Digital Fabrication and the Future of Work

by Joel Cutcher-Gershenfeld, Alan Gershenfeld, and Neil Gershenfeld

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The Gershenfeld brothers...

- Visualize "implications of digital fabrication technologies for the future of work."
- "If the reach and capability of digital fabrication continues to expand at present rates, it will bring unprecedented productive capacity to large numbers of individuals and neighborhoods."
- The transition to a digital fabrication economy can transform markets and society positively, but it must be managed carefully to mitigate risk and prevent it from exacerbating income inequality.

When exploring the future of work, most people focus on the jobs that will be replaced by technology, the new jobs created by transformational technologies, the jobs that will be upgraded or downgraded by technology, and key trends, such as the growth of "gig" jobs. Understanding this entire blend is important but incomplete. The discussions are missing a category of work that is at once ancient and new—which we term "self-sufficient production"—making what one consumes at a personal, family, or local level. Today, this category is expanding through the accelerating advances in digital fabrication, and it is notable because although it does not involve traditional employment, it shares many of the attributes of "work."

Digital fabrication technologies have the potential to redefine how we think about work. When most people think about work, they think of standard dictionary definitions: "the place where one is employed" or "the period of time one spends in paid employment"—conceptions of work that are inextricably tied to paid labor. Self-sufficient production is a new category that keys off a different dictionary definition of work: "activity involving mental or physical effort done in order to achieve a purpose or result." What if a growing portion of the annual household budget for purchasing goods needed by typical individuals or families required only the purchase of raw materials, with the production taking place in local community "fab labs," maker spaces, and even settings with in-home fabrication capabilities?

> We also explore how many people need to be on a path where they are increasingly making what they consume.

If the performance and accessibility of digital fabrication technologies continue to improve at their present, exponential rate, then the potential for a redefinition of work itself is not just an abstract thought exercise. Instead, it becomes possible for individuals, families, and neighborhoods to literally own the means of production. In this article, we extend the analysis introduced in our book, *Designing Reality: How to Survive and Thrive in the Third Digital Revolution*, to focus more deeply on the implications of digital fabrication technologies for the future of work (Gershenfeld, Gershenfeld, and Cutcher-Gershenfeld 2017). In particular, our focus is on how individuals and families can leverage these powerful tools to increasingly make what they consume—advancing self-sufficient pro-

A fab lab in Vestmannaeyjar, Iceland. (© Frosti Gíslason/Saethor Vido)

duction as an important new category in the blend of activities that are part of the future of work.

In order to unpack how this new category is expanding around the world, we begin with an overview of digital fabrication as a third digital revolution, followed by an analysis of the implications of this technology on the future of jobs debates and then a dive into what the technology can and can't do. We also explore how many people need to be on a path where they are increasingly making what they consume for this to be truly a transformation in the landscape of work.

Three Digital Revolutions

Digital fabrication is different from analog fabrication. Instead of hand-guided tools and machinery, computer-aided design combines with computer-aided fabrication to reduce the capital and skills needed to produce physical objects of all kinds. Increasingly, digital fabrication technologies are becoming available in schools, libraries, museums, universities, community centers, and even homes. When the digital fabrication hardware and software is interoperable across locations, it enables network effects, greatly accelerating the innovation in a way that is not possible with analog fabrication.

Digital fabrication builds on two earlier digital revolutions—in digital computation and communication. Much as these first two digital revolutions transformed the nature of work, so too will the third digital revolution in fabrication. Digital fabrication is currently less visible than the first two digital revolutions and is often misunderstood. It is less visible since the technology today mostly resides in rapid prototyping facilities for industry and community fab labs or maker spaces (of which there are several thousand in the world today).

Digital fabrication is often misunderstood in that people think of it as being just 3-D printing. It actually involves a wide range of additive and subtractive technologies, as well as computer-aided design and embedded electronics. It is the community fab labs that are of particular interest in that they have both a common footprint of software and hardware, making network effects possible, and an underlying ideology centered on open access to technology. In fact, all over the world, people in fab labs are making everything from food, furniture, and crafts to computers, houses, and cars. They're sharing knowledge globally while moving toward local self-sufficiency.

Just as digital computation went through successive stages of development from one computer in the world to massive mainframes to large minicomputers to personal computers to universal computing (phones, pads, etc.) to ubiquitous computing (the Internet of Things), we project the same for digital fabrication. In our book, we offer a fifty-year road map that begins with the first digitally controlled machine tool to massive prototyping facilities to community fab labs to personal fabrication to a stage that sounds more like science fiction than science.

This is a stage that is analogous to universal and ubiquitous computing, which involves not just digital fabrication with analog consumable materials, but fabrication with digital and programmable materials in ways that begin to look like the Star Trek replicator. There are early examples of these very advanced stages of the road map already visible in research labs today (Gershenfeld et al. 2017).

For today's jobs debate, however, we focus here on the current stage of community fabrication and the emerging shift toward personal fabrication. This parallels where the first two digital revolutions were in the late 1970s and early 1980s. The key question at this stage concerns the degree to which people can make things in a fab lab or with emerging personal fabrication machines that replaces, to a substantial degree, their need to work. Were that to happen, it would be a historical inflection point, requiring a rethinking of the nature of work.

Today's Jobs Debates

Most of the debates around technology and work are centered on the potential for large-scale job loss due to transformational technologies. The focus is on the "rise of the robots" (Ford 2015), the "sentient machine" (Husain 2017), and the need to "digitize or die" (Windpassinger 2017). These debates have prompted calls for a universal basic income for those displaced, funded presumably by the vast increases in productivity enabled by automation, robots, artificial intelligence, and other related technologies.

But these concerns and recommendations are all premised on the notion that paid work itself remains unchanged, with the only question being whether the work is done by people or machines and, if by people, the degree to which these are good jobs. In the context of digital fabrication, this way of thinking would draw our attention to the 1,819,300 assembler and fabricator jobs in the *BLS Occupational Handbook* (Bureau of Labor Statistics 2016), for which there is a predicted 14 percent decline by 2026, or a loss of 261,900 jobs. With the growing interest in bio fab, it would also draw our attention to the 82,100 biological technicians employed in 2016 (projected to grow by 10 percent, or 8,400 jobs, by 2026). This is an important and related analysis, but it is not our focus here.

Our focus is on people who fit into a new emerging category, those who are able to reduce their household costs by increasingly assembling and fabricating what they need. The ability to make more of what one consumes also has benefits beyond the cost savings. One of the big criticisms of the universal base income is that it doesn't acknowledge the meaning, purpose, dignity, and social aspects of work. Making things for oneself, one's family, and one's community is not easy, but it is extremely rewarding. In fact, when coupled with potential base income, fab training could create a powerful new blend of work.

A potential vision for this new blend is represented in the inspiring work of Blair Evans, an accomplished automotive engineer and educational leader who is now developing a local ecosystem of fab labs in an economically distressed part of Detroit. His vision is about what he calls "thirds"—building out the digital fabrication capability to the point that people might spend one-third of their time in paid labor to buy what they can't make, one-third of their time using digital fabrication facilities to make what they can (with a focus on furniture, housing, aquaponic food production, and other practical things), and one-third of their time to follow their passions in whatever way they choose. This is a very different assumption about what constitutes a work week. And emerging new models are not only urban. Many are happening in rural communities where just a few generations back many individuals and families were completely self-sustaining—using local materials to fabricate local solutions. Given more powerful tools, this may be the leading edge, where this new category of self-sufficient production emerges fastest.

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Documenting the emergence of new categories of work is difficult. In a 2016 study of alternative work arrangements, Larry Katz and Alan Kruger found that "the percentage of workers engaged in alternative work arrangements—defined as temporary help agency workers, on-call workers, contract workers, and independent contractors or freelancers—rose from 10.7 percent in February 2005 to 15.8 percent in late 2015." They point out, however, that most of these, such as what are termed "gig" jobs, are not new categories of work. On this subject in the United States, they find that "workers who provide services through online intermediaries, such as Uber or TaskRabbit, accounted for 0.5

Table 1. Classifying practical and innovative outputs from fab labs against the U.S. Consumer Price Index basket of goods.

U.S. CPI Basket of Goods	Selected examples of "the most practical thing produced in your fab lab"	Selected examples of "the most innovative thing produced in your fab lab"
Food/beverages	Custom chocolate bars	Aquaponics
Housing	Flat-pack furniture	Flat-pack CNC cut tiny home
Apparel	Shoes for children in Africa	A dress that changes color and shape according to feelings picked up by brainwave sensors
Transportation	Electrical-assisted bike	Fab car
Medical care	Prosthetics	Automatic temperature-scanning baby bassinet
Recreation	Parts for an accordian	Smart juggling balls
Education and communication	Laser-cut wedding invitations	Totem poles for English and social studies class
Other goods and services	-- Laser cutter -- CNC router -- Wind sensor -- Drones -- Safety-mechanism for gamma-ray sensor	-- Sensors for climate-controlled bee shelter -- Low-tech robot to clean plastic from river -- A hologram that reacts to sound -- DIY CNC plasma cutter

percent of all workers in 2015." There were approximately 150 million people employed in the United States in 2015, so that would put the number of "gig" jobs at 750,000.

Apparently, 0.5 percent is enough of a shift in the job market, if it is happening with sufficient speed, to get people thinking that we are at or approaching a historic inflection point. So let's consider what it would take for digital fabrication technologies to fundamentally change work for 0.5 percent of the U.S. workforce and for similar proportions of people's work to change around the planet.

What Can Be Made in a Fab Lab?

If people are to genuinely own the means of production, the key question is whether they will be producing a sufficient proportion of the goods purchased in a year to reduce their dependence on commercial industry, with its global supply chains. In 2017 we conducted a survey of 179 fab lab leaders from around the world. Responses came in from fifty countries. Among the questions we asked folks was a request for examples of the most practical thing they had seen produced in their fab lab, as well as examples of the most innovating things they had seen produced. Table 1 lists an example of the responses to both questions in each of the categories used in the U.S. Consumer Price Index (CPI) basket of goods purchased by a typical family in a year.

A scan of these entries reveals both the breadth of what can be made in a fab lab and the unique nature of many of the items. Some of the entries could be the basis for larger-scale production, but the technology in a fab lab is not designed for production at scale. Instead, people might make one or a few of something and often do so with a high degree of personalization. Moreover, there was no single dominant response from the 179 fab leaders. Even the most common responses, such as furniture or prosthetics, were not mentioned by more than one-half dozen people in response

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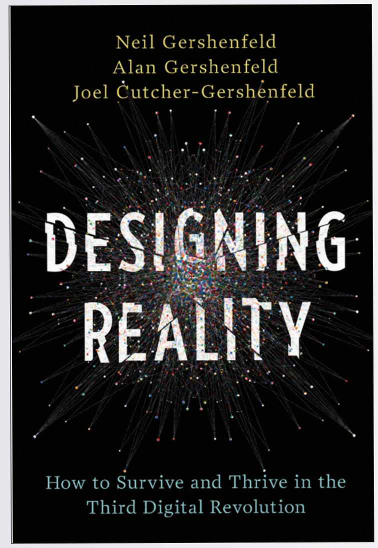

Designing Reality:
How to Survive and Thrive in the Third Digital Revolution

by Neil Gershenfeld, Alan Gershenfeld, and Joel Cutcher-Gershenfeld (Basic Books, 2017)

Designing Reality website:
http://designingreality.org

From the Designing Reality website:

Over the past fifty years, two digital revolutions—in computing and communication—have transformed our world. They have led to unprecedented productivity, generated enormous wealth, and fundamentally altered everyday life. But these revolutions have left a great many people behind: today, half of the planet is not connected to the Internet, inequality is on the rise, and issues around privacy, security, and civility emerge daily. With more foresight, we could have avoided many of these pitfalls.

We now have another chance. Neil Gershenfeld, Alan Gershenfeld, and Joel Cutcher-Gershenfeld foresee a third and even greater digital revolution in fabrication. The third digital revolution is about much more than 3-D printers and hobbyist makers; it's about the convergence of the digital and physical worlds. Drawing on the history of digitization and exploring the frontiers of research, *Designing Reality* outlines a vision for a future radically transformed by digital fabrication that takes us from community fab labs to personal fabrication to replicators right out of Star Trek that will allow anyone to make (almost) anything.

Accelerating digital fabrication capabilities could enable self-sufficient local communities and global sustainability. But it could also reinforce existing inequality and create new, destabilizing "fab" divides. We can do better this time.

Designing Reality is your guide to not just surviving but also thriving in the third digital revolution.

to either question. So, the challenge of filling the basket of goods for even 750,000 people will not follow the standard Bureau of Labor Standards methods of looking for common purchases of a representative sample of households.

Table 2. Growth in fab labs and Fab Academy graduates, 2003–16.

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Fab Lab Growth	1	2	5	7	12	35	43	75	129	217	289	605	950	1298
Fab Academy Graduates	0	0	0	0	0	2	7	15	26	55	93	163	303	464

In order for the category of self-sufficient production to increase to the level where it is a meaningful part of the future of work blend, critical issues around fab access, literacy, enabling ecosystem, and risk mitigation will have to be addressed. With the first two digital revolutions, we have seen the impact of digital divides, where half the planet does not have access to the Internet and billions more have very limited access. We could see a growing fab divide, where only the well-off have the access to the powerful tools and therefore the option for self-sufficient production.

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Fab access is necessary but not sufficient. Once individuals, families, and communities have access to digital fabrication tools, they need the literacies to be able to use them to meet personal and local needs. To cultivate broad-based fab literacy, we need fab-based learning pathways in K–12, higher education, and lifelong learning and an ecosystem of mentors (local and global). In fact, a number of the responses to our survey emphasized learning and community building as key values of the fab lab experience, even when the focus of the survey question was on things produced in the lab. For example, some of the responses on the most innovative thing produced in a fab lab were more about learning and community building, such as these three examples:

- "Having youth serve as fab stewards, providing open access and meaningful making experiences for both youth and adults."
- "Co-created public space structure blending digital fabrication and local traditions."
- "Placing a fab lab in the heart of an underserved community in Northern Ireland as a social experiment to work with the unemployed and disengaged has provided an innovative service in a place that has been starved of investment and access to technology."

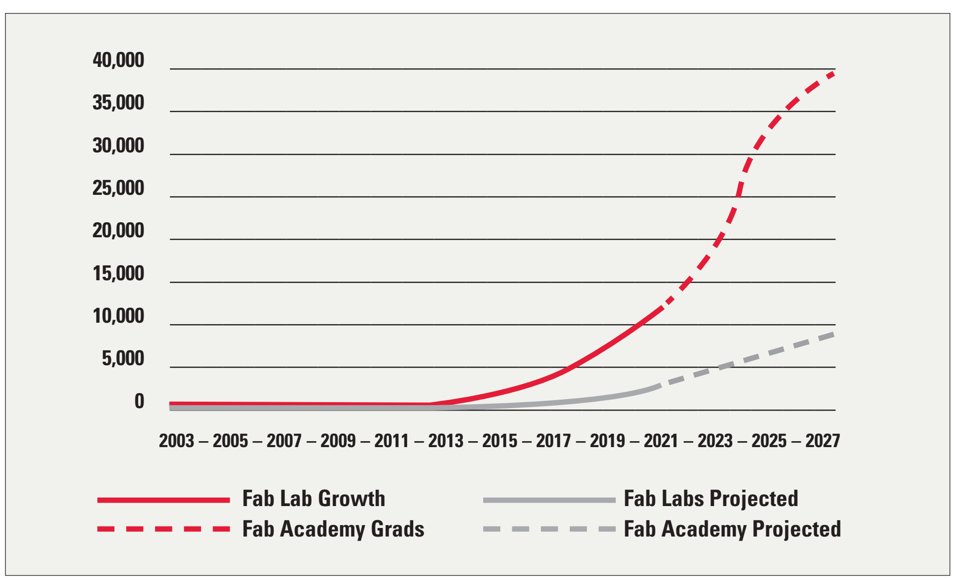
At this stage in the third digital revolution, access to the design and fabrication experience is at least as important as the ability to make things. While our focus here is on the basket of goods, in the conclusion we will come back to the value of the intangible benefits of digital fabrication as well as of the tangible goods produced. Finally, it is also essential that while we work on maximizing the benefits of fab labs, we also mitigate the potential harm—everything from bad people making dangerous things in fab labs to safety and other "workplace" protections. Not addressing the risks early, while the culture and core assumptions of the ecosystem are forming, could set back the entire movement.

Projecting the Growth of Digital Fabrication

The first fab lab was established in 2003, and the number of labs in the world has been doubling approximately every eighteen months. There is the prospect of this doubling continuing at least through 2025, after which the technology may have been taken over by smaller, personal fabricators, who won't need a room-filling fab lab. Table 2 indicates the growth at present in two key variables: the labs themselves and the people with the skills and knowledge to lead the labs.

The following figure begins with the actual data on fab lab growth to date and assumes that the rates of change for fab labs maintains the exponential

Projected growth in fab labs and Fab Academy graduates, 2003–2027.



growth through 2025, followed by a leveling off as the next phase of technology—personal fabrication—takes hold. This is a common trajectory with a technology curve (Perez 2002), and it gives us the ability to consider the pace at which access to digital fabrication technologies may be growing. It also reveals the more linear rate of change with Fab Academy graduates, an issue that we will address further in the conclusion since it is a potential rate-limiter in this analysis.

If there are indeed the projected 25,000 fab labs worldwide by 2026 and one-fifth of them (5,000) are in the United States, then a conservative count of 100 people utilizing the fab lab to fill part of their basket of goods would mean that 500,000 people would be engaged in self-sustaining work activities that meet some of their annual needs. This growth begins to approach our suggested criteria of impacting a minimum of 750,000 people with an exponential rate of change.

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An alternative formulation with a remarkably similar scope comes from Tom Kalil, former deputy director of the White House Office of Science Technology and Policy. His model contrasts with the traditional high-tech "unicorn," where a billion-dollar valuation makes a small number of investors and founding employees incredibly wealthy. Instead, he posits a billion-dollar innovation that makes or saves a thousand dollars each for a million people. Digital fabrication technologies accessible to 500,000 people, who would account for the one-third of personal expenditures that we quoted earlier from Blair Evans, would fit this model.

Conclusion

Observers differ in their counts of technological inflection points. Michael Piore and Charles Sabel suggested in 1984 that we were entering the second industrial divide in which mass production would give way to new forms of flexible production serving specialized niche markets. Carlota Perez, in 2002, counted five different technological and market shifts over the last two centuries, with financial capital abandoning old technologies and pouring into new technologies with each shift.

The World Economic Forum's Klaus Schwab counts four industrial revolutions (Schwab 2017) and has spawned a mini-industry of economy 4.0 consultants across Europe. Just focusing on digital technologies, we count three digital revolutions (Gershenfeld et al. 2017), each marked by exponential rates of change. While different underlying logics lead to different counts, one thing is common in all the analyses, which is that these changes in technology and markets are inflection points that bring great challenges and opportunities for society.

If the reach and capability of digital fabrication continues to expand at present rates, it will bring unprecedented productive capacity to large numbers of individuals and neighborhoods. In this article we have suggested that bringing sufficient digital fabrication capacity to approximately 500,000 to one million people—enabling them to significantly reduce their household spending—might be compelling as the early indication of a historical inflection point. Looking ahead, we welcome others to join in fleshing this scenario out more fully.

Will access to digital fabrication ultimately be sufficient to constitute revolutionary change in markets and society? The potential is there, but it will only be realized through choices made to ensure a social infrastructure that can co-evolve with the technology. Thus, the slow rate of change in generating graduates from the Fab Academy is a rate limiter until additional fab education and development models are developed. On the other hand, the intangible benefits of increased design literacy enabled by a fab lab, as well as general benefits of project-based learning, represent a rate accelerator for self-sufficient production.

At this stage, scholars would be well served to visit their local fab lab or maker space and judge for themselves whether they are seeing the equivalent of computers in the late 1970s and early 1980s. If so, we have a rare opportunity to shape the revolution early on, rather than wait to deal with the evolving technology decades later.

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