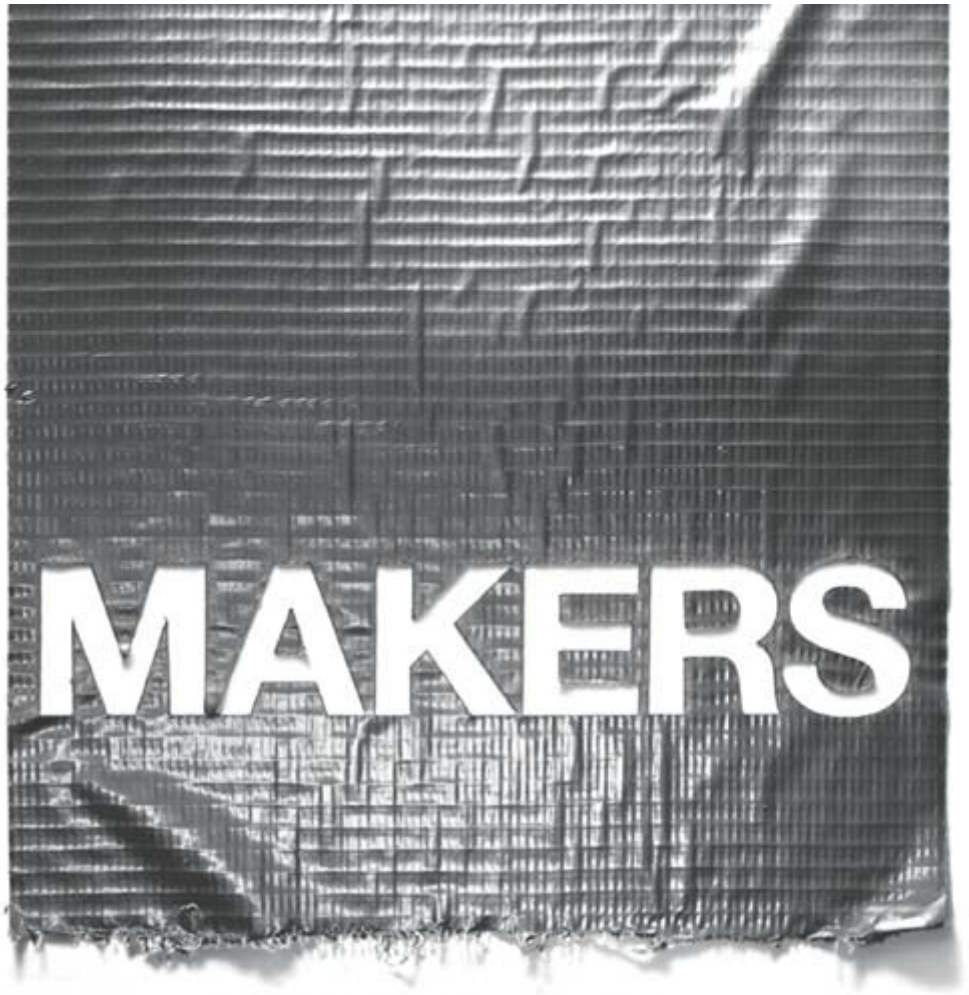

THE NEW INDUSTRIAL REVOLUTION

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MAKERS

The New Industrial Revolution

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Chapter 2

The New Industrial Revolution

What happens when the Web generation turns to the real world.

Here's the history of two decades of innovation in two sentences: The past ten years have been about discovering new ways to create, invent, and work together on the Web. The next ten years will be about applying those lessons to the real world.

This book is about the next ten years.

Wondrous as the Web is, it doesn't compare to the real world. Not in economic size (online commerce is less than 10 percent of all sales), and not in its place in our lives. The digital revolution has been largely limited to screens. We love screens, of course, on our laptops, our TVs, our phones. But we live in homes, drive in cars, and work in offices. We are surrounded by physical goods, most of them products of a manufacturing economy that over the past century has been transformed in all ways but one: unlike the Web, it hasn't been opened to all. Because of the expertise, equipment, and costs of producing things on a large scale, manufacturing has been mostly the provenance of big companies and trained professionals.

That's about to change.

Why? Because making things has gone digital: physical objects now begin as designs on screens, and those designs can be shared online as files. This has been happening over the past few decades in factories and industrial design shops, but now it's happening on consumer desktops and in basements, too. And once an industry goes digital, it changes in profound ways, as we've seen in everything from retail to publishing. The biggest transformation is not in the way things are done, but in *who's doing it*. Once things can be done on regular computers, they can be done by anyone. And that's exactly what we're seeing happen now in manufacturing.

Today, anyone with an invention or good design can upload files to a service to have that product made, in small batches or large, or make it themselves with increasingly powerful digital desktop fabrication tools such as 3-D printers. Would-be entrepreneurs and inventors are no longer at the mercy of large companies to manufacture their ideas.

This appeals to the Web generation in a way that tinkering in the workshops of old did not. At the same time, the digital natives are starting to hunger for life beyond the screen. Making something that starts virtual but quickly becomes tactile and usable in the everyday world is satisfying in a way that pure pixels are not. The quest for "reality" ends up with making real things.

This is not just speculation or wishful thinking—it can already be felt in a movement that's gathering steam at a rate that rivals the First Industrial

Revolution and hasn't been seen since, well, the Web itself.

Today there are nearly a thousand "makerspaces"—shared production facilities—around the world, and they're growing at an astounding rate: Shanghai alone is building one hundred of them.[4] Many makerspaces are created by local communities, but they also include a chain of gym-style membership workshops called TechShop, run by a former executive of the Kinko's printing and copying chain and aiming to be as ubiquitous. Meanwhile, consider the rise of Etsy, a Web marketplace for Makers, with nearly a million sellers who sold more than $0.5 billion worth of their products on the site in 2011.[5] Or the 100,000 people who come to the Maker Faire in San Mateo each year[6] to share their work and learn from other Makers, just as they do at the scores of other Maker Faires around the world.

Recognizing the power of this movement, in early 2012 the Obama administration launched a program[7] to bring makerspaces into one thousand American schools over the next four years, complete with digital fabrication tools such as 3-D printers and laser cutters. In a sense, this is the return of the school workshop class, but now upgraded for the Web Age. And this time it's not designed to train workers for low-end blue-collar jobs, but rather it's funded by the government's advanced manufacturing initiative aimed at creating a new generation of systems designers and production innovators.

Meanwhile, the rise of "open hardware," another part of what's known as the Maker Movement, is now doing for physical goods what open source did for software. Just as online communities of programmers created everything from the Linux operating system that runs most of today's websites to the Firefox Web browser, new communities of Makers are doing the same with electronics, scientific instrumentation, architecture, and even agricultural tools. There are now scores of multimillion-dollar open-hardware companies (including my own company, 3D Robotics[8]); some of them, such as the Arduino electronics development board, have sold more than a million units. Google, too, has joined the movement, releasing open-hardware electronics to connect to the hundreds of millions of phones and other devices that now run its Android mobile operating system.

What started as a cultural shift—a fascination with new digital prototyping tools and a desire to extend the online phenomenon into real-world impact—is now starting to become an economic shift, too. The Maker Movement is beginning to change the face of industry, as entrepreneurial instincts kick in and hobbies become small companies.

Thousands of Maker projects have raised money on "crowdfunding" sites such as Kickstarter, where in 2011 alone nearly 12,000 successful projects (from design and technology to the arts) raised nearly $100 million[9] (in 2012, that is on track to reach $300 million[10]). Venture capitalists joined in, investing $10 million each into Kickstarter, MakerBot, an open-hardware company making 3-D printers, and Shapeways, a 3-D printing service in 2011, as well as $23 million into Quirky, another Maker marketplace.[11]

Some of the biggest companies in the world of professional product design and engineering are now shifting their focus to the emerging Maker market.

Industrial giants such as Autodesk, PTC, and 3D Systems have released free design software for amateurs and even kids, along with service bureaus that let them upload their designs and have them 3-D printed or laser-cut. Like IBM a generation ago, which went from corporate mainframes to personal computers, they are recognizing that their futures lie with regular folks. They are pivoting from professionals to everyone.

In short, the Maker Movement has arrived.

This nascent movement is less than seven years old, but it's already accelerating as fast as the early days of the PC, where the garage tinkerers who were part of the Homebrew Computer Club in 1975 created the Apple II, the first consumer desktop computer, which led to desktop computing and the explosion of a new industry.

Similarly, you can mark the beginnings of the Maker Movement with such signs as the 2005 launch of *Make* magazine, from O'Reilly, a legendary publisher of geek bibles, and the first Maker Faire gatherings in Silicon Valley. Another key milestone arrived with RepRap, the first open-source desktop 3-D printer, which was launched in 2007. That led to the MakerBot, a consumer-friendly 3-D printer that is inspiring a generation of Makers with a mind-blowing glimpse of the future of desktop manufacturing, just as the first personal computers did thirty years before.

Makers united

What exactly defines the Maker Movement? It's a broad description that encompasses a wide variety of activities, from traditional crafting to high-tech electronics, many of which have been around for ages. But Makers, at least those in this book, are doing something new. First, they're using digital tools, designing onscreen, and increasingly outputting to desktop fabrication machines. Second, they're the Web generation, so they instinctively share their creations online. By simply bringing the Web's culture and collaboration to the process of making, they're combining to build something on a scale we've never seen from DIY before.

What the Web taught us was the power of "network effects": when you connect people and ideas, they grow. It's a virtual circle—more people combined create more value, which in turn attracts even more people, and so on. That's what has driven the ascent of Facebook, Twitter, and practically every other successful company online today. What Makers are doing is taking the DIY movement online—"making in public"—which introduces network effects on a massive scale.

In short, the Maker Movement shares three characteristics, all of which, I'd argue, are transformative:

1. People using digital desktop tools to create designs for new products and prototype them ("digital DIY").
2. A cultural norm to share those designs and collaborate with others in online communities.
3. The use of common design file standards that allow anyone, if they desire, to send their

> designs to commercial manufacturing services to be produced in any number, just as easily as they can fabricate them on their desktop. This radically foreshortens the path from idea to entrepreneurship, just as the Web did in software, information, and content.

Nations have always had their tinkerers and inventors. But the shift to digital changes everything about the ability to get those ideas and inventions produced and sold. Workshops of the world, unite!

Today the Maker Movement is where the personal computer revolution was in 1985—a garage phenomenon bringing a bottom-up challenge to the ruling order of the time. As then, the sudden liberation of industrial technology inspires exuberant imagination and some sweeping predictions (including here). The leaders of the Maker Movement echo the fervor of Steve Jobs, who saw in the personal computer not just the opportunity to start a company but also a force that would change the world.

But don't forget: he was right.

Indeed, Jobs himself was inspired by his Maker upbringing. Writing in *Wired*,[12] Steven Levy explained the connection, which led to the original Apple II in 1977:

> His dad, Paul—a machinist who had never completed high school—had set aside a section of his workbench for Steve, and taught him how to build things, disassemble them, and put them together. From neighbors who worked in the electronics firm in the Valley, he learned about that field—and also understood that things like television sets were not magical things that just showed up in one's house, but designed objects that human beings had painstakingly created. "It gave a tremendous sense of self-confidence, that through exploration and learning one could understand seemingly very complex things in one's environment," he told [an] interviewer.

Later, when Jobs and his Apple cofounder, Steve Wozniak, were members of the Homebrew Computer Club, they saw the potential of desktop tools—in this case the personal computer—to change not just people's lives, but also the world.

In this, they were inspired by Stewart Brand, who had emerged from the psychedelic culture of the 1960s to work with the early Silicon Valley visionaries to promote technology as a form of "computer liberation," which would free both the minds and the talents of people in a way that drugs had not.

In his biography of Steve Jobs, Walter Isaacson describes Brand's role in the origins of what is today the Maker Movement:

> Brand ran the Whole Earth Truck Store, which began as a roving truck that sold useful tools and educational materials, and in 1968 he decided to extend its reach with *The Whole Earth Catalog*. On its first cover was the famous picture of Earth taken from space; its subtitle was "Access to Tools." The underlying philosophy was that technology could be our friend. Brand wrote on the first page of the first edition, "A realm of intimate, personal power is developing—power of the individual to conduct his own education, find his own inspiration, shape his own environment, and share his adventure with whoever is interested. Tools that

aid this process are sought and promoted by *The Whole Earth Catalog*." Buckminster Fuller followed with a poem that began, "I see God in the instruments and mechanisms that work reliably."[13]

The Homebrew Computer Club, where Jobs and Wozniak brain-stormed the first Apple computer, was founded on these principles. Today it carries on in hundreds of makerspaces, each using twenty-first-century tools to try to effect the same sort of revolutionary social and economic change.

Real countries make stuff

Any country, if it wants to stay strong, must have a manufacturing base. Even today, about a quarter of the U.S. economy consists of the manufacturing of physical goods. When you include their distribution and sale in retail outlets, you're talking about closer to three-quarters of the economy. A service economy is all well and good, but eliminate manufacturing and you're a nation of bankers, burger flippers, and tour guides. Software and information industries get all the press, but they employ just a small percentage of the population.

Some of us say that we "live online," but it's not true when it comes to spending or living our everyday lives. Our commercial lives reside mostly in the real world of bricks and mortar, of food and clothes, of cars and houses, and, until some sci-fi future arrives where we're just disembodied brains in vats, that will continue to be the case. Bits are thrilling, but when it comes to the overall economy, it's all about atoms.

Yet the cost of labor has made it harder and harder to keep manufacturing industries going in the rich countries of the West. Driven by the exodus of factory jobs due largely to Asian cost advantages, manufacturing employment in the United States is at a century-long low, both in absolute numbers and as a percentage of total working population. What's worse, those factories that are bucking the trend are having trouble finding qualified workers, as a generation has turned away from manufacturing as a career option. The industry that created the middle class in America is now seen to be in terminal decline (as we'll see later, this isn't the case, but without a reset, appearances risk becoming reality). Working in a factory sounds boring, dangerous, and dead-end.

But today we have a path to reverse that—not by returning to the giant factories of old, with their armies of employees, but by creating a new kind of manufacturing economy, one shaped more like the Web itself: bottom-up, broadly distributed, and highly entrepreneurial.

It is almost a cliché that anyone with a sufficiently good software idea can create a fabulously successful company on the Web. That's because there are practically no barriers preventing entry to entrepreneurship online: if you've got a laptop and a credit card, you're in business.

But manufacturing was always seen as something else entirely. Making stuff is expensive; it needs equipment and skills in everything from machining to

supply-chain management. It usually requires huge up-front investments, and mistakes lead to warehouses of unsellable inventory. Failure may be celebrated online, where the cost of entry is relatively low, but in the world of making stuff, failing means ruination. Atoms are weighty, and so are the consequences of their failure. When you shut down a website, nobody cares. When you shut down a factory, lots of people lose their jobs, and the debts can haunt the owners for the rest of their lives.

Or at least that's the way it used to be. But over the past few years, something remarkable has happened. The process of making physical stuff has started to look more like the process of making digital stuff. The image of a few smart people changing the world with little more than an Internet connection and an idea increasingly describes manufacturing, too.

DIY manufacturing

Why? Because even commercial manufacturing itself has become digital, networked, and increasingly open—just like the Web. The biggest manufacturing lines speak the same language as a MakerBot ("G-code"), and anyone can move from one to the other. As a result, global manufacturing can now work at any scale, from units of one to millions. Customization and small batches are no longer impossible—in fact, they're the future.

It's like the photo management software, such as Picasa or iPhoto, that you probably already use on your own computer. They have a menu that allows you to choose whether to print your photos on your desktop printer or upload them to a service bureau to be professionally printed, or even bound into a photo album. The same ability has come to desktop CAD tools, where you can design 3-D objects onscreen. Once you've created something in a CAD program, you can choose whether to "print local" (prototype one copy on your 3-D printer or other desktop fabricator) or "print global" (send it off to a service bureau to be manufactured in volume). The only real difference is that sending it off to a service bureau adds a credit-card or invoice step, just like the photo printing services you already use.

This ability—to manufacture "local or global" at will—is a huge advantage. That simple menu option compresses three centuries of industrial revolution into a single mouse click. If Karl Marx were here today, his jaw would be on the floor. Talk about "controlling the tools of production": you (you!) can now set factories into motion with a mouse click. The distinction between amateur and entrepreneur has been reduced to a software option. The step from making one to making thousands is simply a matter of what menu options you select and how much you want to pay (or put on your credit card).

You can already see this in Autodesk's free 123D CAD program, which has a "Make" menu option that walks you through the choice between desktop prototyping and service bureaus. Over time, more such CAD programs will come with software "wizards" that can help you choose whether to fabricate in 2-D or 3-D, choose different materials based on their physical properties and costs, and integrate off-the-shelf parts that the service bureau can order for you.

Companies such as Ponoko already provide this sort of online service, serving as the Web link that connects desktop tools to global manufacturing capacity, which will eventually power the "Make" button in the program you use to create anything. The expertise of the machine shop is being replicated in software algorithms.

The reinvention of the sprinkler

Remember my grandfather's automatic sprinkler and my thought experiments in how differently its creation would have played out if he had invented it today? Rather than having to patent it and license it to a manufacturer (and lose control of his invention in the process), he could have brought it into production himself, becoming not just an inventor but also an entrepreneur.

Well, rather than just imagining what that would have been like, I thought it would be interesting to try it. So I decided to reinvent the automatic sprinkler system in the modern Maker model.

I am, it must be said, not a natural sprinkler entrepreneur. For starters, our "lawn" is ten feet long and four feet wide (the perils of living in the Berkeley hills); you can mow it with a pair of shears. I have absolutely no interest in gardening, and set foot on the grass only about once a year to set up a pup tent so the kids can conduct their annual adventure in "camping." My wife is the gardener, and she guards the flowerbeds with an iron fist; she was clear from the start that we would be doing no sprinkler experimentation in her domain.

But because my grandfather's big idea was the automatic sprinkler, for the sake of the family legacy a sprinkler it must be. So I talked to friends with proper lawns and sprinkler systems, visited garden stores, and started reading gardening sites. If I were to become a sprinkler inventor *and* entrepreneur, what problems would I be solving?

My assumption was that the best way to reinvent a mature industry would be to open it up to the ideas of others. So I asked a few basic questions, which you could call a toolkit for transformation (it can apply to practically any product):

1. How would these products be improved if they were connected to the Internet?
2. How would they be improved if the designs were open, so anyone could modify or improve them?
3. How much cheaper would they be if their manufacturers didn't charge for their intellectual property?

It didn't take me long to decide that sprinklers, despite my grandfather's wisdom and the collective innovation of a huge industry built over half a century or more, could be made a lot better. For starters, all the products on the market were proprietary, which meant that even if they did connect to the Internet (and few did), you had to pay a service fee for the privilege and were limited to what the manufacturer allowed. You could connect only the sensors that the manufacturer sold, and use them only the way the manufacturer had provided for. And they were expensive: a full installation could easily run into

the thousands of dollars and typically needed a consultant.

Now imagine a way better sprinkler—call it OpenSprinkler.

First, let's make it easy to control the sprinkler with your phone. Left for a vacation but forgot to set the sprinkler system? There's an app for that. Want to know what the soil moisture level is in the strawberry patch on a hot day while you're at work? Just check your pocket.

What if your sprinkler system knew it was going to rain tomorrow, so it didn't have to water today? Sure, you can buy high-end proprietary systems that will do that, but you have to pay a subscription fee. And if you have a better local weather data source than the one they use, you're out of luck—you are stuck with theirs. Let's make that free and open, too.

What if you don't want to have to read the manual just to figure out how to use your sprinkler system's cryptic menus? With OpenSprinkler you can set it up on a simple website with an easy-to-use graphic interface. And if you don't like the control panel we created, there are dozens of others to choose from, thanks to a community encouraged to create their own.

So there you have it, a recipe for a better sprinkler: open, Internet-connected, and inexpensive.

Easy enough to imagine. But how to make it real?

My electronics company, 3D Robotics, is based on an open-source computing platform called Arduino, which is a cheap and easy-to-use processor and free programming environment. It allows anyone to connect computing and the physical world, by making it easy to attach sensors and actuators to a computer program. This is often called "physical computing" or "embedded computing," and you see examples of it all around you. Practically every electronic device in your home works this way, from your thermostat to your alarm clocks, stereos, microwave oven, and portable music players. Your car has dozens of embedded computers. The difference is that they are all closed and proprietary, while Arduino is designed to be easy for anyone to use and modify. Much of the emerging "Internet of Things" movement is built on Arduino-based devices connected to the Web, from coffeemakers that tweet their status to pet feeders you can control from your phone, wherever you are.

So, because I knew it best, I decided to base the sprinkler controller on Arduino. That meant it could tap into a huge community of people who are using Arduino for all sorts of other purposes, and who had already solved most of the problems of connecting it to the Internet and any sensor you can imagine. My hope was that by using Arduino, most of my work would already have been done.

A quick search confirmed that this was the case; indeed, it showed that there was already a quite active Arduino sprinkler subculture. There were countless projects to control drip irrigation, to monitor soil moisture, even to steer plant containers toward the sun. Why so many? Well, most of it was simply putting together two geeky passions—gardening and computing—but the truth is that some were also driven by hydroponic "gardeners," who I assume are mostly people growing high-quality pot. Now there's a market not well served by the traditional sprinkler makers!

Nevertheless, there were still improvements to be made, and I found a few like-minded souls: Rui Wang, a University of Massachusetts professor who had figured out how to connect Arduino to a cheap commercial water valve that was easily available. And Andrew Frueh, who had started the sophisticated GardenBot project. All they needed was a better way to hook all this computer-controlled garden technology to the Internet, and we'd be in business. A few months of tinkering and we had a very functional prototype. It connected to the Web and thus any weather service online, and had a nifty wireless connection from your home network to a sprinkler controller box that could manage any number of valve networks and sensors.

At that point we had completed the invention stage, which was pretty much as far as my grandfather got on his own. But what would happen next is what shows the difference between then and now. My grandfather was forced to patent his invention, which was an expensive and time-consuming process involving lawyers and piles of paperwork. We, in contrast, just published everything online under open-source licenses. My grandfather had to find a manufacturer who would license his patents and put the sprinkler into production on its own terms. We just had to send the electronics designs to an assembly house (I chose Advanced Circuits, with which I had worked before) and sent the CAD design of the enclosure to a service that would turn it into a mold for injection-molding, which could then be sent to an injection-molding plant that would work at a small scale.

We calculated that an OpenSprinkler controller box, which is to say a Web-connected, easily programmable, cell-phone-friendly sprinkler brain, could be made and sold at a modest profit for about $100. That's between one-third and one-fifth of the price of commercial sprinkler systems with similar features. When your R&D is free (thanks, open-source community!) and you don't charge for intellectual property, it's not hard to undercut proprietary alternatives, even at lower volume.

In fact, it was even cheaper—today you can buy an OpenSprinkler kit for $79.95. Rui Wang used commercial suppliers to make the electronics boards and supply the necessary components, and he set up a Web store to sell it. It cost less than $5,000 to get to market, all told. While that's not pocket change, it's a lot less than my grandfather had to pay just for his patent attorneys' fees. The company that eventually licensed his patent no doubt spent a hundred times that to get a product out the door.

The point is that as entrepreneurship goes, this is dirt cheap. It's within the bounds of a credit-card limit and a tiny fraction of what starting a manufacturing operation used to cost.

One way or another, the sprinkler industry will change over the next few years as other newcomers build projects on Internet-centric, open-innovation models and enter the market. Maybe they will use our work, or maybe they'll come up with better designs of their own. But the point is that the real innovators probably won't be established players in the garden equipment market. Instead, they'll be startups cast more from the Web model. Today entrepreneurship is a choice in the way it never was for my grandfather.

And now for everything else

If sprinklers aren't your thing, you can substitute almost any other product or industry. Just in the past half hour as I was writing this, my news feeds brought me reports of similar Web-enabled hardware projects in horse management (electronics in barns that track animal comings and goings; apparently that's something ranchers need), home thermostats, biology lab centrifuges, and weather stations. Organizations as large as the Pentagon's research group—the Defense Advanced Research Program Administration (DARPA)—and General Electric are using open innovation for creating everything from small drones for the Army to smart electric outlets in your home.

Of course the New Industrial Revolution is not limited to open innovation. Conventional proprietary product development benefits from the same desktop prototyping tools, from 3-D printers to CNC (computer numerical control) routers. These new capabilities are accelerating innovation in the biggest companies in the world, from Ford's automobile interiors to IKEA's new kitchenware. As we'll see later, companies such as General Electric are using Maker-like community innovation methods among their own employees to develop proprietary products—open innovation doesn't have to be *wide* open. Midsized manufacturing companies in the United States and Europe are increasingly able to compete with low-cost labor in China by using digital manufacturing techniques to automate what used to require either lots of human labor or ruinously expensive equipment and tooling.

Behind all of them are the same thing: people working together with extraordinary new tools to create a manufacturing revolution. The shape of the twenty-first century's industrial structure will be very different from the twentieth century's. Rather than top-down innovation by some of the biggest companies in the world, we're seeing bottom-up innovation by countless individuals, including amateurs, entrepreneurs, and professionals. We've already seen it work before in bits, from the original PC hobbyists to the Web's citizen army. Now the conditions have arrived for it to work again, at even greater, broader scale, in atoms.