MAKER INNOVATIONS SERIES

Mastering Digitally Controlled Machines

Laser Cutters, 3D Printers, CNC Mills, and Vinyl Cutters to Make Almost Anything

Jean-michel Molenaar
Daniele Ingrassia

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About the Authors

Jean-michel Molenaar helped create the first Fab Labs in the Netherlands, after which he moved on to other countries to do the same. He has managed a company in the UK selling tools internationally, implemented the use of digitally controlled machines at Tufts University as a Professor of the Practice, and started the Resilience Collective, a humanitarian effort to use digital technology for the most vulnerable populations. He has created makerspaces in over 12 countries and has spoken about education and digital tools during various conferences around the world. He currently works for the Fab Foundation and lives in the French Alps with his wife and their three sons.

Daniele Ingrassia has taught at Fab Academy for six years and served as a Fab Lab mentor since 2017. He is a Fab Lab Guru and founder of InMachines, a company focused on open source digital fabrication machines for makerspace and fab labs. With a background in computer science, he now implements local digital fabrication courses in official university programs and develops open source hardware. Leaving behind a long series of Fab Lab–made projects, Daniele managed to develop several open source machines, such as a dual-source laser cutter and the largest open source 3D printer. With projects being replicated in many other countries worldwide, Daniele has held several fabrication and machine building workshops around the world. He lives in Schleswig-Holstein, Germany.

About the Technical Reviewer

Wendy Neale, DipEd, is a word nerd and editor, maker, mender, and gleaner.

About This Book

The maker movement, Fab Labs, makerspaces, hackerspaces, 100K garages …

There was a time when, if you needed a table, you went to see a woodworker and you would explain the size of your living room, the kind of wood you liked, and the shape of your desired table, and with chisels and blades, saws, and glue, the craftsman would build you a table.

You can still do this.

But not many people do.

Instead, they go to stores, the names of which we won’t mention, where they get tables that are fabricated by the thousands and often contain more air per cubic centimeter than wood.

This is not a mistake we made as a society, but the progress we have gone through, thanks to, among many others, Henry Ford. If it wasn’t for this model, not nearly as many people would have access to the kind of products they can now afford in their daily lives.

But perhaps this model is no longer the best model for the world we live in, nor has it developed in a way that is healthy for the planet.

In recent years, many different places have been created where (almost) anyone can access and use machines to make whatever they want. Some are more connected than others, but they are all spaces for turning ideas into objects, which places the power (and responsibility) to create back into partially everyone's hands and allows us to start making changes to how we consume and create.

One of these kinds of spaces, Fab Labs, came into being as a result of Neil Gershenfeld, an MIT[1] professor, teaching a class on "How to Make (Almost) Anything" and installing a digital fabrication space (or lab) for his students. The content of this space he shared freely with the world in conjunction with a vision of shared designs and open access to anyone interested. This, coming at the time where more and more people all over the globe started to call themselves "makers," came at the right moment, and the idea (and the spaces) spread quickly across the globe. The grand vision behind the class, which was at the birth of these spaces, is the eventual creation of the "*Star Trek* replicator" or a machine that makes anything, anywhere. This machine is still quite some years of research away, but it's something we are heading toward.

If we look at the progression of digital computation, we often forget how quickly we went from computers being very bulky and expensive tools accessible only to researchers and wealthy companies to being so ubiquitous that we don't even notice them anymore. Your house is filled with them, you carry them around, and we rely on them like it has always been like that.

Now imagine a similar progression in digital fabrication. Will we carry "personal fabricators" in our pockets in 30 years? Society will have to undergo a profound change if this becomes a reality, and we can hardly imagine how this is possible looking at the tools of today's makerspaces. But don't forget that Kenneth Harry Olsen from Digital (a company building computers) famously said, "No one needs a computer at home." The company closed its doors not long after, and chances are you are reading this on a tablet or phone.

Fab Labs, makerspaces – for us they are the start of a new socioeconomic era, the ramifications of which we cannot yet fully foresee. But their open nature and accessibility imply that this paradigm shift can come from not just the hands of the big companies building the

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[1] Massachusetts Institute of Technology (Cambridge, USA).

matter of our lives, but YOU. You can go to any one of these spaces and learn how to make things, things you or others need in their lives, and learn how to become something other than a consumer in the world of Henry Ford. Look at these tools as the first computers, not that easy to use maybe, but already very powerful in the implications they carry. So appropriate yourself these tools, and become an actor in the changing field of fabrication and consumption, and perhaps in the future we'll see fewer trucks crossing each other when they drive across our countries full of silica, or products derived thereof.

So Why This Book?

This book is meant for people interested in learning more about the currently available tools and means of fabrication that are accessible today, but also for those who have been working in these kinds of spaces and looking to deepen their knowledge of the techniques or are looking for inspiration.

You can thus read it cover to back, but also treat it as a source of technical info, skipping directly to the part you need to know more about.

We have divided the book into chapters about individual machines (laser cutter, vinyl cutter, CNC [computer numerically controlled] mill, 3D printer) and a chapter about building machines yourself, and of course we also discuss computer-aided design (CAD), or how to design for digitally controlled tools. At the very end of the book, you'll find a section with only technical info, like recommended cutting speeds for CNC milling, general settings for laser cutters, and detailed information on materials you might use.

We hope you won't just enjoy reading all this but that it will inspire you to go into your garage or out of your door and to a makerspace, Fab Lab, or community workshop and *start building stuff* – for you, for your neighbors, for your family, for a better planet, for the fun of building, for your kids, for your company, your startup, your grandma, or just because you can.

Building the future with Fab Labs - Neil Gershenfeld

Prof. Neil Gershenfeld is the Director of MIT's Center for Bits and Atoms, where his unique laboratory is breaking down boundaries between the digital and physical worlds, from pioneering quantum computing to digital fabrication to the Internet of Things. He's the founder of a global network of over two thousand fab labs in 125 countries, chairs the Fab Foundation, and leads the Fab Academy.

After digital revolutions in communication and computation, we're now living through a digital revolution in fabrication. This one completes the other two, and is likely to be even more significant than them, because it brings the programmability of the world of bits out here to the world of atoms where we live.

The digital revolutions in communication and computation were forecast by Gordon Moore based on five data points, showing the doubling of the number of transistors in an integrated circuit. He projected that forward for ten years; the doubling actually continued for fifty.

The digital revolution in fabrication can now be seen in the doubling of fab labs, from one to over one thousand. These room-filling facilities for digital fabrication correspond to the minicomputer stage in computing. Those technologies eventually evolved to fit in your pocket, but that's the time when the Internet, email, video games, and word processing all evolved. And that's when the corresponding new kinds of businesses and institutions emerged along with them.

Likewise, it's not necessary to wait for the research roadmap to lead to Star Trek-style replicators. Programs like the Fab Academy, Fab Foundation, and Fab Cities are now doing the same for this digital revolution. Jean Michel Molenaar and Daniele Ingrassia have been leaders in the spread of fab labs, technically, organizationally, and pedagogically. Mastering the material in this book is the path to participating in this revolution today, and to shaping a future where anyone can make (almost) anything, anywhere.

Introduction

This book can be read and/or used in a few ways. Here we will take a quick look at the subjects discussed in this book, whom it is for, and how we have put it together.

When writing this book, we realized it's quite a challenge to create something that appeals to many (aspiring) makers of different skill and knowledge levels and to make sure there is enough, but not too much, information about all the possibilities digital tools give you.

We believe we have been able to create a great collection of information for you, the reader, but are also sure there is much more out there we did not speak about or explain. So take this book not as a final step, but either as an entry to learn more about the exciting possibilities of digital fabrication or to deepen your knowledge and widen your skill set!

You will need several parts to go from an idea to a running machine. First is the CAD (computer-assisted design) software, which as you will learn in Chapter 1 can be one of many. After that, you will need to generate a toolpath from that two- or three-dimensional (2D or 3D) design, so you need a CAM (computer-assisted manufacturing) program. Then, you'll need to decide on how you are going to control your machine and send it the G-code that has been generated in the CAM software.

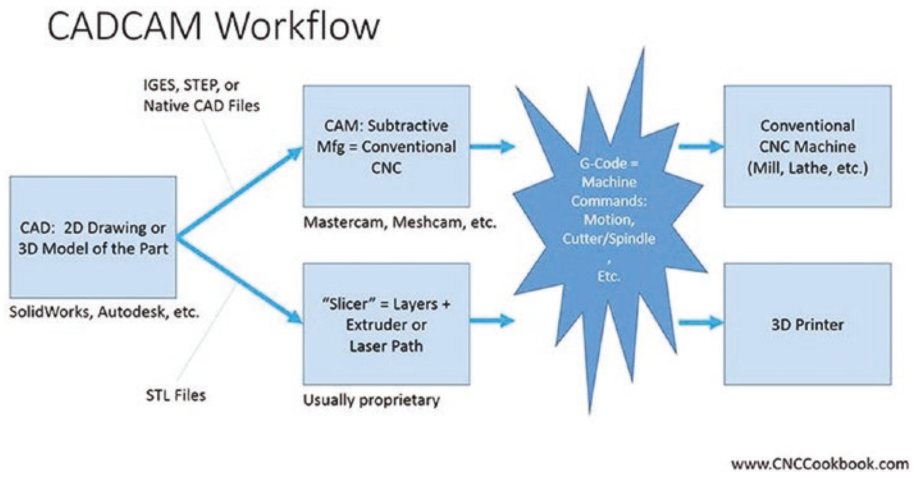


Figure 1. *CADCAM workflow (`www.cnccookbook.com/MTCNCSoftware.htm`)*

Each chapter of the book is either about a different digital fabrication machine type, software about how to make designs and operate machines, or how to build one. If you are interested in a specific type of machine, you can directly jump to the chapter and dive in to learn related information on how to use it, how it is made, or how to look for one to buy. Knowledge from chapters and parts made with different machines can be combined to achieve more advanced results, which can allow you to prototype your idea or even to build your own machine.

Let's start by taking a look at some history of numerically controlled machines and their impact over the years and then explore the capabilities.

History of Computer Numerical Control

The basis of the machines you'll read about in this book comes from NC – short for numerical control. But it could be traced back further to automated systems that were built in the 1820s or 1830s or even further to automata built long before that.

In 1818, Thomas Blanchard, an American inventor, created a machine for copying gun barrels. The lathe that he built basically copied an existing shape by following its contours with a roller and cutting a duplicate of the part using that movement. This obviously had no numerical control – the original shape had to be made by hand, and there was no possibility to truly program the machine.

Figure 2. *A Blanchard lathe, with gun stock on the machine (https://commons.wikimedia.org/wiki/File:Harpers_Ferry_gun_smith_shop_-_Blanchard_lathe_-_01.jpg)*

By using cams (a mechanical linkage that allows you to translate rotational movement into linear motion or the other way around), systems were built that could be "programmed" in an abstract way. You could not directly encode the information about the part to be made into the system, but manually had to make the part that encoded the information. The Jacquard loom, invented by Joseph Marie Jacquard in 1804, used a series of punched cards that were "read" by the machine and translated into patterns of movement. This kind of information encoded on cards was also used by early computers and things like automata and self-playing pianos.

Before the birth of true numerical control, other systems were built that could copy shapes or that could be first moved by hand, where the moves were “saved” so they could be repeated without human intervention after.

The real start happened in 1942, when Parsons Corporation got the request to manufacture complex parts for helicopter rotor blades that were traditionally made of wood. To build these parts, Sikorsky Aircraft (the client) shared the shape with John Parsons by giving him a design made of 17 points that he had to connect using curves. This was used to make an outline and cut the final parts. But one of the wooden parts failed, and they started to look into other options, like making the parts out of metal. The tools they needed to make to use metal would have to be made out of tool steel, which was complex to shape.

Parsons went to visit Wright Field, an aircraft base, where he met Frank Stulen, who had such good ideas that he ended up working at Parsons Corp. Stulen’s brother, who worked at Curtiss-Wright Propeller Division, gave him the idea of using punched card machines to calculate 200 instead of 17 points along the curves of the desired shape, which could then be used to drill on those locations and create the rough outline that could be shaped into its final form by hand. Basically the idea was to take a line and create points on that line that were spaced using the diameter of the tool to drill, thus creating enough holes to cut out the part wanted.

Once the calculations were done, they took them to the machine shop and manually moved a Swiss jig borer (a tool to drill holes, basically) to each of the positions before drilling down. This was a slow process, but it allowed them to reach high accuracy in the final product.

Having finished the process, Parsons realized the potential if the system they had developed would be further automated. In 1949, the Air Force provided him with funding to further develop his ideas, but they quickly ran into technical difficulties. The system they were using was not able to drive the motors with enough precision to make the wanted cuts. What they needed was a feedback loop from the motors, to make sure they moved the right distance. Since this was beyond the capabilities of Parsons himself, he got in contact with Gordon Brown, who was working on feedback systems at MIT.

The team at MIT that started working on the new system realized that Parson's idea could be further perfected. If the machine would not just drill down at the given points but follow the line between the points, it would produce products that would need less or no finishing after the automated process.

Initially the project at MIT would create a controller that could then be attached to a machine at Parson's workshop, but eventually MIT simply purchased a 28-inch Cincinnati Hydro-Tel vertical-spindle contour milling machine, which they modified significantly. Many original parts of the machine were removed or replaced, and controllers were fabricated for each of the axes. The numerical system that would control the machine was almost the same size as the machine itself, something hard to imagine today looking at a laptop or tablet computer that can control many different machines! The newly created system was able to move three axes with a precision of 0.0005" (0.0127 mm) by programming it using punched tape. The machine was also equipped with a feedback system – motors that would send electrical signals back to the controllers allowing them to assure the distance moved was correct.

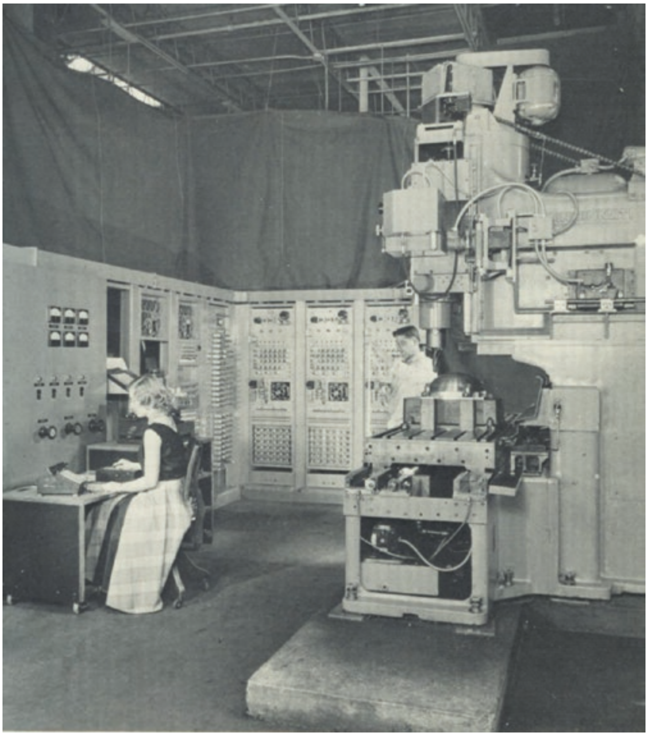
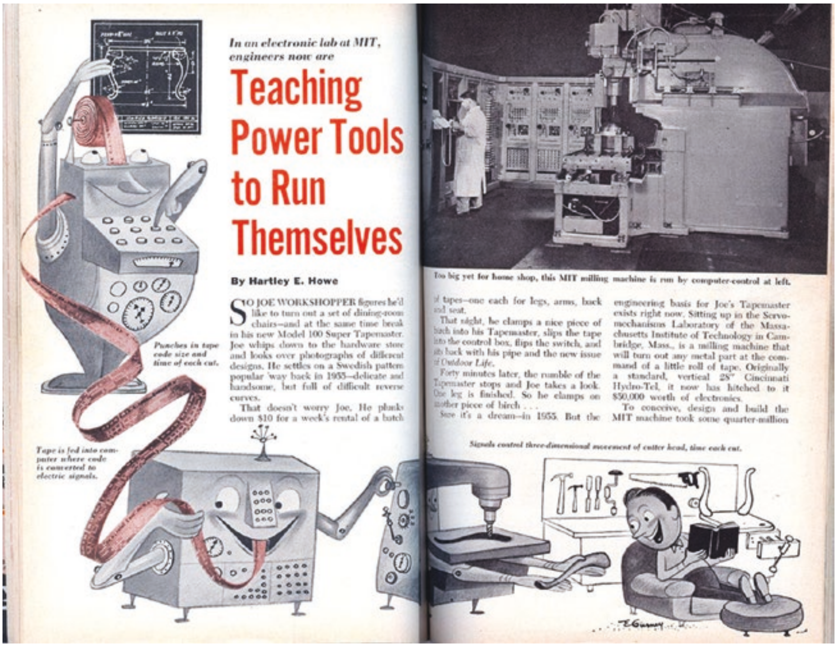


Figure 3. *The first numerically controlled machine at MIT (`www.joostrekveld.net/wp/wp-content/uploads/2016/11/MITnumericcontrol1.jpg`)*



In an electronic lab at MIT, engineers now are

Teaching Power Tools to Run Themselves

By Hartley E. Howe

SO JOE WORKSHOPPER figures he'd like to turn out a set of dining-room chairs—and at the same time break in his new Model 100 Super Tapemaster. Joe whips down to the hardware store and looks over photographs of different designs. He settles on a Swedish pattern popular 'way back in 1955—delicate and handsome, but full of difficult reverse curves.

That doesn't worry Joe. He plunks down $10 for a week's rental of a batch of tapes—one each for legs, arms, back and seat.

That night, he clamps a nice piece of birch into his Tapemaster, slips the tape into the control box, flips the switch, and sits back with his pipe and the new issue of *Outdoor Life*.

Forty minutes later, the rumble of the Tapemaster stops and Joe takes a look. One leg is finished. So he clamps on another piece of birch . . .

Sure it's a dream—in 1955. But the engineering basis for Joe's Tapemaster exists right now. Sitting up in the Servomechanisms Laboratory of the Massachusetts Institute of Technology in Cambridge, Mass., is a milling machine that will turn out any metal part at the command of a little roll of tape. Originally a standard, vertical 28" Cincinnati Hydro-Tel, it now has hitched to it $50,000 worth of electronics.

To conceive, design and build the MIT machine took some quarter-million

Too big yet for home shop, this MIT milling machine is run by computer-control at left.

Punches in tape code size and time of each cut.

Tape is fed into computer where code is converted to electric signals.

Signals control three-dimensional movement of cutter head, time each cut.

***Figure 4.** Article on the first CNC mill, as published in Popular Science, August 1955 (`www.turkcadcam.net/rapor/CADCAM-tarihcesi/MITcnc1.jpg`)*

While the project was a great success looking at the new technological advances that were made, the machine was extremely complex and expensive to build.

While various efforts were made to develop similar but cheaper systems, the idea of automating fabrication did not immediately take off, probably also because of the fact that the time needed to produce parts was not significantly reduced, but simply shifted to a different task, that of translating the designs to punched cards for the controllers.

The step toward CNC (instead of just NC) was taken when MIT researchers created a program that would create the punched cards automatically instead of making them by hand. This led to the creation of teams working on a standardized language to program machines and several groups joining together to combine this into the world's first computer-controlled NC system.

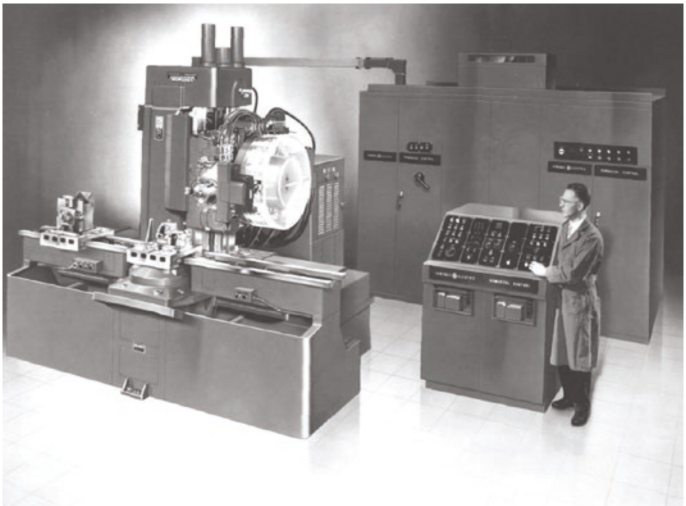


Figure 5. *The first CNC mill, with the computer/controller on the right (`www.cncmanufacturing.com.au/wp-content/uploads/2016/06/The-CNC-Story.jpg`)*

From 1959 on, parallel to the advancement of machines, different organizations were working on CAD, and it was the combination of that with CNC and the drastic decrease in the cost of computers that led to the systems we have today.

In 1968, John Parsons got recognition for the work he had done and the revolution he started when he was given the Numerical Control Society's inaugural Joseph Marie Jacquard Memorial Award. Next to that, the Society of Manufacturing Engineers named Parsons "The Father of the Second Industrial Revolution" in 1975.

Today, you can go out and buy a machine yourself that is better than some of the first machines, or you could even choose to build it yourself! While the initial CNC machines were mills and drills, today you can buy or build laser cutters, vinyl cutters, 3D printers, and more, which are all controlled from your laptop or even your phone.

If you want to know more about how CNC mills further developed over the years, just go to the beginning of Chapter 4.

Overview of Capabilities

If you learn how to use all the machines described in this book, you'll be able to make (almost) anything, provided you also know how to design parts and electronics. Some materials are harder to work with than others, and machines that are able to work with materials such as metal or glass are less often found in makerspaces, but are still within reach. Similarly, learning how to weld or blow glass can often be done with professionals in dedicated spaces and is a rewarding hobby to take up, even if you don't yet know what to make!

This general overview will give you an idea of the capabilities of the different tools, but is absolutely not exhaustive.

Machines	Capabilities	Materials	Additional Needs
Laser cutter	2D	**Cutting:** Wood and derivatives, (some) plastics, cardboard, paper **Engraving:** Same as the preceding ones + glass, ceramics, stone, some metals (depending on the laser)	Compressed air, filter, and/or fan for extraction of fumes
CNC mill	2D and 3D	**Cutting:** Wood and derivatives, plastics, soft metals, composites, printed circuit boards (PCBs) **Engraving:** Glass, ceramics, stone, PCBs	Dust collection
Vinyl cutter	2D	**Cutting:** Vinyl, paper, copper tape	None
3D printer	3D	**Printing:** Nylon, PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), resin, gypsum, gold, silver, stainless steel, titanium, paper	Proper ventilation and in some cases additional systems

Now that you know how we arrived at the point in time where almost anyone can use these tools and machines (so that includes you), it's time to look at the machines that you will be able to find close to you and what you can do with them.

One of the best ways to really understand and learn how to make the things in your head is to try and experiment, check the results, and go try again adjusting parameters. While you are reading this book, try and locate a makerspace, tech shop, or Fab Lab close to you, and find out how you can use their machines. You can start with cheap materials, and if you don't yet know what to make yourself, you can duplicate some projects of others, which is a great way to understand the machines and techniques better.

Are you ready? Let's start by diving into CAD and then look at a machine that is both easy to use and gives you many different possibilities – the laser cutter.

CHAPTER 1

Computer-Aided Design

Introduction

Before you can make anything with a computer-controlled machine, you'll have to "tell" the machine what you'd like to fabricate. Any object you like to fabricate needs a 2D and/or 3D design file to start from, which you can either make by yourself or grab online. Before being usable by machines, data in the file is converted to a toolpath, telling the machine what to do to fabricate the desired object. It's like converting bits (of the model file) to atoms (of the fabricated object).

There are a myriad of ways you can go about this, and if you are a beginner at this point, we recommend trying different programs until you find the ones that fit your way of thinking and your needs. There usually isn't a single solution to make everything, but rather different ways or combinations, depending on the object you'd like to make. Before starting to use any of the machines in this book, a good grasp of CAD programs will prepare you to design parts for them.

You could also start designing something without a computer at all and then digitize the drawing or image and use it with a machine. We sometimes do this in workshops with kids (especially if they are numerous) where everyone makes a drawing with a pencil, which we then scan (with

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a flatbed scanner) and engrave onto a material with a laser cutter. This way everyone gets a laser cut object they designed to take home, without the need to know how to use a computer!

In general you can design in 2D or 3D using GUIs (graphical user interfaces) where you use the mouse or a stylus to design by dragging around objects and parts, or you can use code, describing the object as formulas and mathematical equations. Modern CAD software often offers functions beyond the creation of shapes, like simulation, rendering, animations, virtual reality, and more.

The programs that we will discuss in this chapter all belong to what is known as CAD – computer-aided design. This works together with CAM (computer-aided manufacturing) to create parts. You'll learn more about CAM in each chapter, as toolpathing is specific for each machine.

Because there are so many different software solutions out there, we cannot discuss all of them in this chapter. At the end of this book, you will find a list of software available at the time this book was written, both open source and commercial, so that you can try and find one that is a perfect fit for your needs.

History

All CAD programs are based on Euclidean geometry, so in a way we could say computer-aided design could not exist if it weren't for Euclid of Alexandria who laid down the ground rules in 350 BC. But let's look at the more recent history.

In 1957, Dr. Patrick J. Hanratty created PRONTO (Program for Numerical Tooling Operations), which was CAM software. It was built to control machines, rather than design parts. Even so, he is mostly referred to as the "father of CAD/CAM."

It was in the early 1960s that the first program was developed that allowed a user to design lines on a computer. Ivan Sutherland developed his program "Sketchpad" as part of his study at MIT, which made use of