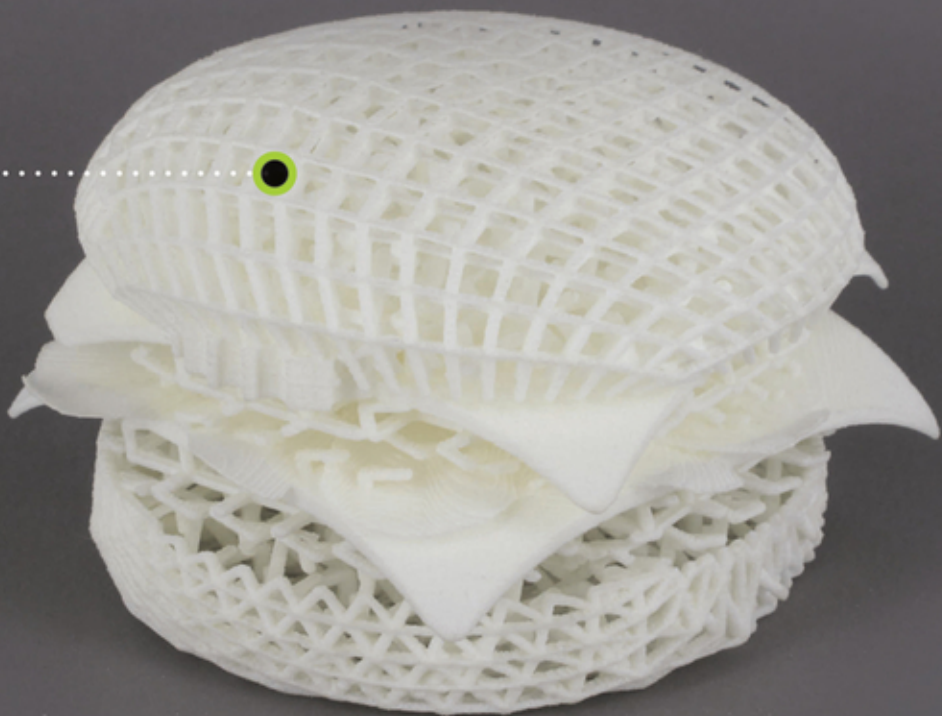


HOD LIPSON  
MELBA KURMAN

# FABRICATED

THE NEW WORLD OF **3D PRINTING**

The promise and peril of a machine  
that can make (almost) anything





**Fabricated**



# Fabricated

The New World of 3D Printing

Hod Lipson

Melba Kurman



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## **Fabricated: The New World of 3D Printing**

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*To Tiina and Jüri Kurman*

*To Rina and Stephen Lipson*

# About the Authors

**Hod Lipson** is a professor of engineering at Cornell University in Ithaca, New York. His work on automatic design and manufacture of robotic life forms, self-replicating robots, food printing, and bioprinting has received widespread media coverage including *The New York Times*, *The Wall Street Journal*, *Newsweek*, *Time*, and NPR. Lipson has co-authored hundreds of papers and speaks frequently at high-profile venues such as TED and the National Academies. Hod directs the Creative Machines Lab, which pioneers new ways to make machines that create, and machines that are creative. Visit <http://www.mae.cornell.edu/lipson>.

**Melba Kurman** is a technology writer, analyst, and popular blogger. She became interested in additive manufacturing and emerging design software two years ago when she noticed that the same manufacturing machine could print custom dental crowns, coffee tables, and heavy-duty, end-use metal machine parts. Her passion is explaining the value of complex technologies in everyday language. In the past she helped Cornell University, Microsoft, and other organizations bring new technologies to market. Melba is a graduate of Cornell University, the University of Illinois, and the U.S. Peace Corps.

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# Preface

One of the great things about 3D printing is that the field moves faster than the speed of light and technological advances take place in huge leaps and bounds. Yet, rapid innovation is a difficult topic to capture. Just as you figure out how to pin down an elusive and squirming new idea onto paper, it's already out of date. Everybody has moved on.

We wrote this book over nine feverish months, constantly seeking a broader perspective by speaking with experts we already knew and obsessively combing the web and twittersphere for new information and people to talk with. We chose not to write a simple “here’s how to use a 3D printer” since such a book would be obsolete in just a few months. Instead, since the technology changes faster than a book can be produced, we dug below the surface and chose to explore the deeper implications of 3D printing technologies, how this new capacity for production will change our lives, our laws and our economy.

Writing a book with two authors is both a blessing and a curse. There’s nothing like having a fellow traveler in the grueling and solitary writing process. No one else in the world is as eagerly willing to discuss and dissect arcane ideas for hours at a time. But having two authors presents a challenge: How do you manage two narrative voices?

Should two authors consolidate their individual experiences and insights into a collective “we?” Or should two authors differentiate each individual thought and experience by the name of the individual author (e.g., Melba or Hod)? After some thought and quite a few revisions, we settled on the following: new insights are “we.” Individual past experiences are “I”; however, in the chapters we don’t differentiate which “I” that is. So sometimes the “I” is Hod. Sometimes the “I” is Melba.

While writing this book, we had the privilege of interviewing more than 20 experts from different sectors and parts of the world. Their excitement for the topic was contagious and their feedback on the chapters invaluable. Here we'd like to express our appreciation for their time, patience, and best of all, the fact that their creative energy is changing the world as we know it.

We hope you will enjoy the book.

**Fabricated**



# 1

## Everything is becoming science fiction

Place: Your life

Time: A few decades from now

*... even in the future, it's still hard to get up in the morning.*

*The smell of freshly baked whole wheat blueberry muffins wafts from the kitchen food printer. The cartridges to make these organic, low-sugar muffins were marketed as a luxury series. The recipes were downloaded from different featured artisan bakers from famous restaurants and resorts.*

*The first time you showed the food printer to your grandfather, he thought it was an automated bread machine—an appliance from the 1980s that took foodie kitchens by storm. He couldn't understand why you wanted to print processed food until his anniversary came. To celebrate, you splurged on deluxe food cartridges and printed him and your grandmother a celebratory dinner of fresh tuna steaks, couscous and a wildly swirled chocolate-mocha-raspberry cream cake with a different picture within every slice.*

*Managing your diabetes has gotten easier since the health insurance company upgraded your food printer to a high-grade medical model. New medical-grade food printers for diabetics read streams of wireless signals from a tiny skin implant that tracks your blood sugar. When you wake up in the morning, the FoodFabber receives the first reading of the morning and adapts the sugar content and nutritional balance of your digitally cooked breakfast accordingly.*

*After breakfast, it's time to check the news. The top story is an update on a rescue operation of several miners who have been trapped underground for a week. Their mine shaft collapsed, stranding them deep underground. At first rescue teams tried to dig them out until their shovels nearly triggered a deadly rubble slide.*

*Fortunately, the mining company followed federal safety regulations and properly equipped its miners with regulation safety gear. 3D safety printers are a standard tool that mining crews carry with them into deep mine shafts. Before they*

descend into the shaft, technicians make sure each printer has updated design files for every essential machine part that will go down into the mine. The 3D printer goes down with other machinery in case a part breaks and needs to be quickly replaced deep underground.

Today's news update on the mining disaster reports that the portable safety printer has become an unlikely hero. For several days, the trapped miners have been conversing with above-ground technicians over a limping wireless connection. Both teams—one above and one underground—are working together to refine the printer's design blueprints for the replacement parts.

What should have been a short, standard rescue operation has grown complicated. Just printing a few replacement parts would have been easy. The reason the rescue effort has been delayed is because the design for the broken part keeps buckling after it's installed because of unexpected high levels of humidity inside the mine shaft.

The good news is that the situation in the mine looks brighter today. The reporter explains that the third attempt to print the replacement part passed its stress tests under simulated conditions at the mining company's headquarters. Today the miners will print the updated design underground and, if that works, start rebuilding their damaged machine tonight.

As you leave your house for work, a crane and a lone construction worker toil silently on an empty lot across the street. Your neighbor's construction project is the talk of the neighborhood. A few weeks ago your neighbor knocked down his old-fashioned wooden house to fabricate a new eco-friendly luxury home.

He waves from the mailbox and shows you the marketing brochure. The new home is a luxury model from a company called FoamHome and will be completed in two more weeks. FoamHome's catalog explains that each home's walls are constructed with built-in weather sensors. The roof, when it's laid on top at the very end of the process, will contain solar panels. Walls will be fabricated with electrical wiring and copper pipes already in place.

Together you and your neighbor watch the construction crane slowly maneuver a gigantic nozzle over the top of the new foundation. The nozzle simultaneously scans the landscape and adapts the blueprint, as it squeezes out a paste made of a blend of cement and some synthetic building materials. The crew member's job is to make sure no one walks on site during construction. The brains of the outfit is a small computer attached to the construction crane that guides the fabrication process.

*The neighborhood has been watching the FoamHome project with great interest as the home's walls slowly grow. What was that old joke about the early days of factory automation? "All you need these days to run a factory is a man and a dog. You need the man to feed the dog and the dog to bite the man if he tries to touch anything."*

*So far, the slowly growing house looks gorgeous, its walls curved in organic patterns and soft curves and hollows. Nobody could build a house like this with frame carpentry, no matter how many people worked on the construction crew. No one has yet seen the inside of the new home, but rumor has it that your neighbor ordered designer inner walls that will look like they're made of old-fashioned brick and mortar.*

*Finally you reach your office and catch up on the details of the final stages of a long investigation you've been leading for months. Your team was assigned to investigate a new sort of black market, one that deals in replacement body parts. More and more patients, desperate for replacement organs, are purchasing them from uncertified rogue bioprinting services rather than a certified medical provider. Bioprinting custom body parts continues to be a controversial topic in the public mind, more polarizing even than the stem cell, abortion, or cloning debates of your grandparents' generation.*

*It's gotten too easy to get replacement organs made. The cost of a high-res full body scan has plummeted in the past few years. People like to get them in their 20s and save the data for later, just in case if something goes wrong and they need a quick replacement organ. Sometimes it's their joints that fail. In reality, the most common use of "body design files" is for cosmetic surgery, to recapture the tight wrinkle-free skin and body of youth.*

*Bioprinting isn't the problem. In fact, most people believe that bioprinting is a life-saving technology. The challenge is what to do about the growth of these new black markets. Regulating the production of new printed body parts is difficult since the cost of bioprinters has also plummeted. Black marketeers snap up cast-off medical bioprinters for less than the price of a new car as last year's bioprinter models are sold off each year by hospitals and surgical clinics.*

*During the investigation, you've learned that most of the time black market organs actually work pretty well. The problems arise from faulty design files or sloppy organ makers who cut corners and don't use a sterile printing environment. In a recent case a few patients died from uncertified "vanity organs" they purchased to improve their athletic ability and appearance. Their families are trying to figure out who to sue: the rogue manufacturer, the bio-ink supplier, the organ designer, or the company that certified the design.*

Black market bioprinters range from well-intended, would-be healers to deadly, profit-driven peddlers of rogue, counterfeit flesh. Some call the competent and hygienic black marketeers heroes for helping ill people obtain vital new organs at a lower price. Others deplore the organ merchants' eagerness to profit from buying and selling essential tissue to vulnerable people, especially in cases where the new printed organ is poorly crafted.

At the end of the work day you stop by your daughter's middle school. You're one of the parental sponsors of this year's Science Fair. Your daughter's teacher tells you that 3D printers are disrupting the culture of the Science Fair. Lazy students 3D print elaborate objects with little effort and no skill—they just need to have a good design file. Many lower income students do not have home 3D printers so they aren't getting the design time and practice they need for a level playing field.

There's another twist. The teacher explains that for this year's fair, parents will serve on a clean-up crew. Last year after the fair ended, the school's custodians complained that the gym floor was littered with the debris of dozens of frenzied printing demonstrations. Even worse, for several days after the fair, students and teachers stumbled over dozens of mouse-sized, ready-made robots that clanked and rolled around school hallways. Some printed robots recited appropriate and preprogrammed bits of scientific lore. A few of the roaming robots, however, seemed to have mastered a few unauthorized and slightly more colorful bits of wisdom.

When you and your daughter get home, your spouse shares good news. His 3D printing manufacturing business just got accepted into an aerospace cloud manufacturing network. Cloud manufacturing is a new way to make things that's starting to replace mass manufacturing. Cloud manufacturing—like cloud computing—is a decentralized and massively parallel model of production. Large companies order parts and services on demand from a vetted network of several small manufacturing businesses that have joined forces to manufacture specialized parts.

Cloud manufacturing is catching on quickly in the electronics, medical, and aerospace industries. These companies need complex, highly sophisticated parts, but not in huge batches. Clouds of small manufacturing companies save the big companies money. Cloud networks tend to be located near their clients so there's less long-distance shipping of printed parts. The companies keep designs for product parts in digital inventory and make just one or a few at a time. Cloud manufacturing networks have been a boon for regional economies everywhere, creating local jobs in specialized small manufacturing and services companies.

Your spouse's particular cloud consists of small companies that fabricate specialized fuel injector parts for military and commercial airplane manufacturers. To get into this particular network, his business had to demonstrate its manufacturing

*prowess by 3D printing sample airplane machine parts in a specified time frame. The manufacturing network stress-tested his sample parts and they performed well. After some negotiation on profit margins and manufacturing capacity, his business was admitted into the network.*

*Finally, the day winds down. Your son likes his bedtime routine in which he brushes his teeth and you tell him a story once he's in bed. Tonight you discover that, as usual, his toothbrush has somehow gone missing. He thinks he may have left it at his friend's house yesterday. You could run to the store to buy a new one, but there's an easier way.*

*You boot up your home Fabber and let your son eagerly scroll through several different toothbrush designs. Several different companies sell designs on the Fabber but your son already knows he wants a zBrush—still a bargain at 99 cents. Your son likes the fact that there are several different cartoon figures offered for the toothbrush handle. You authorize his purchase and scan your son's custom measurements—the size of his hand and shape of his open mouth—with a small wand attached to the Fabber.*

*The Fabber starts printing. On its glowing screen a list of design credits scrolls past that resembles those of a movie—from the designer of the toothbrush program to the company that owns the copyrights of the designs for the cartoon figures. The new toothbrush will be ready for use in 15 minutes.*

*As the Fabber prints you tell your son his bedtime story. It's about the old days, one of those “when I was your age” tales. Your son listens skeptically. He has a hard time believing that when you were young, each toothbrush looked alike. If you ordered something from the Internet it took forever—24 hours—until it was delivered to the door.*

*“Wow,” he says politely. “Life must have been hard back then.”*



# 2

## A machine that can make almost anything

**W**hat would you make if you had a machine that could make anything? In England a technician scans the feet and ankles of Olympic sprinters and puts the data into a computer. The computer does a few quick calculations. The technician 3D prints new track shoes that are customized for each athlete's unique body shape and weight, gait and tastes.

On the other side of the world, NASA test-drives a version of its Mars Rover in the Arizona desert. On board the Rover are several custom-made 3D printed metal parts. Many of these parts have complicated shapes made of curves and inner hollows that could not have been manufactured by anything other than a 3D printer.

In Japan, an expectant mother wants to create the ultimate commemoration of her first ultrasound. Her doctor edits her ultrasound image and 3D prints a precise, highly detailed replica of the fetus. The result, an avant-garde 3D printed plastic tribute to the tiny fetus, encased for posterity in a block of hard transparent plastic.

These modest manufacturing miracles are already taking place. In the not-so-distant future, people will 3D print living tissue, nutritionally calibrated food, and ready-made, fully assembled electronic components. This book is about a new way of making things. In the following chapters, we explain 3D printing technologies and design tools in simple language. For readers of a technical bent, a few chapters delve deeper into the details of 3D printing's current and future. We then explore the downstream implications—economic, personal, and environmental.

3D printing opens up new frontiers. Manufacturing and business as usual will be disrupted as regular people gain access to power tools of design and production. Intellectual property law will be brought to its knees.

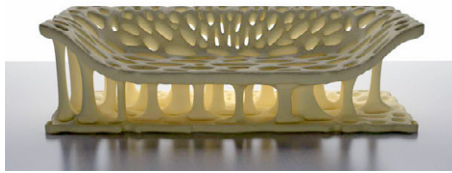


Image courtesy of Andrea Mor-  
gante and Enrico Dini, D-Shape

### **A printed full-scale bench in stone-like material**

Some people remember exactly where they were when they watched the first moon landing. Others remember the confusing first weeks when the Berlin wall came tumbling down. I remember the first time I heard about 3D printing.

The time was the late 1980s. The place, a tedious engineering seminar on manufacturing engineering. The classroom was warm. The professor had the misfortune to have a droning, unintentionally soothing voice that lulled my classmates and me into a sort of group stupor.

The classroom door banged open, disrupting the peaceful drowsy calm of the afternoon's lecture. An unfamiliar man burst into the room. Our surprise visitor announced he was a salesman from a company called Cubital Systems. We had never heard of Cubital Systems, which at that time was one of the two companies in the world selling commercial 3D printers.

The salesman animatedly waved a plastic object over his unruly mop of hair and announced that a manufacturing revolution was brewing. "I am holding the future of manufacturing in my hands," he boldly claimed. "This plastic object was made by a laser that 'printed' plastic."

Intrigued, my classmates and I stirred curiously and wondered why he had come to our class. At that point, sensing our interest, our professor wisely handed over the classroom to his animated visitor. We learned later that the Cubital salesman had been invited by our professor as a guest lecturer.

A skilled showman, the salesman ceremoniously paused, relishing our confusion. In the quiet that followed, he asked a student to turn the crank sticking out of the plastic object. I can still hear the crisp clicking sound in the classroom as my classmate energetically turned the crank for what seemed

like an endless minute. Inside the device, complicated interlocked gears tugged one another into motion.

Our sleepy brains struggled to life and we whispered questions to one another. “Did he just say that he *printed* that thing using a laser?” My classmates and I studied the grinding gears, trying to figure out where this unexpected entertainment was going.

## ‘Revolutionary’

### Machine makes 3-D objects from drawings

By Kathleen Sullivan  
American-Statesman Staff

Wedge into the corner of an unused photo lab at the University of Texas is an ungainly machine that can transform a computer drawing into a three-dimensional model at the touch of a button.

Sometime next year, the machine, which was developed by a UT graduate student, will make its way out of the lab and into the commercial arena. It will leave with the blessing of the UT Board of Regents, which Thursday gave an Austin company exclusive licensing rights to the “revolutionary” new technology embodied in the machine.

The licensing pact paves the way for the first transfer of technology from the University of Texas at Austin to a commercial venture.

The company that won the right to market the invention is Nova Automation Corp., whose principal shareholders are an Austin consulting engineer and Nova Graphics International Corp., an Austin-based computer graphics software firm.

The agreement represents a “hard fought” victory for UT’s fledgling Center for Technology Development and Transfer, said Meg Wilson, coordinator of the center, which was given life during the last Texas Legislature and got

**See Inventor, A11**



Staff photo by Ralph Barrera

Associate Professor Joe Beaman shows some three-dimensional plastic models made by the ‘selective laser centering’ device developed by Carl Deckard, left.

Image courtesy of Carl Deckard and Joe Beaman

**Carl Deckard and Joe Beaman inventing the first Selective Laser Sintering printer (circa 1986) at the University of Texas**

We became even more confused when the salesman dropped his next bombshell. “All of the gears, handles, and knobs that you see here were never assembled. They were all printed in place as a single, preassembled bunch of distinct parts.”

The confused buzz in the classroom increased in volume as our energetic visitor gleefully closed his presentation with a final data point: A computer, not a human, had been the guiding “hand” that steered this miraculous machine through the production process. The salesman rummaged through his bag and pulled out a piece of paper he waved in front of us. The page showed a photograph of a computer on whose screen was a design file for the same plastic object he had just shown us.

The Cubital salesman smiled and asked whether we had questions. Somnolence forgotten, my classmates and I peppered him with questions. What did he mean he “printed” all the plastic parts using a laser? And what sort of manufacturing machine could possibly fabricate something made of interlocked parts that didn’t need to be assembled? Could it print in materials other than plastic? And, of course—how much would it cost to get such a machine for oneself?

Traditional manufacturing felt instantly obsolete.

I still remember that day. Our guest lecturer’s enthusiastic pitch convinced me that this miraculous machine would indeed spark a revolution in the way we make and design things. I’d never seen such a close connection between the software design of an object (design software was a new and growing passion of mine at that time) and its physical manifestation.

That day was two decades ago. The revolution we were promised didn’t happen as quickly as planned. A few years later, Cubital went out of business. Like many pioneering technologies, Cubital’s 3D printing process was too complicated and slow, and its machines were too expensive for margin-conscious manufacturing companies to embrace.

I sometimes wonder where that salesman went after Cubital folded. His sales pitch—unabashedly dramatic as it had been—was dead on target. It’s just a matter of time until regular people will rip, mix, and burn physical objects as effortlessly as they edit a digital photograph.

## Printing three-dimensional things

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Like the magic wand of childhood fairy tales, 3D printing offers us the promise of control over the physical world. 3D printing gives regular people powerful new tools of design and production. People with modest bank accounts will acquire the same design and manufacturing power that was once the private reserve of professional designers and big manufacturing companies.

In a 3D printed future world, people will make what they need, when and where they need it. Yet, technologies are only as good as the people using them. People might fabricate weapons and create unregulated or even toxic new drugs. Our environment may be littered with quickly discarded print-on-demand plastic novelties. Ethical challenges of bioprinting will make stem cell controversy seem simple in comparison. Black marketeers will be tempted to earn quick and dirty profits by making and selling faulty machine parts whose shoddy construction could fail at a critical moment.

When most people first hear about 3D printing, their mind leaps to their old, familiar desktop printer. The biggest difference between an inkjet printer and a 3D printer is one of dimension. A desktop printer prints in two dimensions, spraying colored ink onto flat paper documents. A 3D printer fabricates three-dimensional objects that you can hold in your hand.

3D printers make things by following instructions from a computer and stacking raw material into layers. For most of human history, we've created physical objects by cutting away raw material or using molds to form new shapes.

The technical name for 3D printing is "additive manufacturing," which is actually more descriptive of the actual printing process. 3D printing's unique manufacturing technique enables us to make objects in shapes never before possible.

3D printing is not a new technology. 3D printers have been quietly doing their work in manufacturing machine shops for decades. In the past few years, 3D printing technology has been driven rapidly forward by advances in computing power, new design software, new materials, and the rocket fuel of innovation, the Internet.



Image courtesy Stratays Inc.

**This printer costs about \$10,000 USD and is the size of a microwave oven.**

Computers play a critical role in the 3D printing process. Without instructions from a computer, a printer is paralyzed. A 3D printer comes to life when it is fed a well-designed electronic blueprint, or design file, that tells it where to place the raw material. In fact, a 3D printer without an attached computer and a good design file is as useless as an iPod without music.

The way the 3D printing process works is as follows. The 3D printer, guided by instructions in the design file, squirts out or solidifies powdered, molten or liquid material into a specific flat pattern. After the first layer solidifies, the 3D “print head” returns and forms another thin layer on top of the first one. When the second layer solidifies, the print head returns yet again and deposits another thin layer on top of that. Eventually, the thin layers build up and a three-dimensional object forms.

3D printers don’t cut or mold things into shape the way humans or traditional manufacturing machines do. Making objects in layers opens up the ability to physically output a broader range of digital concepts. If a shape’s design has precise internal hollows or interlocked parts, a 3D printer is the first output device that can realize such designs in the physical world.