breakthrough digital communication capabilities, but we failed to build in cultural norms, feedback loops, and algorithms that could have reinforced civil discourse. We created incredibly efficient new models of digital commerce, but have also introduced new threats to privacy and security. We value the advances made possible with digital automation, even as we struggle with the impacts of lost jobs due to technology.

It would have been impossible, of course, to foresee and forestall all the negative consequences of the first two digital revolutions. However, by waiting decades to prioritize helping individuals, organizations, and institutions co-evolve with the technology, we have missed great opportunities to proactively create value and mitigate harm as the technologies were developing. In 2015, President Obama declared that “high-speed Internet is a necessity, not a luxury”—like electricity or water. That was a half century after the publication of Moore’s paper. Imagine if developing a culture of digital inclusion, digital and programming literacies, and digital civility was a shared public-private priority starting in the mid-1960s. Imagine if there had been as much social innovation shaping the impact of the technology as there was innovation in the science and technology itself—so that both the social and the technical systems had more effectively co-evolved.

We largely missed this opportunity with the first two digital revolutions. But we now have another chance. It comes with the third digital revolution—in fabrication.

THE THIRD DIGITAL REVOLUTION

The third digital revolution completes the first two revolutions by bringing the programmability of the virtual world of bits into the physical world of atoms. Since that physical world is out here where we live, the implications of the third digital revolution may be even greater than those of its predecessors. This revolution is built on the same fundamental science of digital, only now it enables both bits and atoms to be exponentially manipulated. Just as communications and computation went from analog to digital, resulting in personal computers, mobile phones, and the Internet, the digitization of fabrication offers the promise of personal fabrication, enabling individuals and communities to produce and share products on demand, wherever and whenever something is needed.

The similarities between digital fabrication and digital communication and computation are striking. Much like the early mainframe computers, most serious digital fabrication today is done with enormous machines run by highly trained operators at leading research institutions and big companies. Soon, however, the power that lies in these enormous machines will become accessible to anyone—just as the computer you carry in your pocket has the power of what was once a mainframe computer. We can already see around the corner into a future where anyone can turn data into things and things into data, and can share this information across an Internet of bits *and* atoms.

As with the early stages of the first two digital revolutions, this vision seems, well, fantastical. And yet, not only is this vision theoretically possible, we are already on an exponential path to it becoming a reality. *Fab labs*, community-based labs where individuals can access powerful tools for digital fabrication, have been doubling in number every year and a half, since the first lab was established in 2003. Like the early years of the first two digital revolutions, however, the exponential nature of the third digital revolution is not readily apparent to the casual observer. As inventor and futurist Ray Kurzweil points out in his book *The Singularity Is Near*, “exponential growth is deceptive. It starts out almost imperceptibly and then explodes with unexpected fury—unexpected, that is, if one does not take care to follow its trajectory.”

Designing Reality is about taking care to follow the exponential trajectory of digital fabrication. It aims to help you use this knowledge to both prepare for and shape the third digital revolution. In small and possibly big ways, everyone has agency to contribute to this revolution. We do not need to wait a half century for future political, educational, and philanthropic leaders to realize that fab access and literacy is a necessity, not a luxury. We are still in the early stages of the third digital revolution. Research priorities are being formulated, core technologies are developing, and the organizations and institutions essential to universal fab access and literacy are emerging.

Every new technology has inherent attributes that affect the capabilities and behaviors of people using the technology. Digital technologies enable rapid duplication, manipulation, and propagation of content. This property has been central to the transformation of virtually every sector of the economy, how we spend our leisure time, and how we connect with each other. Over the past few decades, we have seen the economic and social impact—both positive and negative—of our ability to duplicate, modify, and share music, videos, blogs, news, email, text messages, and other digital material at virtually no additional marginal cost. This capability is inherent in the very nature of the technology.

Digital fabrication shares some, but not all, of the attributes of digital communication and computation. In the first two digital revolutions, bits changed atoms indirectly (by creating new capabilities and behaviors); in the third digital revolution, the bits will enable people to directly change the atoms. This difference is not yet literally at the atomic level (for most people), but it does mean the ability to use digital design interfaces to modify the physical world. Despite the enormous changes brought on by the first two digital revolutions, much of the physical world around us—roads, houses, appliances, transportation, food—have remained remarkably the same. But in the third digital revolution, the very nature of how the physical world around us is constructed will change. Across the global network of fab labs, we can already see a steady stream of innovations around cost-effective models for individuals and communities to make clothing, furniture, toys, computers, and even houses and cars through designs sourced globally but fabricated locally. These capabilities will continue to improve over time, with exponentially better, faster, and cheaper digital fabrication technologies.

The third digital revolution taps into a deeply held human desire to make things. As Dale Dougherty, founder of *Make* magazine, points out in his book *Free to Make*, “making engages us fully and deeply as human beings, and it satisfies our creative souls,” and helps us “see ourselves as confident, capable and creative individuals.” Whether it is a machinist at home in a basement workshop, a farmer at a fab lab in rural India, or a twelve-year-old kid at a Maker Faire DIY gathering, making things is deeply satisfying and inspires hobbyists, artists, inventors, engineers, and enthusiasts.

We can see the early signs of the transformative power of digital fabrication in the work of fab pioneers from around the world. Throughout this book, we will meet people like Blair Evans from the

Incite Focus fab lab in Detroit. Blair has developed a thirty-acre parcel of land on Detroit's East Side and is boldly exploring new social and economic models where everyone can choose to "work and spend less, create and connect more." Building personal and community self-sufficiency is not a new idea, but Blair and his colleagues are showing how digital fabrication platforms can accelerate self-sufficiency when the platforms are used to collaboratively produce practical goods, from food to furniture.

This increasing ability to make what one consumes at a personal or community level will help address one of the greatest challenges emerging from the first two digital revolutions—the number of jobs being replaced by technology. Some estimates project that as many as half of all jobs could eventually be automated because of advancements in artificial intelligence, robotics, and other rapidly accelerating technologies. These losses are not just blue-collar jobs such as factory work or truck driving, but also white-collar jobs ranging from paralegal work to radiology, and even computer programming. There is debate as to whether new jobs, associated with the new technologies, will make up for lost ones. Even if this emerges (and that is by no means certain), there will be gaps between the loss of old jobs and the emergence of widely accessible new ones. The toxic blend of technologically driven unemployment, income and wealth inequality, and constant change driven by digital technologies, have left many people feeling unmoored and angry, driving nationalist movements throughout the world. These are big challenges, yet the increasing democratization of manufacturing could lead to a more appealing future where personal and community self-sufficiency is combined with global interdependence and knowledge sharing—grounded in capability rather than fear. It could help break down the false dichotomy of globalization and local self-sufficiency, and help transcend political divides.

The foundation for a more sustainable and enriching future is happening not only at a personal and community level, but also on a city and country scale. Another fab pioneer we will meet, Tomas Diez, from the Barcelona fab lab, is leading a global Fab City movement. At the tenth annual global convening of fab labs, the mayor and the chief architect of Barcelona made a bold commitment. They pledged that in forty years, Barcelona would replace its global supply chains with sustainable local production—becoming a city able to make what it needs. This declaration is not a throwback to the craft era, but rather a vision for a postindustrial city where bits that travel globally can manipulate atoms that stay locally to empower cities to become sustainable. Following the Barcelona declaration, several other cities and a few countries, from Santiago to Shenzhen, from Boston to Bhutan, have signed on. Tomas describes the Fab City movement: “We need to reinvent our cities and their relationship to people and nature by re-localizing production, so that cities are generative rather than extractive, restorative rather than destructive, and empowering rather than alienating.”

We also introduce fab pioneers working in indigenous communities from Alaska to the Amazon. These innovators are using advanced technologies to keep alive ancient practices for local self-sufficiency and community building. Providing more effective tools to use local materials to collaboratively solve local challenges taps into a deep desire on the part of many people in both traditional and modern societies to be more connected to nature and the physical world around them. Even the most ardent proponents of digital technologies recognize the risk of being sucked into ever-more-enticing social media and immersive virtual worlds. We see anxiety about this risk in the Silicon Valley execs who send their children to “tech-free” schools and in the broader trends such as digital-free holidays and initiatives like the National Day of Unplugging. The third digital revolution can help drive us toward a more healthy balance of time spent in the digital world of bits and the “real” world of atoms.

These aspirational visions will only be urged into existence if we engage and inspire individuals, create the needed organizations, and transform the inherited institutions. The first steps are in recognizing that we are, indeed, on the cusp of a third digital revolution and in understanding its trajectory. The signs are all there, and *Designing Reality* will show you where to look. It will show you how we know the third digital revolution is happening, why it’s happening, and, crucially, how you can prepare for and help shape it as it happens.

When exploring exponential technologies, we can very easily fall into either a dystopian vision of the future, where humans have little agency as the technology runs amok and robots steal all our jobs, or be lulled into a techno-utopian vision of the future, where we can just sit back and technology will solve our problems. Both these extremes are continually reinforced in popular media. As we have seen with the first two digital revolutions, the reality is much more textured. The benefits and risks of accelerating technologies are very real, with deep impacts on many lives, but we have the agency, individually and collectively, to shape these impacts now.

We can all help bend the arc of the third digital revolution to create a more self-sufficient, interconnected, and sustainable society. Such a transition will not happen overnight. There will be continued employment for work that cannot be replaced, along with new jobs that leverage these digital fabrication technologies. As individuals and communities increasingly make what they consume, emerging models will challenge our conceptions of work—providing new options for balancing how we will live, learn, work, and play. Making this blend of societal arrangements benefit everyone won't be easy. Yet, if we see a billionfold increase in the capability and reach of digital fabrication technologies over the next few decades, we can realize the vision of working and spending less while creating and connecting more. We could build on the Fab City vision of a society that is "generative rather than extractive, restorative rather than destructive, and empowering rather than alienating."

Designing Reality is written around two broad themes that are together essential for realizing the power and promise of digital fabrication: understanding the technology powering the third digital revolution, and advancing the social systems that must co-evolve with the technology.

TECHNOLOGY

Your guide for understanding the technology is Neil Gershenfeld, director of the Center for Bits and Atoms (CBA) at MIT. Neil has been working at the frontier of digital fabrication for two decades and has a track record of seeing around the corner into the future of digital technologies. His 1999 book, *When Things Start to Think*, anticipated and helped shape what became known as the Internet of Things. His 2005 book *Fab* described the emergence of fab labs and the maker movements, introducing many people to the power and promise of digital fabrication.

Now, in *Designing Reality*, Neil shows how these trends have added up to a third digital revolution that can be seen today after a decade of the spread of the technologies for digital fabrication; how it can be historically understood through the alignment of all three digital revolutions; and how it can be seen in the future in an evolving research roadmap. He shows how the hype surrounding 3D printing is just the tip of a much bigger story, leading up to a *Star Trek*–style replicator that can make (almost) anything, including itself. It will do this by digitizing not just the designs of things but also the construction of the materials that they're made of.

Neil opens in Chapter 1 with the story of the accidental origin of the fab lab movement from his How to Make (almost) Anything class at MIT. He then provides a tour of how community fab labs are being used across the global network, highlighting how today's digital fabrication processes are already empowering people. From the northern tip of Norway to the southern tip of Africa, from rural villages to sprawling cities, community-based fab labs have sparked an outpouring of innovation, providing early indications of the power and potential of digital fabrication.

From the present, Neil then explores in Chapter 3 the history of the core scientific foundations of the third digital revolution. He explains how these go back four billion years to when life evolved the machinery for molecular manufacturing and how the underlying principles of reliability, modularity, locality, and reversibility serve as the core ideas that unify digital communication, computation, and fabrication. He highlights the historical lesson that the implications of these processes could be seen and used long before the technology had reached its final form.

Neil anchors this section with an introduction to Lass' Law, an analogue to Moore's Law for digital fabrication. The law is named for Sherry Lassiter (aka Lass). Along with leading the Fab Foundation (the nonprofit that supports the fab lab network), Lassiter manages outreach for CBA. As the pile of fab lab requests on her desk grew, she first noticed that the number of fab labs was doubling roughly every year and a half.

When Neil wrote *Fab*, he neither planned for nor envisioned this exponential growth. At the time, CBA had only recently launched the first few fab labs. For Neil, the year 2003 was the equivalent of 1959, the start of the data points that Gordon Moore had plotted. Now, after more than a decade of the number of fab labs doubling—along with continued advancements in the research roadmap and a growing fab ecosystem—we can predict a likely exponential trajectory for digital fabrication performance and reach.

As with Moore's Law after its first decade, we can extrapolate this exponential trend. This means the equivalent capability of a million fab labs over the next ten years or so, and a billion over the following ten years. This doesn't mean a billion room-filling facilities. Rather, each of these decades marks a technical stage in the integration, accessibility and reach of the technology. As the scaling progresses, what is counted is no longer fab labs as they exist today but rather the equivalent capability to fabricate physical forms and program their functions. As Moore's Law reaches its physical and economic limits, Lass' Law continues an exponential growth trend.

This brings us to Neil's Chapter 5, a roadmap for the future of digital fabrication. He opens the chapter with an inventory and a description of the current tools in a fab lab. He then outlines four distinct stages: community fabrication (powered by computers controlling machines), personal fabrication (based on machines that can make machines), universal fabrication (marking a transition to digital materials), and ubiquitous fabrication (with programmable materials). Each of these stages represents an exponential improvement in digital fabrication performance.

Much as the core elements of the first two digital revolutions were visible in the labs of the mid-1960s, when Gordon Moore wrote his article, all the core elements of the third digital revolution are visible in research labs today. The question is, how long it will take for them to emerge from the lab and impact society? And will we be ready?

SOCIETY

Your guides for exploring how social systems can effectively co-evolve with the accelerating technologies of the third digital revolution are Joel Cutcher-Gershenfeld and Alan Gershenfeld. Joel is a professor in the Heller School for Social Policy and Management at Brandeis University and past president of the Labor and Employment Relations Association. He has researched and facilitated large-scale systems change in the auto industry, the aerospace industry, health care, biomedicine, and the nonprofit sector. Joel is a macro social scientist with a track record for advancing theory and practice in negotiations and high-performance work systems. He is now pioneering new models for multi-stakeholder alignment within and across levels: workplace, enterprise, community, industry, national, and international levels.

Alan is president and co-founder of E-Line Media, a “double-bottom-line” company (committed to both positive financial returns and meaningful social impact), harnessing the power of digital media and games to help people understand and shape their world. In his work at E-Line and in his former roles as a studio head at Activision and board chair for Games for Change, he has worked on social-impact media projects with NSF, DARPA, USAID, the White House Office of Science and Technology Policy, the Smithsonian, PBS, the Gates Foundation, the MacArthur Foundation, and others that have collectively engaged and empowered millions of people all over the globe.

Both Joel and Alan have been collaborating with Neil in the fab lab movement since the launch of the first lab, where Joel and his oldest son volunteered for many years. Joel also helped launch a fab lab in Champaign-Urbana, Illinois, and has led the application of new stakeholder alignment methods across the fab network. Alan has researched sustainable business models for fab labs, and E-Line has worked on a DARPA-funded video game exploring the future of digital fabrication, in collaboration with the Fab Foundation and CBA. In conducting research for this book, Joel and Alan have visited fab labs throughout the world, interviewed dozens of fab pioneers, and surveyed hundreds of stakeholders.

Neil explores the technology roadmap and offers tools and techniques for leveraging the technology; Joel and Alan explore the social roadmap and offer methods and mind-sets so the social systems can co-evolve with the technical systems. In Chapter 2 Joel and Alan also open by observing the current global network of fab labs. But unlike Neil, they don’t only present exhilaration and empowerment; they also highlight the tensions and challenges that permeate the fab network. Despite the promise of personal fabrication and individuals’ ability to make what they consume, digital fabrication is still a long way from being a reality for most people. There are significant challenges around fab access, literacy, and the cultivation of an ecosystem that ensures truly democratized technologies. A close look at these challenges is essential if we are to address them. Observing disconnects throughout the fab ecosystem provides a window into the embedded underlying assumptions and conflicting values. Today, the benefits of fab labs come more from the process of making than they come from the result, because of the difficulty of mastering current workflows. Over time, this balance will need to change if the impact of digital fabrication is to move beyond just the cultivation of new skills and dispositions to increasingly make what we consume.

Like Neil, Alan and Joel then turn to the past. In Chapter 4, they highlight how Moore's Law is as much a social construct as a technical one. Moore's Law was never a law of physics, but rather an observation that became a core business strategy for a company, an industry benchmark, and finally a galvanizing framework for better, faster, cheaper digital technologies. The chapter illustrates how the interweaving of social and technical change is not new—how the modern social sciences, that is, the study of human societies and relationships, began in reaction to the rise of the industrial revolution. And yet, because the social sciences began by reacting to technology, the dominant practice in this field is the observation of technology rather than its co-creation. Taking a more proactive stance begins with understanding rates of change for individuals, organizations, and institutions, which takes on new meaning in a world of accelerating technologies. This points to the key roles of rate limiters and rate accelerators to positive social change, as well as lessons learned from the first two digital revolutions in harnessing the power of digital platforms and emergent ecosystems to effectively co-evolve technical and social systems.

Joel and Alan conclude with specific guidance for shaping the future of digital fabrication (Chapter 6). They describe eight aspirational scenarios, jointly created with fab pioneers across five continents. In these scenarios, social systems and technical systems co-evolve in transformational ways. To shape the future, we need mental maps for not just possible futures, but for preferable ones. To help transform these preferable futures into reality, Joel and Alan offer a framework for fostering new mind-sets and applying effective methods so that everyone can find meaning, purpose, and dignity in the third digital revolution.

Designing Reality brings the perspectives of science, technology, social science, and humanities to the third digital revolution—through three brothers who are not only observers of the revolution but also active participants in helping guide it. Each brother brings a different lens to the book. Like all lenses, each brother's clarifies some things and makes other things less clear. Their disagreements have been even more important than their agreements as they came together to write this book. The same is true any time very different sectors or domains need to collaborate around complex, rapidly changing technology to accomplish collective goals—collaboration that the third digital revolution demands.

This is a unique historical moment: we can foresee the likely trajectories, and it is still early enough that we can shape the technology before it shapes us in ways we will regret. The stakes are high. If our projection is correct, the third digital revolution will have as much impact as, if not more impact than, the first two digital revolutions. We will soon be facing a torrent of new opportunities and challenges that go to the very heart of how we exist. Literacy scholar James Paul Gee from Arizona State University summarizes the opportunity and challenge in his essay "Literacy: From Writing to Fabbing":

> Fab could create a world with yet deeper inequalities than we currently have, a world where only a few engage in the alchemy of turning ideas into bits into atoms and back again. The rest will live in a world where the stuff of life and the world—objects, cells, materials—are owned and operated by only a few. Fab is a new literacy and we have as yet no real idea how it will work out. But it is a special and, in some sense, final one....
>
> How many of us will get to be homo fabber? Humans have always been the ultimate tool makers. Soon the tools for world making will be cheap enough to be in the hands of everyone, should we want to make that happen. Will we, as a species, make a better world or a worse one when some or many or all of us become god-like creators, calling worlds into being? Fab is to literacy what fire was to human development: a tool that can light the way or burn it down.

Will we light the way or burn it down? We have the agency, individually and collectively, to tip this balance. As digital fabrication becomes increasingly democratized, we'll have the ability to leverage bits to manipulate atoms to improve lives. We will be able to design reality, both metaphorically and literally.

CHAPTER 1

How to Make (almost) Anything

The first digital revolution was in communication. Before that, analog telephone calls degraded with distance. We now have a globe-spanning Internet that makes it as easy to talk to someone around the world as it is to chat with someone around the corner.

The second digital revolution was in computation. Analog computers used to fill rooms with gears and pulleys or vacuum tubes and produced answers that accumulated errors the longer that they ran. Today, you can carry in your pocket a computer with the power of what was once a national lab's supercomputer.

We are now living through the third digital revolution, in fabrication. The first two revolutions rapidly expanded access to communication and computation; this one will allow anyone to make (almost) anything. This time around, it's likely to be even more significant than the first two, because it's bringing the programmability of the world of bits out into the world of atoms.

The defining application for digital computing was personal computing, which upended the existing computing industry that initially ignored it. Likewise, the defining application emerging for digital fabrication is personal fabrication, which allows consumers to become creators, locally producing rather than purchasing mass-manufactured products.

Digital fabrication has a decades-old meaning, referring to computers controlling machines that make things. And it has a much deeper meaning that, as we'll see in the coming chapters, is both much newer and much older: the digitization of not just the description but also the actual construction of an object. As was the case with the earlier digital revolutions, we don't need to wait for the technology to reach its final form to recognize or use it. The third digital revolution can be seen today in the spread of technology for digital fabrication and the impact that it is already having (the subject of this chapter). It can be seen in the historical alignment of all three digital revolutions (Chapter 3). And it can be seen in the coming research roadmap (Chapter 5). Together, these chapters survey the science and technology required to understand the third digital revolution, providing the background needed to be able to shape it.

The exponential change in all three digital revolutions began with weak signals in the first few doublings; today, the signals for the third digital revolution are more like honking horns (if you're paying attention to them). This chapter examines what is already happening today, introducing Sherry Lassiter's original observation (which we're calling Lass' Law) that the number of fab labs has been doubling every year and a half. It explains what a fab lab is, how to use one, what the applications and implications of these labs are, and how they are organized.

This tour through the present is important for seeing the future because the most significant implication of projecting the continuation of Lass' Law, like Moore's Law, is to change not just what the technology can do, but who can do it. On this tour, we'll meet pioneers who are already using fab labs to produce a range of remarkable things, fabricating the physical forms of objects and programming the functions that the objects can perform. Today, these tasks require access to the tools in a fab lab along with the supply chain that supports one. Over time, the equivalent capabilities will become available to many more people as the progression of performance improvements we'll see in the subsequent chapters decreases the cost and increases the capability of digital fabrication.

FABRICATION

Fab labs are laboratories for fabrication (which we also think are fabulous labs). They began as an outreach project from MIT's Center for Bits and Atoms (CBA), which I direct. CBA was founded to study the boundary between computer science and physical science, a distinction that I never understood. Computation both requires and is used to represent physics; CBA researchers have participated in projects like creating among the first computers to use the strange behavior of microscopic quantum systems to solve important problems faster than a conventional classical computer can. Another CBA collaboration contributed to creating some of the first living organisms designed in a computer. These activities can’t be neatly separated into hardware and software; they are intimately integrated. The most important conclusion from this research is the recognition of the fundamental convergence of digital communication and computation with fabrication, a concept that will be unpacked in the coming chapters.

A fab lab in Vestmannaeyjar, Iceland. *Frosti Gíslason/Saethor Vido*

The initial funding to create CBA came from the National Science Foundation (NSF), which supported our ambitious proposal to put together a facility that could make and measure things with sizes ranging from molecules to buildings. CBA includes million-dollar research instruments like electron microscopes and X-ray scanners. Within that facility is a workshop containing hundred-thousand-dollar manufacturing tools, like machining centers, that we use to develop the experimental apparatus. Within the workshop is a collection of ten-thousand-dollar rapid-prototyping tools, like laser cutters, that make parts of projects. And those in turn get used with thousand-dollar tools to perform processes, like molding components. The nesting of these scales is key to understanding fab labs, which fall in the middle of this hierarchy; they represent the core capabilities needed to make not just something but (almost) anything.

Fab labs began as an experiment to see what would happen if the most popular of CBA's tools internally become widely available externally. They arose not from a transformative vision but much more modestly to meet a bureaucratic requirement. When CBA started in 2001, the government had begun enforcing legislation called the Government Performance and Results Act, which required agencies to measure their progress against performance goals and to document their impact in a broader context. NSF responded in turn by asking grantees like CBA to show the broader impacts of their work. My colleagues and I, who had no idea how to do that, had encountered an unexpected impact in rural India.

On a trip there in 2002, I met S. S. Kalbag, who had run research for Hindustan Lever. When he reached the Hindu life stage when it's traditional to renounce worldly attachments, he approached that as a scientist by setting up a school (Vigyan Ashram) to teach technical skills to dropouts. He intentionally located this in one of the poorest, driest parts of India: Pabal, in western Maharashtra. When I visited him there, he had a long list of local needs that he could have met with the tools in his former lab but not with the resources available in the small village of Pabal. Rather than invest in expensive special-purpose lab equipment, we began a collaboration to equip their lab to make lab instruments for purposes like agricultural testing. That could be called fab lab number zero, the chicken before the egg (or is it the egg before the chicken?). It inspired the first full community fab lab that was later opened in Boston, and itself grew into a full fab lab in 2005. Although Kalbag passed away in 2003, that fab lab has flourished under his successor, Yogesh Kulkarni, teaching classes, incubating businesses, and supporting the community.

To respond to NSF's requirement to show broader impacts, we proposed to base an outreach program on the experiment in Pabal. Our adventurous program managers agreed, and the concept of a fab lab was born. The contents of a fab lab were based on a kind of market research done by running CBA's facility at MIT, incorporating the most useful core set of tools. Today, this suite adds up to about a hundred thousand dollars, weighs around two tons, and fills a room. A fab lab naturally includes a 3D printer, which has been the subject of a great deal of coverage in the popular press, but it is just one of the computer-controlled machines. We'll meet the rest in Chapter 5, including a laser cutter that's much faster than the 3D printer, a large milling machine that can make things like furniture, a small precision milling machine that can make electronic circuit boards and molds for casting parts, tools to assemble and program electronics, a scanner to digitize objects, and computers for design and modeling.

When microwave ovens were introduced, they were the basis for the 1950s version of the push-button kitchen of the future. You, of course, still use a stove, an oven, and maybe a toaster along with a microwave. All these tools just heat food, but each is needed to make a range of recipes. Working in a fab lab today is like cooking in a kitchen. Think of the 3D printer as the microwave oven of the fab lab. You could use only the microwave, but you would be missing the capabilities of the other appliances. Just as a basic set of processes is assumed in cooking, a basic set is assumed in digital fabrication.

You can effectively consider the whole fab lab to be a machine: data goes in and things go out, things go in and data goes out. What will change over time is not what can be made but rather what's required to make something. A fab lab today uses bulk materials that can be locally sourced, like wood or cardboard, along with a small set of globally sourced high-tech consumables, like precision bearings and computer chips. The latter can't yet be made in the lab, but that will become possible in the coming years. The transition will be continuous, as more and more of the supply chain to support a fab lab gets replaced with fewer and fewer inputs.

When we were planning to set up the first of these fab labs, Bill Mitchell, then MIT's thoughtful dean of architecture, suggested that I talk to Mel King in Boston. Mel is a community activist who literally helped invent mixed-use urban development by the seat of his pants. He led what was called the Tent City encampment, which forced a developer to include affordable housing and community space in a planned parking garage. Mel's South End Technology Center (SETC) in the resulting complex went on to become a pioneer in electronic media at a time when mass media wasn't telling stories of the inner city. Then SETC innovated in computing access when the Internet threatened to bypass the community. So it was natural to progress from digital communications and computing to fabrication, opening a fab lab there in 2003. As Mel says, “the rear wheels of the train don’t catch up to the front wheels of the train unless something dramatic happens to the train,” meaning that each of these interventions was a disruptive event that challenged the role of technology in society.

Putting a fab lab at SETC was the extent of our vision. After it opened, we expected to just return to research. But a strong Ghanaian community in Boston, after seeing Mel’s lab, collaborated to bring a fab lab to Sekondi-Takoradi on Ghana’s coast in 2004. From one to two, then four, the number of fab labs has continued to double every year and a half for a decade: every time we opened a fab lab, someone else wanted one. Sherry Lassiter was the first to notice this exponential trend; she’s managed the fab lab program for CBA, and leads the Fab Foundation that was spun off to support its growth. Lass came to me with a background in producing science programs on television. She was interested in producing the science itself, which is what she has done ever since with the fab lab network.

In 2005, I wrote the book *Fab* after the first few doublings of fab labs. That year, I was approached to be the first interview in a new magazine called *Make*, which was founded by Dale Dougherty. He coined the term *maker* to describe the emerging community of hobbyists connecting computation with fabrication using the kinds of tools found in a fab lab. He started hosting gatherings called Maker Faires in 2006; the biggest of these, in San Mateo, California, grew from a modest beginning to attract 145,000 visitors in 2015.

Also in 2006, Jim Newton founded TechShop to provide shared access to digital fabrication tools beyond the reach of most individuals. These shops are run with a paid membership model; as of 2016, there are ten of these. More informally, maker spaces and hacker spaces started to spread to provide a place for like-minded individuals to gather. The spaces vary widely in what they offer, but they now number in the thousands.

The next year, in 2007, CBA launched a mobile fab lab to bring tools to people rather than vice versa. Tomas Diez, Amy Sun, and Kenny Cheung (whom we’ll meet later) memorably commissioned the lab by driving it to the Burning Man gathering in Nevada’s Black Rock Desert, for rapid prototyping on the playa. The mobile lab subsequently seeded a network within the network: roving fab labs touring regions of the country.

All these fab labs were early manifestations of the third digital revolution. Two things distinguish fab labs within this growing ecosystem. First, rather than each one being different, fab labs all share the same evolving set of core capabilities, allowing people and projects to be shared among them. The computer networking pioneer Bob Metcalfe observed what is now known as Metcalfe's Law: the value of a computer connected to the Internet is proportional to the square of the number of computers in the network. He proposed that it's the square, rather than merely the number of computers, because that's how many pairs can talk to each other. Some kinds of maker spaces are based on a membership model that's like joining a gym. Gyms provide individual access to exercise equipment; there's no direct benefit if someone is exercising elsewhere. But the value of being connected to the Internet, or working in a fab lab, increases when other computers are connected to the Internet, or when other people are working in fab labs. Both people and projects are mobile in the fab lab network, sharing content that allows them to accomplish collectively what they couldn't do individually.

The other distinguishing feature of fab labs is the coordinated evolution of their contents according to the digital fabrication research roadmap presented in Chapter 5. They began with a carefully curated inventory of common machines, materials, components, and programs and are now migrating to open designs for hardware and software developed by and for fab labs toward the goal of a fab lab's being able to make another fab lab. Although the cost of each type of machine in a fab lab has come down over time, the ambition of what can be made in a fab lab has gone up at the same rate, so the overall cost has stayed roughly constant, on the scale of a community resource.

Together, these attributes allow the collection of fab labs to function as a network. Individually, each site isn't a critical mass, but the collection of them is. No one is pushing anyone to start a fab lab, but sites continue to join the network for the benefits they get from being part of something larger.

The biggest surprise for me has been how similar rather than how different the uses of fab labs are around the world. Mel King captured this when we took him, a community activist from Boston, to the far north of Norway to meet the Sami-descended herder Haakon Karlsen. After spending a few days in Haakon's fab lab, Mel commented that it was "just around the corner." He might have been a few hours above the Arctic Circle, but he recognized the same hopes and fears as those he found in his own urban lab.

Common to fab labs is how they mix ages, from very young to very old, and applications, spanning education, entertainment, and business. In this diversity, they're serving a role analogous to libraries. Andrew Carnegie invested in setting up town libraries around the turn of the last century (1900); by the time he was done, there were about twenty-five hundred such libraries dotting the nation. The overall mission of a library is literacy, expanding access to knowledge. But within that mission, they're used for purposes ranging from playgroups to classes to research to civics. From what was initially a novelty, libraries are now an expected component of a civilized community. You can think of fab labs as doing the same, but they now aim at a new form of literacy: going from bits to atoms.

EDUCATION

Once CBA had set up its digital fabrication research facility, we had a problem: because these tools are conventionally segregated by both discipline and the scale at which they operate, it would have taken a lifetime of MIT classes to learn how to use them all. As a shortcut, in 2001, I started a new class: How to Make (almost) Anything. The class was aimed at a small group of students doing digital fabrication research, but every year since then, hundreds of students have shown up for the class, just wanting to learn how to make things.

Along with mastering individual skills, they did projects to integrate these skills. One of the stars the first year was Kelly Dobson, who went on to become the head of the Digital + Media department at the Rhode Island School of Design. She made a wearable device that could save up screams and play them back later when it was convenient to let them out. A few years later, Meejin Yoon, who later became the head of the department of architecture at MIT, made a dress, replete with sensors and spines, that could defend a wearer's personal space. These kinds of inventive projects happened so consistently year after year, I realized that the students in the class were answering a question that I hadn't asked: What is digital fabrication good for? While I was asking how to do it, and not why, they were showing that just as the killer app for digital computing was personal computing, the killer app for digital fabrication is personal fabrication. The point was not to make what you could buy in stores; it was to make what you couldn't—products for a market as small as one person.

Hans-Kristian Bruvold (*left*) and Tshepiso Monaheng working in their fab labs. *Neil Gershenfeld*

In the same way that the arrival of CBA's research tools presented a training problem that was solved by the How to Make (almost) Anything class, the spread of fab labs made training a problem on a global scale. Bright kids would learn skills in fab labs that were far ahead of local educational opportunity, and then they'd fall off a cliff. Hans-Kristian Bruvold was considered something of a problem in the local school system of Lyngseidet in the far north of Norway. Because he had already mastered everything the teachers were teaching, he wasn't an attentive student. He started going to Haakon's fab lab instead, which is where I met him and showed him a few demonstration projects from my How to Make (almost) Anything class. When I next returned, I was astounded to see that he had integrated the techniques into a toy robotic truck, including the design of the body, incorporating the motors and their controllers, and adding a windshield display. In South Africa, something similar happened when we opened a fab lab in what had been an apartheid-era township, Soshanguve. There, I was startled to later find that a local girl, Tshepiso Monaheng, had been using the lab to remotely follow along with the work of my classes at MIT.

The usual message for someone like Hans-Kristian or Tshepiso is, "You're smart, so you have to leave now." Bright students like them have to go far away to study somewhere more advanced. But this migration takes the most valuable people away from where they're most needed. We initially tried to pair with local schools around the world to fill this void but consistently found that an even greater limitation than a lack of technical skills was how a school's regimented approach to education can stifle creativity. For these reasons, we started what's now called the Fab Academy.

It grew out of a video link that I initially had set up so that fab labs could remotely sit in on the How to Make (almost) Anything classes at MIT. When there were more fab labs attending than students in person, we spun off the remote sessions as a separate program. The local mentors, who had initially been the remote students, proved to be essential. New students joined workgroups in their local fab labs, where they worked with these mentors, their own peers, and the machines. We then connected everyone globally by video for interactive lectures and collaborative content sharing.

In computing terms, you can think of MIT as a mainframe where you go for processing. It works well but for a very limited population. You can think of massive open online classes (MOOCs) as corresponding to the time-sharing era in computing, when users sat at isolated terminals connected to central mainframes. And the Fab Academy model that we stumbled on is more like the Internet, linking nodes in a learning network that grows at its edges rather than at its center.

Initially I directly supervised all the students. Then as the model grew, I supervised the mentors who supervised the students. As it grew further still, I supervised supernodes that emerged to supervise regional labs, which in turn supervise the students. In this, the model is again like the Internet, which handles the routing of information in a tree with trunks, branches, and leaves. And like the Internet, any node can talk to any other; the heart of the weekly Fab Academy cycle is a giant video conference where everyone can see and hear everyone else. The conference includes a lively discussion of successes and failures in the preceding week and an interactive introduction to new material for the next week. All this collaboration is supported by a distributed workgroup led by Luciana Asinari rather than a central office.

This structure maintains a direct traceability in the web of relationships to maintain quality control. But we needed a way to document that, which led me to approach EDUCAUSE, the group of IT professionals in higher education that runs the .edu domain. They require institutions wanting an .edu domain for their websites to be accredited. The accreditors that I spoke with appreciated what we were doing but explained that giving the Fab Academy an .edu domain name would violate their rules. Because they accredit organizations that have a physical place, the accreditors have no way to recognize a network. But the accreditors then said something helpful: "Pretend." By that, they meant we should have students build portfolios documenting the skills they're learning, and the group would eventually catch up to us to recognize the students' work and our evaluation. Although the Fab Academy has no global accreditation, regional accreditations are now beginning to be overlaid on the diploma that the Fab Academy awards. And we've found that for future admission, employment, or investment, the portfolios can matter more than a credential from an unknown body. The cycle of content and evaluation takes about eight months to cover, but a student's progress is determined by the mastery of the skills rather than time in class—some students have taken a few years to finish everything. The level of the students has ranged from home-schooled prodigies to college students, to people doing this instead of college, to midcareer professionals, to late-career retraining, to retirement avocations. This global linking of local learning workgroups balances the distributed nature of fab labs with the need for mentoring.

Absent good mentoring, bad ideas can propagate. The term *maker* has come to have both a negative and a positive connotation, along the lines of *enthusiastic but not well informed*. A staple of the maker movement is the Arduino, a twenty-dollar small computer board used to build intelligence into projects, including reading sensors, controlling output devices, and communicating with networks. The Arduino originally in turn was based on a computer chip family called AVRs, which were designed by two Norwegian students. After introducing the Arduino, the Fab Academy shows how to make such a board in a fab lab for a few dollars in parts. Students then learn how to use other computer chips, from the size of a rice grain up to something that can run a desktop operating system. Another staple of the maker movement is 3D printers. After showing students how to use one, the Fab Academy shows them how to use all the other digital fabrication tools that can operate more quickly or make larger things, stronger things, or things with finer features. Then students learn how to make a 3D printer. These examples each provide a path from introducing easy skills to mastering hard ones.

Do-it-yourself is a recipe for standing on the toes rather than the shoulders of your predecessors; do-it-together or do-it-with-others builds on their accumulated knowledge. We unexpectedly found the Fab

Academy to be at the heart of a virtuous circle. Each cycle would propagate best practices throughout the fab lab network, building a core collaborating community of local mentors and providing a cohort of trained students that then became available to help with new labs and programs.

The Fab Academy was developed to teach digital fabrication. But much of what we had assembled wasn't specific to that content; the infrastructure could be used for any kind of distributed rather than distance learning. I had initially missed the deep connection between communication, computation, fabrication, and learning. Whereas digital communication lets us interact globally and digital computation lets us share knowledge, the addition of digital fabrication lets us exchange things as well as ideas. With the core set of tools in a fab lab, it's then possible to make whatever else is needed, effectively bringing the campus to the student.

George Church, one of the world's leading geneticists, was interested in reaching students beyond those who could fit into his classes at Harvard. This thought led George to add a second distributed class in the fab lab network: How to Grow (almost) Anything. Digital fabrication and biological fabrication connect at two levels. Biologists can use a fab lab to make the tools needed in a bio lab; biological equipment is often both overpriced and cumbersome. The same techniques used to make machines in fab labs have been used to make things like thermal cyclers for DNA amplification and liquid-handling robots to program reactions. At a deeper level, biology itself can be used for fabrication. As we'll see in Chapter 3, biological processes are fundamentally digital, and we're increasingly learning how to program these processes, as fab labs and bio labs converge.

Olafur Eliasson is one of the world's foremost artists. Like George, he wanted to extend his influence beyond the students he could directly teach in his studio. But his interest was not in *how* to make things, but *why*, leading him to begin developing another distributed class, Why Make (almost) Anything, to explore the influences on, and impacts of, the making process.

My student Nadya Peek jokingly called this growing collection of programs the Academy of (almost) Anything. The name stuck, or "Academany" for short, and it is now managed by Jean-Michel Molenaar (who started the Grenoble fab lab). Each of its offerings follows the same model of local workgroups, with mentors connected globally for interactive lectures from world leaders with collaborative content sharing.

While fab labs were spreading around the world, I helped plan a new building at MIT. The task took ten years from start to finish, cost a hundred million dollars, and fits a few hundred people. Each of the thousand fab labs that emerged over those ten years has a community of a hundred or so users. These numbers pose an obvious question: Which activities justify the hundred-million-dollar versus the hundred-thousand-dollar investment?

The existing organization of MIT is based on an assumption of scarcity. To manage access to our tools in labs, books in libraries, and faculty time, we reject most applicants and crowd into a corner of Cambridge, where there's a battle over every square foot of space. It's a false dichotomy to consider the alternative an isolated student sitting in front of a computer connected to an online learning platform; we've consistently found in the Fab Academy that for students to succeed, they need to be in learning communities. The real alternative is distributed rather than distance education, as the Fab Academy backed into doing. The follow-up question is then, how much of what is done at a place like MIT can be distributed this way, and how much needs to be centralized?

I'd say about half. Whenever we open a fab lab, we find the same kind of remarkable, inventive people who I work with at MIT. They're everywhere, appearing so consistently in fab labs because they're unable to find peers, mentors, and tools. About half the activities on MIT's campus could be done in a fab lab setting. The other half differ in that they require much more expensive tools, like the nanoscience instruments we're using to develop molecular-scale assemblers. The skills and knowledge to use these expensive tools are so specialized that it makes sense to do these activities all in one place. These two types of spaces aren't in opposition—you can view all this as a tree, with ten-thousand-dollar maker spaces, hundred-thousand-dollar fab labs, million-dollar super fab labs, and ten-million-dollar research labs. But it's by growing the tree out rather than up that we scale to tap the brainpower of the planet.

Seymour Papert is the father of computers and education. He studied in Switzerland with the pioneering child psychologist Jean Piaget, who argued that children learn like scientists, by doing experiments and testing theories. Seymour then came to MIT to get access to early real-time digital computers, wanting to expand the scope of experimentation available to a child. This was an improbable thought at the time—these computers were expensive, room-filling beasts that were difficult to use. To provide a friendlier interface, Seymour developed robotic “turtles” that he connected to the computer, and a language (Logo) that let children tell the turtles what to do.

One of the people who came to work with Seymour is Alan Kay, who went on to develop the modern computing paradigms of graphical user interfaces and laptops. These design principles weren’t originally intended for business executives to balance spreadsheets; they were for children to discover. Another person who studied with Seymour is Mitch Resnick, who developed Lego’s Mindstorms kits (named after a book that Seymour wrote), which moved the computer into a programmable Lego brick. Mitch also led the creation of the popular Scratch software for kids to program.

As fab labs started doubling and the Fab Academy began to grow, Seymour came by to see me to talk about them. I had considered the whole fab-lab thing to be a historical accident, but he made a gesture of poking his side. He said that it had been a thorn in his side that kids could program the motion of the turtle but could not make the turtle itself. This had been his goal all along. Viewed that way, learning in fab labs follows directly from the work he started decades ago. It’s not an accident; there’s a natural progression from going to MIT to play with a central computer, to going to a store to purchase and play with a toy containing a computer, to going to a fab lab to play with creating a computer.

APPLICATION

Once you’re equipped with access to both the tools in a fab lab and the ability to use them, it’s possible to locally produce the kinds of products that are today purchased at the end of long supply chains. Along with the benefits of using local skills and creating local jobs, a fab lab allows on-demand production and customization to meet local needs. Here are examples of how fab labs are being used, a survey that’s intended to be illustrative but not exhaustive (or exhausting).

Craft

The Cook Inlet Tribal Council (CITC) is a tribal nonprofit serving Alaska’s Cook Inlet region. The Alaska Native communities that it serves have profound cultural traditions but also serious issues with unemployment, alcoholism, and suicide rates. CITC hosts a fab lab that opened in 2013 and is focused on merging culture and technology to serve a new generation that is growing up surrounded by digital devices that frequently have little local context. The White House’s 2014 Native Youth Report found that the high school graduation rate among Native high school students is the lowest of any demographic group across all schools.

Benjamin Hunter-Francis II was sixteen and at risk of becoming one of those statistics when he moved to Anchorage from the remote village of Marshall, Alaska, population 349. Far behind in school, he had a different sense of culture from kids born and raised in the city. He became a fixture in the fab lab, using it both for his classes and for personal projects. One project was a wooden sled based on traditional designs but made with computerized tools and engraved with images from his community. For another project, he used the laser cutter to do marquetry that’s traditionally done laboriously by hand carving. Along with catching up and now enjoying school, he feels that the fab lab is helping him keep in touch with his ancestors, traditions that he wants to help keep alive.

Haystack Mountain School of Crafts is one of the premier artists’ colonies in the United States. Here, renowned glassblowers, blacksmiths, potters, printmakers, and other artists retreat to this collection of studios on the coast of Maine to practice and teach their crafts. In 2009, after the then director Stu Kestenbaum proposed as an experiment to introduce digital fabrication tools, we set up a temporary fab lab there. The response was a bit like when Bob Dylan showed up at the Newport Folk Festival in 1965 with an electric guitar, an event that one observer said “electrified one half of the audience, and electrocuted the other.” Half of the artists were horrified by the intrusion of technology into a temple of traditional crafts; the other half were horrified by the first half for not recognizing that all their practices rested on technologies that were once new and that this was just another one.