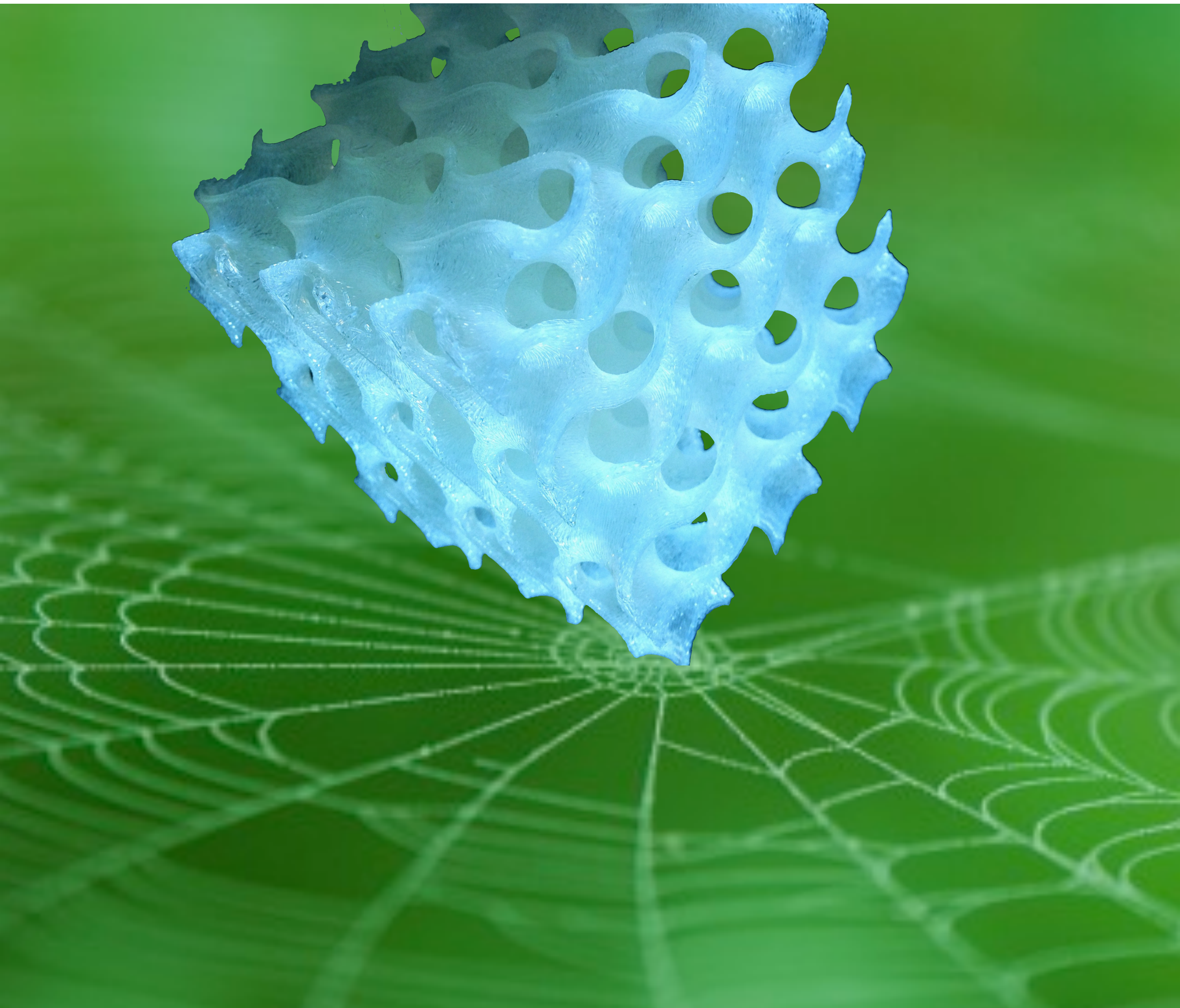
LOW-COST 3D PRINTING

FOR SCIENCE, EDUCATION & SUSTAINABLE DEVELOPMENT



Editors: E. Canessa ✦ C. Fonda ✦ M. Zennaro

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For more information visit us at http://sdu.ictp.it/3D/

Editors: Enrique Canessa, Carlo Fonda and Marco Zennaro

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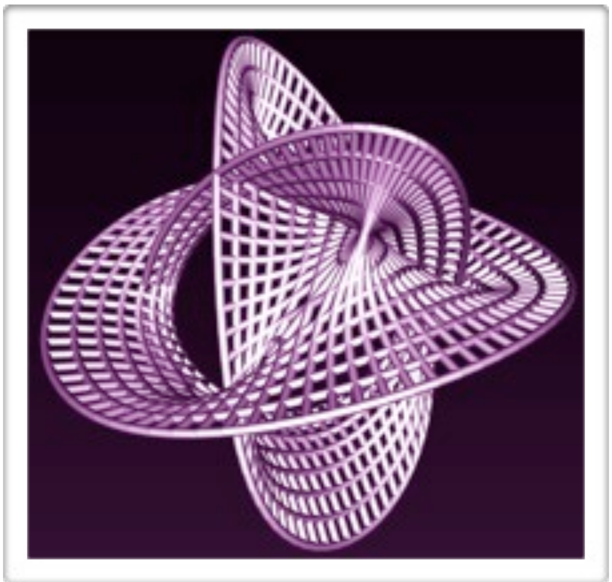

Contents

Low-cost 3D Printing for Science

Low-cost 3D Printing for Education

Low-cost 3D Printing for Sustainable Development

About this Book

Credits

This book was prepared for the First International Workshop on **"Low-cost 3D Printing for Science, Education & Sustainable Development"** held in Trieste, Italy in 2013, organized by the ICTP Science Dissemination Unit (SDU). The purpose of this activity was to discuss and create awareness on the new 3D printing through demonstrations on a number of available competing technologies, as well as presentations of ongoing research into new applications. Special focus was given to the applicability of 3D printing to promote appropriate technologies for sustainable development, scientific research and education.

Editors

Enrique Canessa is a PhD Physicist working as Coordinator of ICTP-SDU. His main areas of research are in the fields of condensed matter and scientific software applications, with particular focus on disseminating science to, and within, developing countries using open source, rich-media, mobile technologies and also 3D printing.

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Marco Zennaro received his Engineering degree in Electronics from the University of Trieste, Italy and his PhD from KTH-Royal Institute of Technology, Stockholm, Sweden. He is currently working at ICTP in projects involving wireless sensor networks, multimedia, open access and Arduino-based technologies. His research interests are also on information and communication Technologies for development (ICT4D).

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ICTP The Abdus Salam International Centre for Theoretical Physics

UNESCO United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

ICTP Science Dissemination Unit

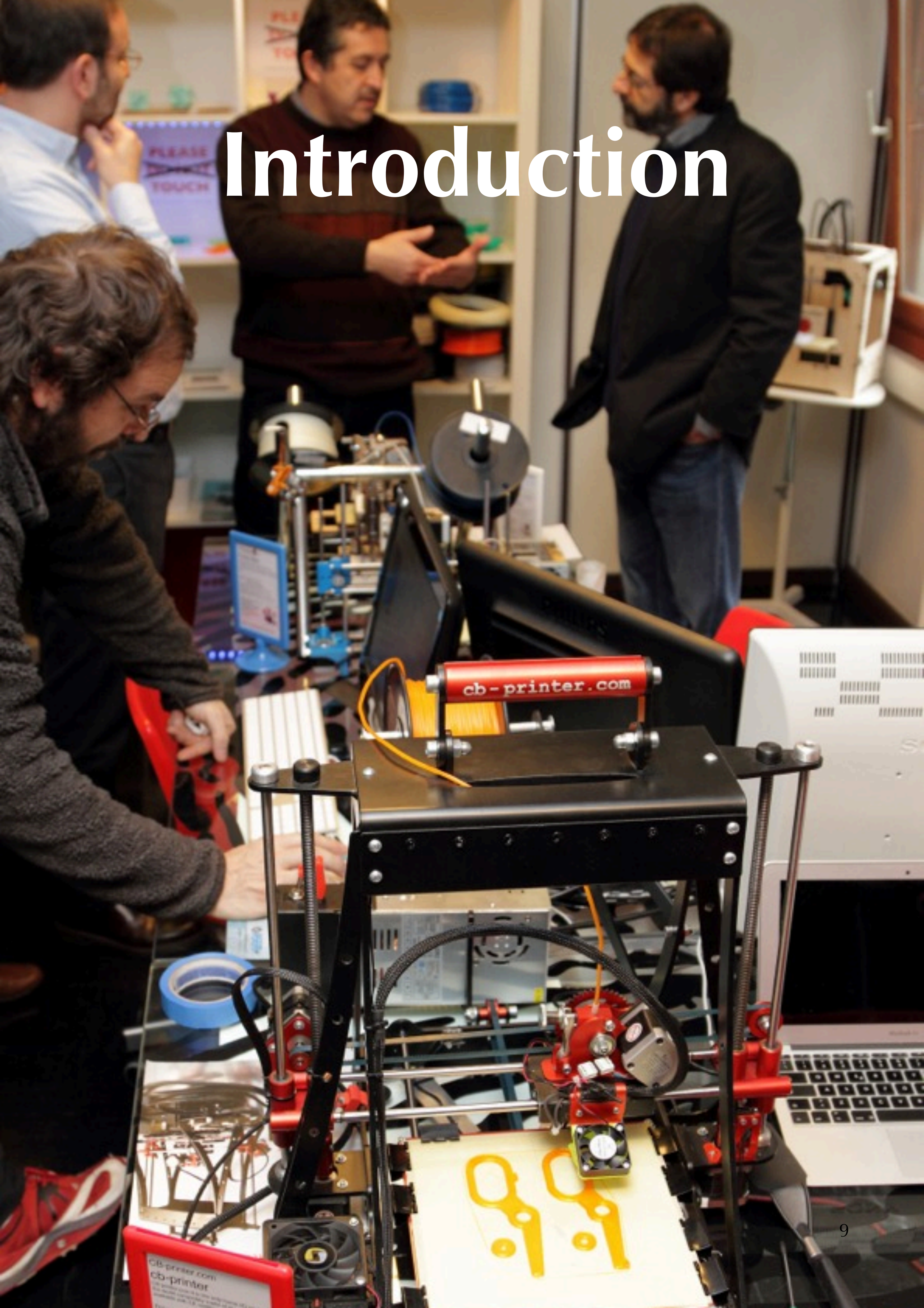
Preface

We hope this book will give you a reasonable, first overview of current research on the 3D printing of objects and how it can be used to teach science beyond a traditional context (*i.e.*, beyond pictorial representations along planar blackboards, visualizations in paper or even within modern digital presentations). We aim to inspire curiosity and deeper understanding in young scholars and new generations of scientists to motivate them to start building up their own 3D printing experiences and to explore the huge potential this affordable technology provides. We invite you all to create prototypes and refine 3D physical products and to share them. This could surely add a welcome boost in motivating you to see the connection between abstract physics and mathematics and real world applications. This book also aims to enhance hands-on learning and interactive class activities, with the final goal of *putting learning literally in your hands*.

Trieste, 29 April 2013.

E. Canessa, C. Fonda and M. Zennaro
Editors

Introduction



Low-cost 3D Printing for Science, Education and Sustainable Development

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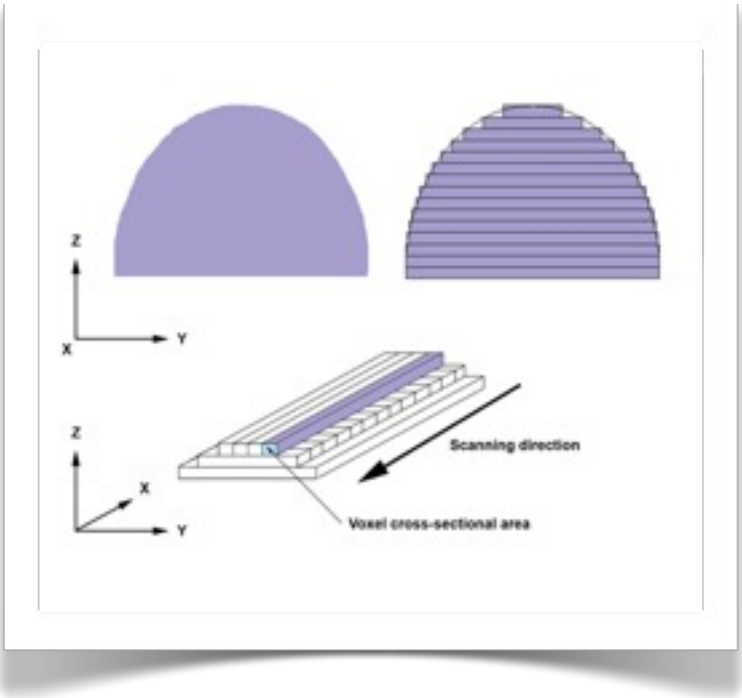
Low-cost, three-dimensional (3D) desktop printing, although still in its infancy, is rapidly maturing, with seemingly unlimited potential. With its capability to reproduce 3D objects – from archaeological artifacts, complex mathematical surfaces, up to medical prostheses– the technology holds a particularly promising future for science, education and sustainable development.

The 3D printing industry started in the late 1980s (with some initial experiments in the 1970s), but these expensive machines limited the use to professionals. The current expansion of new 3D technologies has benefited from the expired 3D printing patents for FDM (Fused Deposition Modeling), where objects are built up layer by layer with extruded melted plastic (as sketched in the figure on the right). New 3D printing technologies also benefit from the open-source movement (for both software and so-called Arduino hardware), and from the free sharing of digital files via the Internet.



3D model slicing (from: Wikipedia)

With open-source software one can find designs for volumetric objects as well as the programming instructions necessary to print the objects. 3D printers produce objects using wheels of filaments made of biodegradable plastic PLA (Polylactic acid), an environmentally friendly material derived from corn starch, or ABS (Acrylonitrile butadiene styrene) polymer derived from fossil fuels. The latter is commonly used to produce car bumpers due to its strength and toughness, as well as the well-known Lego bricks. These filaments melt at about 170 to 250 degrees Celsius to create the multiple layers making up printed 3D objects. The result can be an object like the mathematical model for a Klein bottle surface, or an ensemble of chains made of movable parts as shown below. Some of these new 3D printers can print off some of their own components.

Klein bottle immersed in 3D space

The only limitation for this "simple" alternative technology is the reduced dimension available for printing (typically 20x20x20cm) due to the low cost for the equipment. However, a big 3D object could, in principle, be formed by assembling many small plastic parts. Another great benefit is that this entire process produces much less waste than traditional manufacturing, where large amounts of material are trimmed away from the usable part.

Portable 3D printers can customize products and manufacture (on-demand) spare, replacement or personalized parts to be assembled as needed and completed quickly. Complex small 3D objects can take less than one hour to form, and the results obtained are astonishing: strong, difficult to break, very light (weighing only a few grams) and reasonably cheap because the cost of PLA today is about 30 US$/Kg, and 1 Kilogram is enough to create a dozen or more small objects.

Indeed, its many applications and affordability make 3D printing an accessible technology for the masses. The cost of new generation 3D printers that are based on open-source hardware ranges from 300 to 1,500 US$, and they can be purchased through the Internet. Highly scalable, the printers can be used to print objects at home, at small research labs in a university or in a high school to create educational material, without needing to invest a lot of money. 3D printing opens up novel opportunities that have never before been feasible for creative production and prototypes.

Chains in space with no joints

The hope is that this cutting-edge technology will open new dimensions to science education and will make a marked impact in developing countries. Their affordable costs plus the huge open source 3D examples available for free (usually in ".STL" format) already make the newest 3D printers an attractive technology for low income countries.

3D printing Lab @ ICTP

In February 2013, the Abdus Salam International Centre for Theoretical Physics (ICTP), in Trieste, Italy, inaugurated its 3D Printing Lab to promote, assist and train scientists on the use of this new, affordable technology. Underscoring the capability of the printers to produce usable objects, ICTP's Director Fernando Quevedo cut the ribbon tied across the Lab's main entrance with a pair of scissors created by one of the Lab's 3D printers.

Inauguration of ICTP 3D Printing Lab by Director F. Quevedo using 3D printed scissors

ICTP's innovative lab is designed to be a friendly, modern place open to creativity. It is devoted to explain and show what low-cost 3D printers can do for non-experts, in the fields of science, education and sustainable development. Scientists need to be aware of which 3D printers exist and which of these suits their needs.

Printed cookie-cutters for the inauguration

The ICTP 3D Printing Lab aims to play an significative role as a focal point to help scientists and to train target audiences, including students from high schools. Another goal is to inspire creativity, incorporate new ideas into educational and research efforts, and to create new communities around 3D printing.

Assembling a new printer at the ICTP 3D Printing Lab

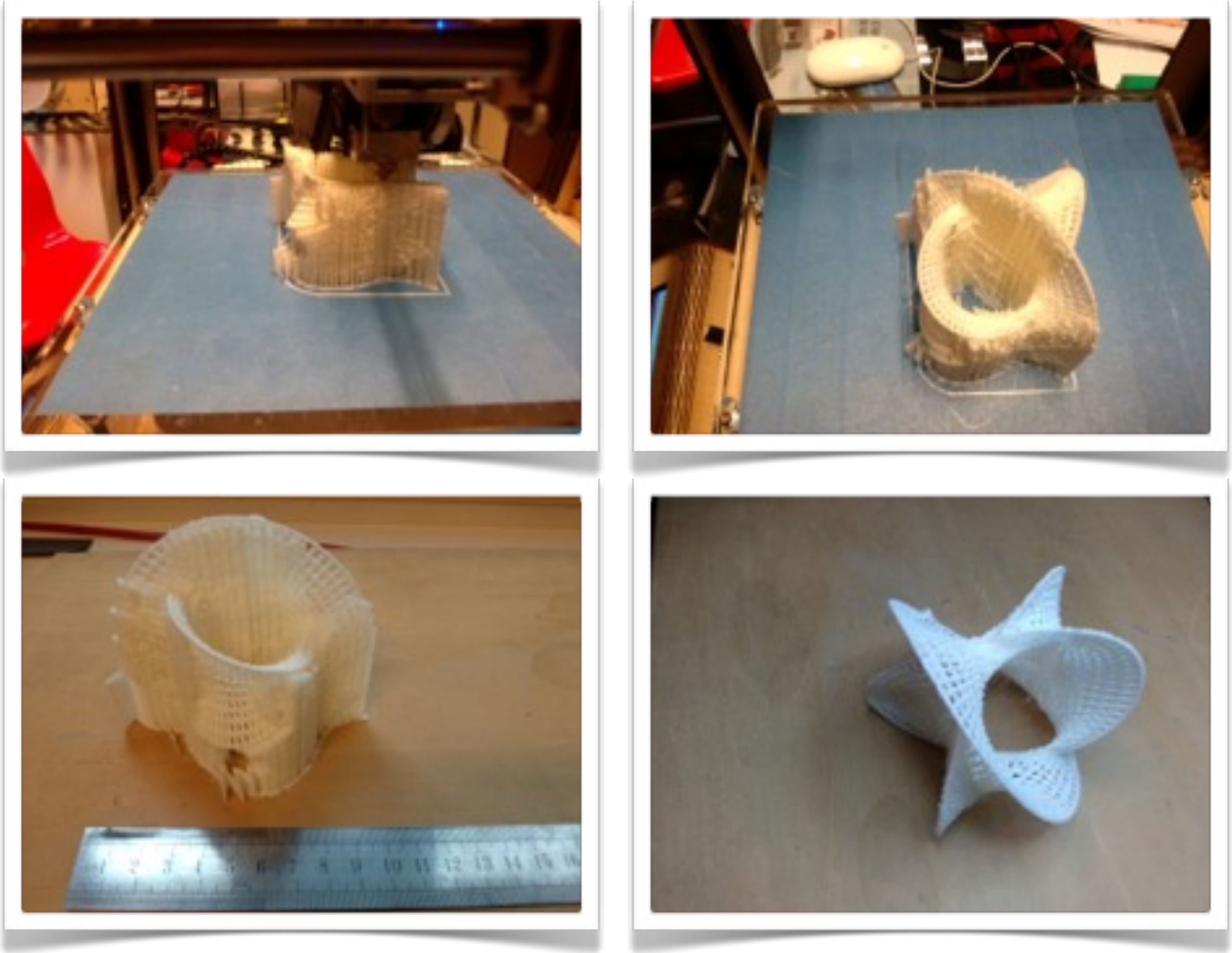
Printing a pair of scissors out of biodegradable plastic

Experimenting with dimensions: a 2D image reconstructed as a 3D object

Imagine and create your own 3D printings

This fast moving 3D printing revolution is growing on a global scale thanks to its many benefits and affordable prices. From education to health, from archeology to engineering, 3D printers are already making many practical impacts around the world. These range from producing prosthetics anywhere and at any time and place (customized legs, arms, hands, *etc*. to teach scholars about the human body), to printing skin cells directly onto a wound, or to printing frames for eye glasses (which break more often than the lenses).

On the education front, scientists can print 3D objects based on geometric formulas to better visualize complex structures. Conceptual knowledge can benefit from 3D printing technology's capability to make malleable objects, shortening the time taken to devise a particular solution and to then evaluate the outcome. With 3D technology, one can learn faster through practice and be more productive through experience.



Calabi-Yau manifold out of the plastic. Printed sequence at the ICTP 3D Lab (STL digital file provided by O. Knill, Harvard Univ.)

3D printing is revolutionizing archeology by providing the capability to copy, on demand, bones of early creatures and fossils. Other objects of great historical value, such as cuneiform tablets and coins, can be replicated. This gives a whole new meaning to fast and accurate (re-)production, triggering the sharing of open archaeological 3D applications globally to museums, *etc*.

The trend is also to have, in the not-to-distant future, bigger printers that could produce anything from water pumps to houses in the context of sustainable development. The cost of shipping to some developing countries is often prohibitively expensive; however by simply sending or downloading small packets of data with the necessary software code (like e-mail, audio, image or video files), useful 3D objects for the developing world, such as replacement parts on sewing machines for the production of clothing, can now be printed at the remote point of need at affordable costs.

Developing countries' scientists could easily adapt this new, affordable 3D technology in their home countries. 3D printing is worth pursuing. It offers the beauty to transform users from consumers to active creators.

3D printed replica of a fossil skull

3D Printing: Glossary

Source:

http://www.reprap.org/wiki/Glossary

http://wiki.solidoodle.com/glossary

ABS

Acrylonitrile butadiene styrene. A thermoplastic used as a 3D printer material. Often ABS is used as a short form, actually referring to filament made of ABS.

Bed

The build plate of the 3D printer on which parts are actually made.

CAD

Computer-Aided Design: software for 2D and 3D modeling.

Carriage

The moving middle assembly on the x-axis of Mendel which holds the extruder. Often referred to as: x-carriage.

Extrude

The act of placing the build material on the build platform, normally by heating thermoplastic to a liquid state and pushing it through a small nozzle.

Extruder

A group of parts which handles feeding and extruding of the build material. Consists of two assemblies: a cold end to pull and feed the thermoplastic from the spool, and a hot end that melts and extrudes the thermoplastic.

FDM

Fused deposition method; same as FFF.

FFF

Fused filament fabrication. Where a droplet of one material (plastic, wax, metal, *etc.*) is deposited on top of or alongside the same material making a joint (by heat or adhesion).

Filament

Two uses: Plastic material made into (often 3mm) string to be used as raw material in 3D printers. Extruded plastic (often < 1 mm)

G-code

The information sent over the wire from a PC to most computer numerical control (CNC) machines –including most 3D printers– is in G-code. While in principle a human could directly type G-code commands to a 3D printer, most people prefer to use one of the many CAM Toolchains that reads a STL file and sends lines of G-code over the wire to the machine. Some researchers are developing alternatives to G-code.

Heated Bed

A build surface that is warmed in order to keep the base of an extruded part from cooling (and shrinking) too quickly. Such shrinking leads to warping internal stresses in printed parts. The most common result is corners of parts lifting off the build surface. Heated beds usually yield higher quality finished builds.

Hot End

The parts of the extruder that get hot enough to melt plastic, or potentially other materials. Hot end parts use materials that can stand up to ~240 C heat (for current thermoplastic extrusion). The hot end usually refers to the tip of the extruder as it should be hottest there.

Infill

This is the inside of the printed part. Infill can be made is various patterns, and generally saves you money on filament vs. a solid part.

Infill Ratio

The ratio of solid material to infill. This will decide how "solid" your part is.

Kapton tape

Heat-resistant polyamide adhesive tape. Used to secure the heating element to the extruder barrel. It can also be used on the surface of a heated bed.

.OBJ

A geometry definition simple data-format that represents 3D geometry alone.

Parametric

(Adjective) Adjustable in all dimensions. A parametric model is one that can be resized and or distorted to suit the user's needs. In CAD software, If a widget has a 1 cm hole in it, you can select that hole and make it a 5 mm hole with a few clicks, as opposed to a triangular mesh (see entry on .STL), which is more difficult to adjust. The native format of several useful software packages can store parametric models.

PLA

Polylactic acid. A biodegradable thermoplastic polymer used as a 3D printer material. Often PLA is used as a short form, actually referring to filament made of PLA.

Raft

A technique used to prevent warping. Parts are built on top of a 'raft' of disposable material instead of directly on the build surface. The raft is larger than the part and so has more adhesion. Rarely used with heated build surfaces.

RP

Rapid prototyping. Creating an object in a matter of hours on a "3D printer" as opposed to sending out a job to a modeling shop that can take days or weeks.

RepRap

A RepRap machine is a rapid prototyping machine that can manufacture a significant fraction of its own parts. The RepRap project is a quest to make a desktop-sized RepRap machine.

Slicing

The process that converts 3D models into a format understood by 3D printers. The model is "sliced" into layers which can be placed by the extruder.

SLS (Selective Laser Sintering)

Additive manufacturing process, which fuses photosensitive powder materials by a laser to form a solid object. It offers a wide range of print materials.

Stepper Motor

Motors which operate only in discrete increments of rotation. This is the type of motor most commonly used in low-cost 3D printers.

.STL (Stereo Lithographic)

A recommended file format used to describe 3D objects. A design (CAD) program can produce an STL file which can then be fed to a 3D printer or 3D rendering graphics package.

Low-cost 3D Printing

A Practical Guide to Your First 3D Print

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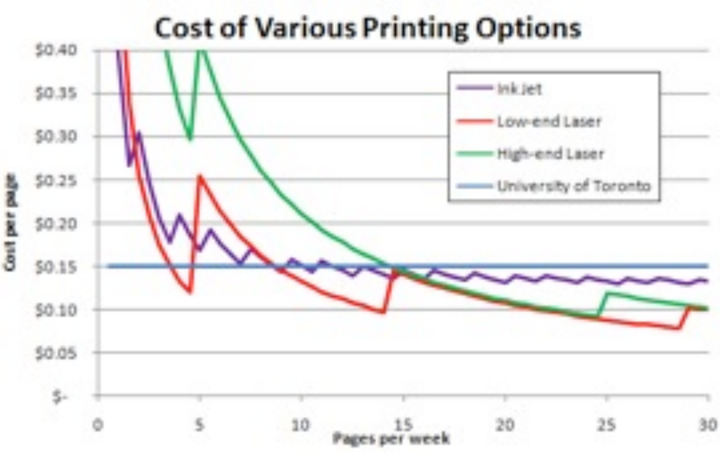
What is low-cost 3D printing?

A brief story: the Laser Printer

This story isn't about 3D printers, it's about a device that can print texts and images on a sheet of paper and has become an unexpensive widespread office and home appliance that people are using everyday, sometimes without even realizing how important it is: the laser printer.

The laser printer was invented[1] at **Xerox** in 1969 by researcher Gary Starkweather (picture on the right), who had an improved printer working by 1971 and incorporated into a fully functional networked printer system by about a year later.

The first laser printer designed for use in an office setting was released with the Xerox Star 8010 in 1981. Although it was innovative, the Star was an expensive ($17,000) system that was purchased by only a relatively small number of businesses and institutions.



Today, after some 30 years, the cost of printing has became two orders of magnitude lower: an small SOHO ("small-office, home-office") inkjet color printer is sold for less than $50, while an entry-level black-and-white laser printer averages at $100 or less. Laser printers (including color ones) are therefore now quite popular at home, making everyone benefit of their excellent performances, speed and printing quality.

Some people think that 3D printers are following the same path, at a much faster pace.

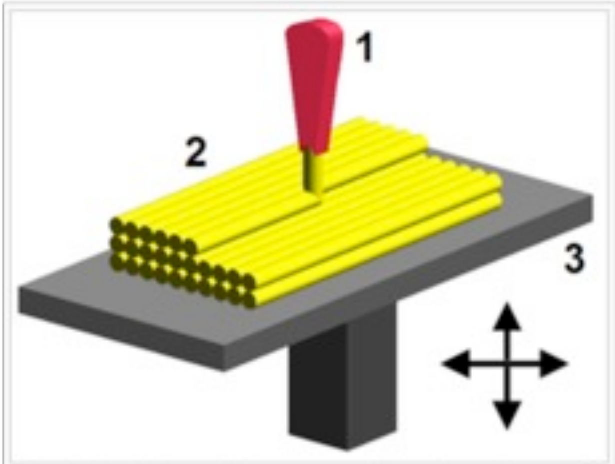
3D printing technologies and professional 3D printers

3D printing[2] (also called additive manufacturing) is a **process of making a three-dimensional solid object of virtually any shape from a digital computer model**. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes. This makes it quite different from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting or drilling (subtractive processes). Objects that are manufactured additively can be used anywhere throughout the product life cycle, from pre-production (*i.e.*, rapid prototyping) to full-scale production (*i.e.*, rapid manufacturing), in addition to tooling applications and post-production customization. Today this technology is extensively used in jewelry, footwear, industrial design, architecture, engineering and construction, automotive, aerospace, dental and medical industries, education, geographic information systems, civil engineering, and for many other professional applications, while new fields are added to this list every year.

Several different 3D printing processes have been invented since the late 1970s, but the printers were originally large, expensive, and highly limited in what they could produce. The most common technology for 3D printing, called fused deposition modeling (FDM), was developed and patented by S. Scott Crump (picture on the right) in 1989 and was commercialized in 1990 by the company he co-founded: **Stratasys**[3] (http://www.stratasys.com). It was merged in 2012 with an other market leader, **Objet**, to become today's largest manufacturer of 3D printers and 3D printing materials.

Fused Deposition Modeling

Although many technologies are possible for 3D printing, the most common one, called fused deposition modeling[4] (**FDM**), is very simple: it creates complex objects from molten plastic extruded through a nozzle. The plastic filament (or even a metal wire) is wound on a coil and unreeled to supply material to the extrusion nozzle, while the nozzle or the object (or both) are moved along three axes by a computer-controlled mechanism, and the material hardens immediately after extrusion. Stepper motors or servo motors are typically employed for all these movements, as well as for pushing the filament into the extruder.



Fused deposition modeling: 1 - nozzle ejecting molten plastic, 2 - deposited material (modeled part), 3 - controlled movable table

Another 3D printing approach is the selective fusing of materials in a granular bed, known as selective laser sintering[5]. The technique fuses parts of the layer, and then moves the working area downwards, adding another layer of granules and repeating the process until the piece has built up. This process uses the unfused media to support overhangs and thin walls in the part being produced, which reduces the need for temporary auxiliary supports for the piece. A laser is typically used to sinter the media into a solid.

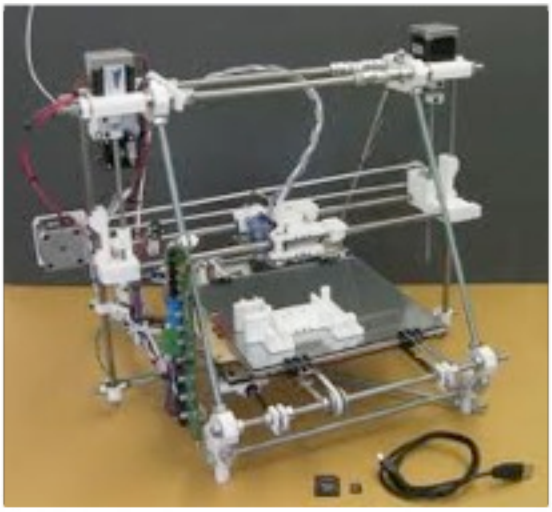
One more method is inkjet-like 3D printing[6]. The printer creates the model one layer at a time by spreading a layer of powder (plaster, or resins) and printing a binder in the cross-section of the part using an inkjet-like process. This is repeated until every layer has been printed. This technology allows the printing of full color prototypes, overhangs, and elastomer parts. It was first developed at **MIT** and is exclusively licensed to **Z Corporation**.

Some professional 3D printers can print metal, ceramics, and a variety of other materials and colors, producing rather big objects (with dimensions up to a few meters) with incredibly high resolution, mainly for industrial and professional use. Of course these are quite expensive and mostly out-of-reach of common people.

A revolution: the Personal 3D Printer

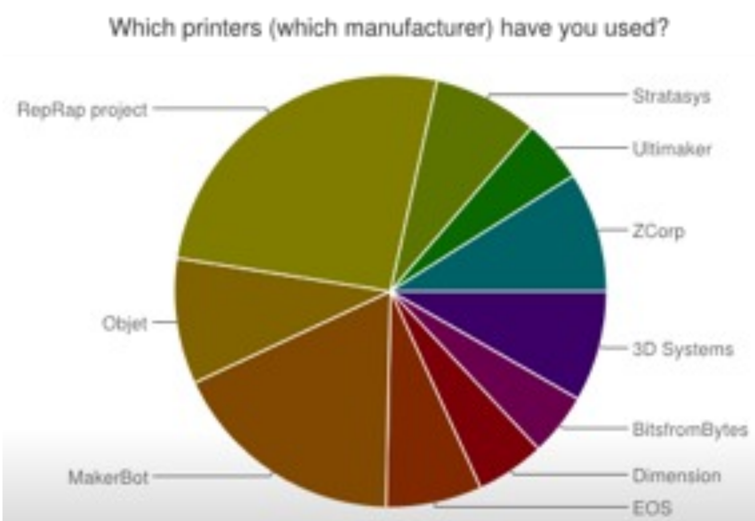
The idea that it is possible to move from professional 3D printer to something new, smaller and more affordable, was first expressed[7] in 2004 in a paper by Adrian Bowyer[8] (picture on the right), at that time an academic at Bath University in the UK. There he envisioned the concept of **self-replicating** machines, able to print (some of) their own parts by themselves, and so simple and easy that anyone would be able to build them. Starting from this simple idea, and with the help of a big virtual community gathered on the Internet, a movement of enthusiastic "makers" was born: the **RepRap**[9] **project**.

These firsts steps towards the practical creation of an inexpensive "personal" 3D printer have been possible inside the so-called **maker culture**[10], which is the modern incarnation of that community of hackers that created the first personal computers in their parent's garages. In fact, this culture represents a technology-based extension of the do-it-yourself (DIY) spirit, with typical interests such as electronics, robotics, 3D printing, and the use of CNC tools, as well as more traditional activities such as metalworking, woodworking, and traditional arts and crafts. Its philosophy promotes new and unique applications of technologies, and encourages invention and prototyping.



Permeated with this culture, the RepRap project aimed to produce a **free and open source 3D printer**, whose full specifications were to be released under an open license (they have chosen the GNU General Public License), and which had to be capable of replicating itself (at least partially) by printing many of its own plastic parts, to create more machines.

Because of the open source aims of RepRap, many related projects have used their design for inspiration, creating an ecosystem of related or derivative 3D printers, most of which are also open source designs. The availability of these designs means that variants of 3D printers have been and are easy to invent. The quality and complexity of printer designs, however, as well as the quality of kit or finished products, varies greatly from project to project. Since around 2008, there have been several projects and companies making efforts to develop affordable 3D printers for home desktop use. Much of this work has been driven by and targeted at DIY/enthusiast/early adopter communities, with additional ties to the academic and hacker communities.



Moilanen, J. & Vadén, T.: Manufacturing in motion: first survey on the 3D printing community, Statistical Studies of Peer Production. http://surveys.peerproduction.net/2012/05/manufacturing-in-motion/

The cost of 3D printers has therefore decreased dramatically[11] between about 2010 and 2012, with many machines now costing less than $1,000 (and some of them even less than $500).

A big change in the public perception of low-cost 3D printing has happened at the same, triggered mainly by a heavy media coverage: a good example is the cover of the October 2012 issue of Wired Magazine[12], that titled *"This machine will change the world"* with a picture of Bre Pettis, Makerbot CEO and co-founder, holding a *Replicator 2*.

In February 2013, President Obama cited this technology during his State of the Union address[13] —as if everyone already knew what the technology was. He expressed hope that it was a way to rejuvenate American manufacturing. "A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything," Mr. Obama said. We should note that he mentioned 3D printing *tout-court*, not specifically its low-cost implementation.

Pro* vs *Personal

At this point we should analyze a few practical differences between a professional 3D printer and one of its low-cost cousins:

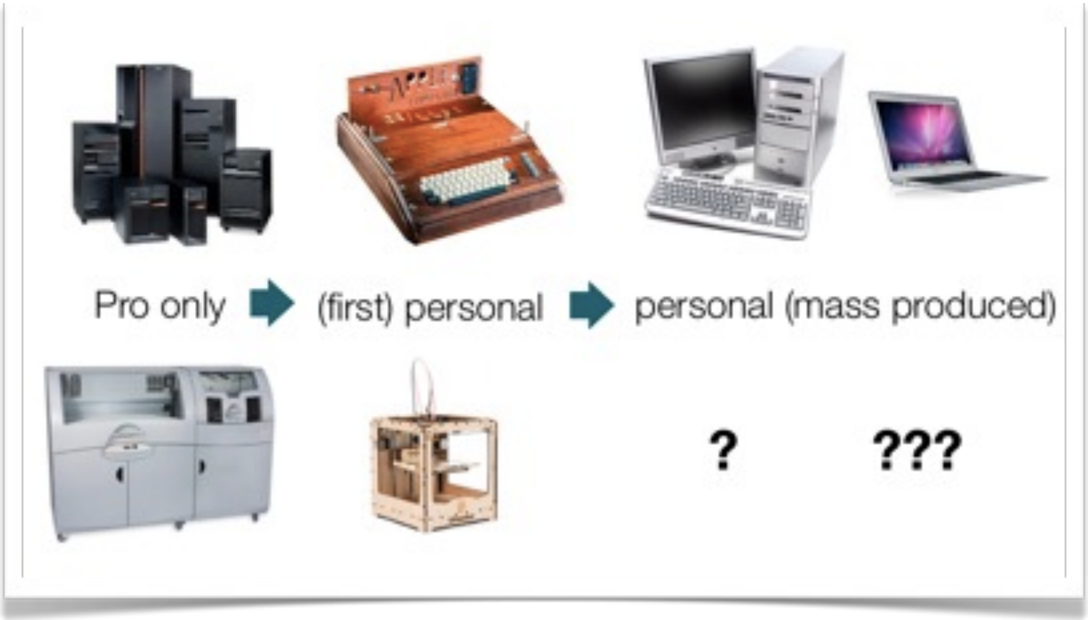
- while the former can be fed only with one (or more) of the specially-made (and expensive) plastic powders allowed by the manufacturer, the latter can use cheap plastic filament (ABS, PLA, *etc.)* from any vendor (with a diameter of 1.75mm or 3mm, depending on the printing head type);
- a professional machine has a solid enclosure usually metallic (or sometimes plastic), while the frame of a low-cost 3D printer is often made out of laser-cut plywood, or printed plastic parts, more rarely of aluminum or steel;
- the software needed to operate a professional unit is proprietary (closed source) and the manufacturers may organize specialized training for the operators, while the software used to operate the low-cost 3D printers is mostly free and open source (not necessarily always features-rich, but often very customizable and subject to a rapid evolution);
- professional machines are controlled by industrial-type proprietary computers and operating systems, their low-cost counterparts make an extensive use of open hardware like Arduino, Pololu, Sanguinololu, *etc.* (*i.e.,* small and very inexpensive computer boards, that are powered by open source OSs).

More differences can be added to this list, all leading towards the same direction: professional 3D printers will always guarantee better performances and more features, at the expense of much less freedom to tinker with the hardware and the software and to make experiments, and of course at a much higher price. Low-cost 3D printers, on the contrary, are rarely suitable for professional use, but can become a valuable and powerful *personal* tool.

Maybe, similarly to the Personal Computer, we can start to call this new Personal 3D Printers just P3DP or P3P. And since we are talking about the Personal Computer, considered by many the biggest revolution of 20^{th} century, it may be interesting to review how it all started…

The story of the Personal Computer (is it repeating all again?)

The story of the Personal 3D Printer appears to be quite similar to the old story of the Personal Computer (PC). Both were only available at the beginning as very costly, "professional-only" and cumbersome to use models (often requiring specialized technicians to be operated) and become really affordable and easy-to-use only after some decades of time. When the PC became really "personal" and ubiquitous (because mass-produced at an increasingly low cost), we got cheap desktop computers for all, and after some years the industry created incredibly slim and powerful laptops, and then quite recently we got smartphones (PC-in-a-pocket) and "magic" tablets. This exciting growth was only possible because of the PC revolution, and the many small and big inventions that permeate and shape the world in which we all live are its children.



We cannot anymore imagine to live without all the modern information and telecommunications (IT) technologies we are used to, and most (if not all) of them were made possible by the personal (*i.e.*, low-cost) computer.

Will 3D printers follow the same path and become soon a *common home appliance*, to be found in all houses and offices next to our PCs? Will the low-cost 3D printing industry, now just in the cradle, then pave the way for a new revolution, making possible unimaginable many new inventions that will change our lives again?

Perhaps a rather exciting time is in front of us and we all need to better understand it, and get ready for it. So let start to learn the basics of low-cost 3D printing.

3D printing step-by-step

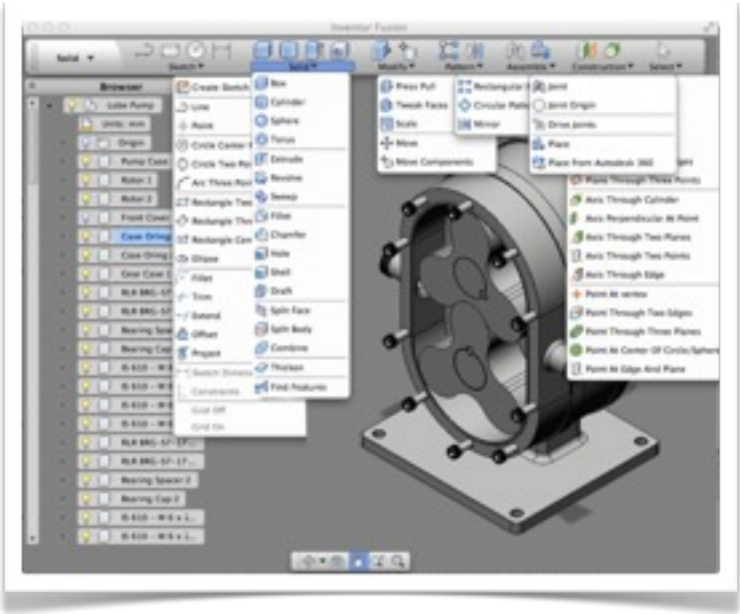
The process that goes from an idea to a colorful plastic object coming out of our 3D printer is a quite long and complex one, and many different parts are involved, that should interact and seamlessly work together:

- The first step is to create a 3D model of our idea, a digital *alter ego* of the object we want to make (**digital modeling**).
- The second step is to generate a file in the proper format (usually "STL") containing all geometrical information needed to represent our digital model (**exporting**).
- If we are lazy, there is a shortcut for the two previous steps: to simply **download** a digital model from the Internet (*i.e.,* from *Thingiverse*).
- If our model hasn't been design carefully, it may end up having some defects: we should try to correct them with software (**mesh repairing**).
- The third step is then to convert the digital model (technically a three-dimensional representation of a *watertight* surface, subdivided in a triangular mesh) into a list of commands that our 3D printer can understand and execute, usually called *g-code* (**slicing**).
- The fourth step is to give such list of instructions to the printer, either via a USB connection to a PC or by copying the file to a memory card that can be read directly by the printer itself (**connecting**).
- The fifth step is to prepare the 3D printer and start the printing, and wait for the result (**printing**).
- The sixth step is to remove the newly created object from the printing platform (*"bed"*), to remove extra parts (*i.e., support* and/or *raft*) if present, to clean its surface (**finishing**).

There are a few more points that should be also considered, in order to get successful results: the **choice of the 3D printer**, its proper **calibration and setup**, the type and quality of the **plastic filament**, the type of surface that covers the **printing platform**. All these and the previously mentioned aspects will be analyzed with some details and practical considerations in the following pages.

3D modeling

The first step for printing a real object is to make a *virtual* digital 3D model of it using a software, often called CAD (*Computer-Aided Design*). There are many of such programs for the most common platforms (Windows, Mac OS X, Linux), some are even available for free or as open source. To start using a CAD program is not easy, it may require weeks or months of time (and a lot of patience and practice) to learn the meaning of its many menus and icons, and even simply understanding how a 2D movement of the mouse translates in the 3D environment of the software may be sometimes hard, making thus difficult to manipulate your model or to change point of view, not to mention complex maneuvers like object rotation, intersections, *etc.*



Examples of *free* software for *technical* 3D modeling:

- *SketchUp*[14] (easy to use, with a worldwide community of users and video tutorials, but somehow limited, it's optimized for the creation of simple architectonic models)
- *FreeCAD*[15] (Win/Mac/Linux open source 2D and 3D parametric modeler with a steep learning curve and a good documentation and user community to help)
- *Blender*[16] (Win/Mac/Linux powerful open source software optimized for complex animations and renderings of 3D objects and figures, unintuitive and hard to master)
- ~~*Autodesk™ Inventor Fusion*~~[17] (Win/Mac professional CAD application but free for non-commercial use, dismissed and replaced by a newer *cloud-based* version: Fusion 360)
- *OpenSCAD*[18] (not an application but a programming language for the algorithmic generation of 3D models, very powerful and versatile, quite difficult but worth trying).

Examples of *free* software for *artistic* 3D modeling:

- *Sculptris*[19] (Win, Mac virtual sculpting application, replicates the act of modeling clay)
- *Autodesk 123D Design*[20] (Mac, Win, iPad, webapp, easy interface with many features).

Sometimes, to create a simple 3D model it is easier and quicker to use one of the many specialized websites that provide visual tools for an easy and immediate creation and/or modification of your design (these tools are called webapps).

Examples of webapps for 3D modeling:

- ~~*TinkerCAD*~~[21] (now closed)
- *3Dtin*[22]
- *ShapeSmith*[23]
- *Cubify*[24]
- *Autodesk 123D Design*[20]

As a last note regarding this quick overview of 3D modeling software, it's worth to mention the recent arrival of similar apps for the touch-based tablets like the Apple iPad, like for example the one listed here:

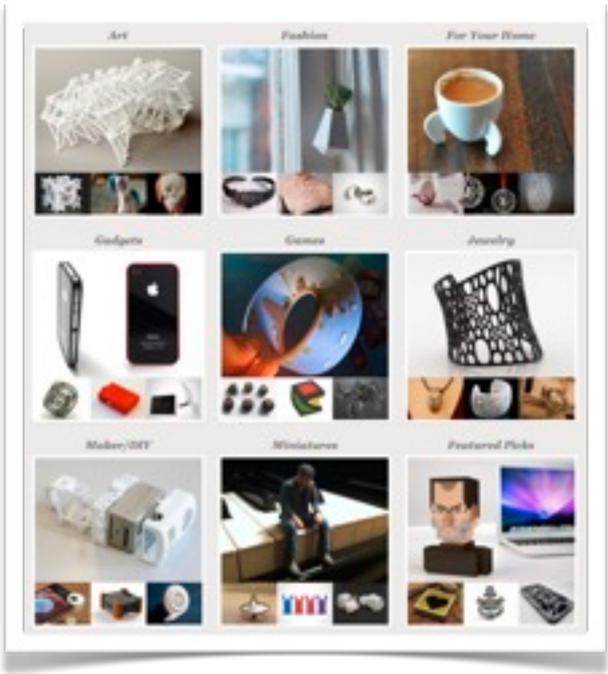
- *netfabb, 3Dskope*, *KiwiViewer*, *vueCAD* and *MeshLab* (viewers for STL files, cannot create or modify models, all are free)
- Autodesk apps of the *123D* family: *123D Sculpt* (for organic "rounded" models, free), *123D Design* (for geometrical "squared" models, free) and *123D Creature* (for creating characters, not free but sold for a minimum price)
- Autodesk 123D Catch (3D scanning with iPad/iPhone camera, free, account required)

Getting 3D models from the web

It may be a good idea, before starting to create our own 3D models making our first steps with a more or less difficult software tool, to have a look at the many thousands models made by others and graciously shared for free on the web. So let's make a quick tour of the most useful web repositories of 3D models that are available:

- *Thingiverse*[25]*:* the repository used by the majority of enthusiasts of low-cost 3D printing to get and share their creations. It offers more than 50'000 3D models generated by users, mostly designed for 3D printing but sometimes also for laser cutting or other more traditional crafting techniques. All of the content is free to download and most of it can be printed quite easily, but it's best to check out if it has been done by other users and with what results (look at the "who has made it" section in the model description).

- Autodesk 123D[26]: a website with a lot of objects you can download for free after signing up. Files are already in STL format.
- 3D CAD bowser[27]: the online 3D models exchange resource for CGI graphic designers and CAD/CAM/CAE engineers. It has many cars, animals, architecture and more. As always, free download in many different formats after signing up. Not all of the models are suitable for low-cost 3D printing.
- GrabCAD[28]: No need to sign in to this huge web repository to download the files, there are many different 3D digital objects –from small nuts and bolts to full race cars with thousands of perfectly designed mechanical parts– but just a small fraction of the models would be actually 3D printable, while most of the others are complex wonderful exercises of 3D photo-realistic rendering.
- Shapeways[29]: Website offering many wonderful designs uploaded by users but almost nothing is free. You can pay to download some of the models or just ask Shapeways to print them out in plastic or metal (from aluminum to brass or steel, also gold or silver-plated) and ship to you, for a reasonable price, with the guarantee of a perfect result.
- 3D warehouse[30]: The repository of SketchUp, with hundreds of models of all kinds of objects, but you should search with care to find printable ones.
- 3D via[31]: A small repository of 3D models you can download for free after signing up.



In most of these websites multiple file formats are offered for download, allowing an easy modification and customization of the models and also a great source of exercises for learning to master the capabilities of modern 3D modeling software. Even in the sites where only STL file are available, it's still possible –natively or using plugins– to import them in a 3D design program after the download, thus gaining the ability to modify them before printing. Models by the most famous "amateur" designers (people like *Dizingof* and *Emmett* on Thingiverse, for example) are downloaded and printed by many, and even used daily as basis and inspiration to create new and better printable models (derivatives), without breaking any copyright or license or moral barrier: a situation that is quite common since a long time for the source code (being at the foundation of the open source philosophy) but that is almost unprecedented in the artistic or technical world, usually much more concerned with the creator's rights to lock down his or her works with all legal and technical means, in the (mostly unsuccessful, anyways) attempt to protect them from being copied or modified by others.

Even if we aren't (yet) capable of modifying the models created by others, the fact that this huge community of creative makers has the possibility of doing so, and the availability of maybe more than a few hundred thousands of 3D models already free to download, gives us both the stimulus and the challenge to improve our own capabilities to create models, in order to avoid to be left behind in what can become *the next kind of digital divide*: the difference between the ones that know how to create all sort of 3D objects they need or like, and the ones that do not. But even if we are the lucky ones, the designers on the "creative" side of the divide, there is an other small step we have to do before becoming actual *makers*: we need to choose our 3D printer (to buy or to build, or most likely to buy & build...), the machine that will transform our beautiful virtual designs into real 3D objects…

Hardware for 3D printing

We could probably spend a hundred pages listing the characteristics and features of the many low-cost 3D printers available for purchasing (either preassembled or as do-it-yourself kits), or the many others that have been developed by enthusiasts of the open hardware movement, which schematics and building instructions have been made available as free downloads from the Internet. In fact this is probably the worst (but at the same time the best) time for getting a 3D printer: too many to choose from, a market that is changing by the day with new models coming and old ones going away, and many big and

rapid improvements in the technology that are bringing to us every month new features, new printable materials, faster and more reliable printers, more accurate results, lower costs, and so on... It's rather hard to follow all these developments, wonder what will happen next, and still be able to decide on a printer to get today.

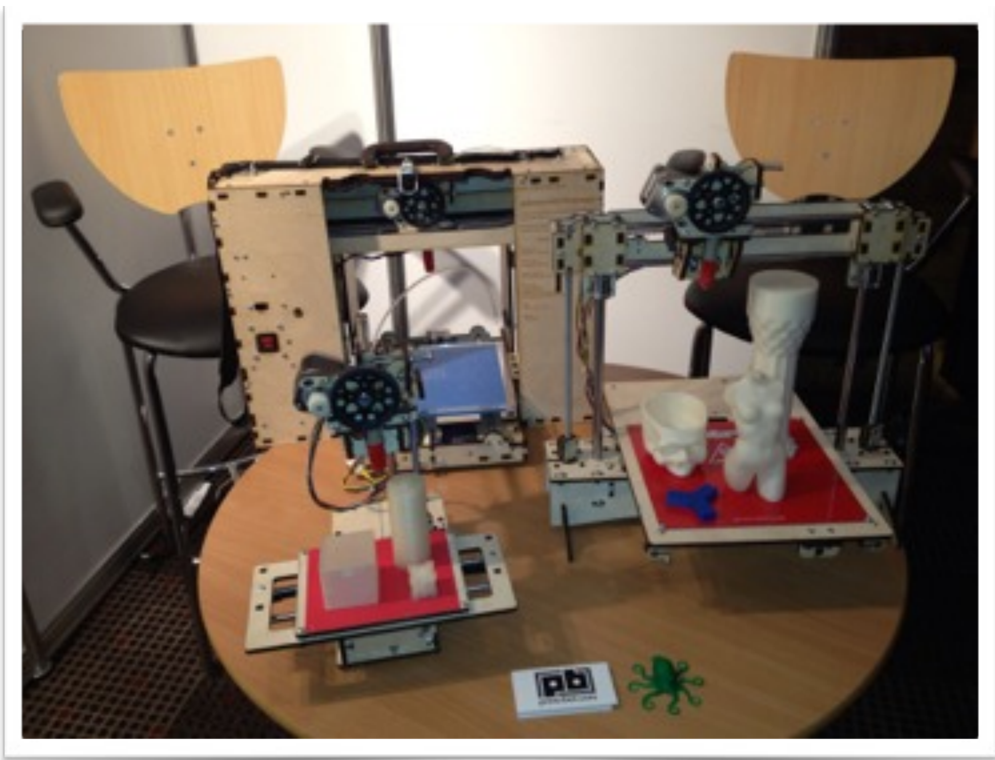
It's clear at this point that any advice or information that we could find and trust today will become obsolete –or simply plain wrong– in a short time, and we shouldn't fall in this temptation and run to get our first 3D printer believing that it will be the best model forever. And most likely is wouldn't even be possible to define which is the best model, since it will depend by our needs, interests and capabilities. Maybe in ten years or so, the things will be much more straightforward and there will be a clear winner in this technology, or maybe not, but currently the only option we have is to follow this rapid development, if not by changing printer every year at least by looking at the news, by tracking how things are changing and –the most important attitude– by experimenting as much as we are allowed to do by our resources (of which, our time is sometimes more valuable than our money, especially when it's scarce).

The ideal choice, when looking for a new printer, is a model that can be updated and upgraded easily, with a large users base experimenting with it, developed by smart people that is always looking for something better, solving issues and exploring new directions. If you ask the name of such printer, different people will give you different answers, simply because there isn't a unique answer: but luckily for us there are very good printers around, interesting models, even great products for you to choose, and they will be different because we are all different. Let see some of the most common low-cost 3D printers that you may want to consider today. We shall categorize them by the philosophy that's at the base of their design, but noting that sometimes there aren't precise boundaries between the three main categories, and the printers are instead distributed with continuity in a spectrum that goes from the extreme of "totally open, full control given to the user, strong experience needed" to the opposite extreme of "totally closed, minimum control left to the user, newbies are welcome" and all the possible intermediate shades.

The author's list of the *best examples to study* (not necessarily the best printers!) is given here –only as a suggestion and starting point– and it's not at all exhaustive:

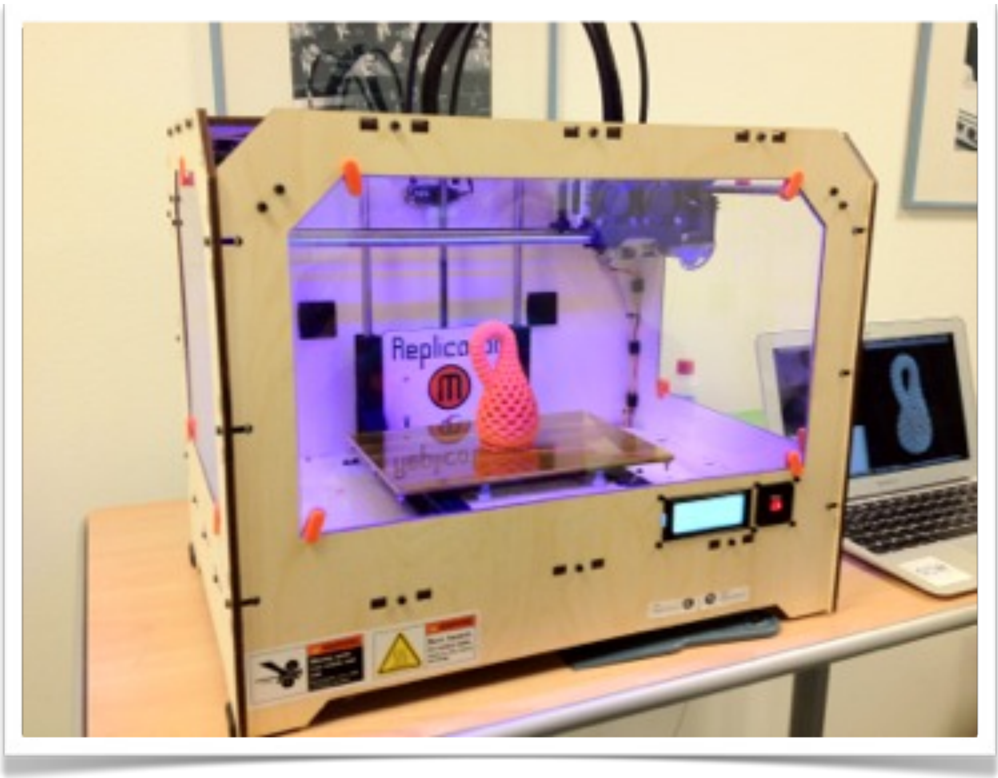
1. **Hacker-style 3D printers**: do-it-yourself, open hardware, fully customizable.

- RepRap[32]: a big family, almost a *tree of evolution* for 3D printers! Many vendors commercialize them with different names and brands, but they all mostly variants of one of the main RepRap designs, that are the:
  - Darwin: the original model, now superseded by the other designs;
  - Mendel / Prusa Mendel / MendelMax: with the characteristic triangular frame;
  - Wallace and Huxley: two models with a smaller printing size and a simpler build;
  - Rostock: *delta-printer* with non-Cartesian design[33] (the printing head is supported and controlled by three arms arranged in a pyramidal configuration and attached to vertical columns, the bed is fixed), it's a very interesting and "unique" model.
- Ultimaker[34] (a very accurate printer, from the Netherlands).
- Printrbot[35] (a set of low-cost printers, including some portable models, from the US).



2. **Hassle-free 3D printers**: a good compromise: fully pre-assembled –still partially customizable– printers with less “openness” but more user-friendliness and predictability.

- Makerbot[36] is a world-famous company that has popularized low-cost 3D printers. The two current available models are the evolution of previous popular printers that were probably the firsts to be marketed to a large number of makers:
  - Replicator (with a *dual head option* that can print in two colors, or with two plastic types, at the same time), with plywood frame and dedicated open source software;
  - Replicator 2 (a newer iteration with a sturdy metal frame, less open –*e.g.,* its drawings aren’t available on line as it was for the Replicator– but even more reliable and easy to use. The software was also upgraded (not open source anymore). There is also a 2X version with dual extruded and heated bed.
- Solidoodle[37], with three generations of affordable 3D printers offering different print size and interesting options like a robust aluminum enclosure and a heated bed.
- Afinia Up![38] its “Plus” and “mini” versions are versatile printers “for the rest of us” that aren’t hard-core hackers but still want some little freedom to experiment.



3. **Plug'n'play 3D printers**: closed "black boxes", very easy to use, but only a few settings are permitted, to get the desired result, similarly to modern laser or inkjet (2D) printers.

- Cube[39], the first and most know *fully plug'n'play* low-cost 3D printer, with some compromises on control and versatility but a hassle-free experience, designed and advertised to be used by non-techies and even children, with its own software (only for Windows), proprietary cartridges of plastic filament and features like *wifi connectivity* and *direct print from USB drive*.

A good comparative analysis of a number of printers of different categories was published in a special issue of **"Make:"** magazine in Winter 2013, fully devoted to 3D printing[40]. It's a very interesting reading (it costs $6,99 for the digital download as ebook or PDF, and $9,99 to get a printed version) also for the other detailed guides on 3D printing for beginners, modeling software, *etc*.

Another comprehensive list of 3D printers ordered by their price (that goes from 400$ to almost 25'000$!) has been compiled by **3ders.org** –a good source of news from the world of 3D printing technologies– and it is freely available on-line at this address:

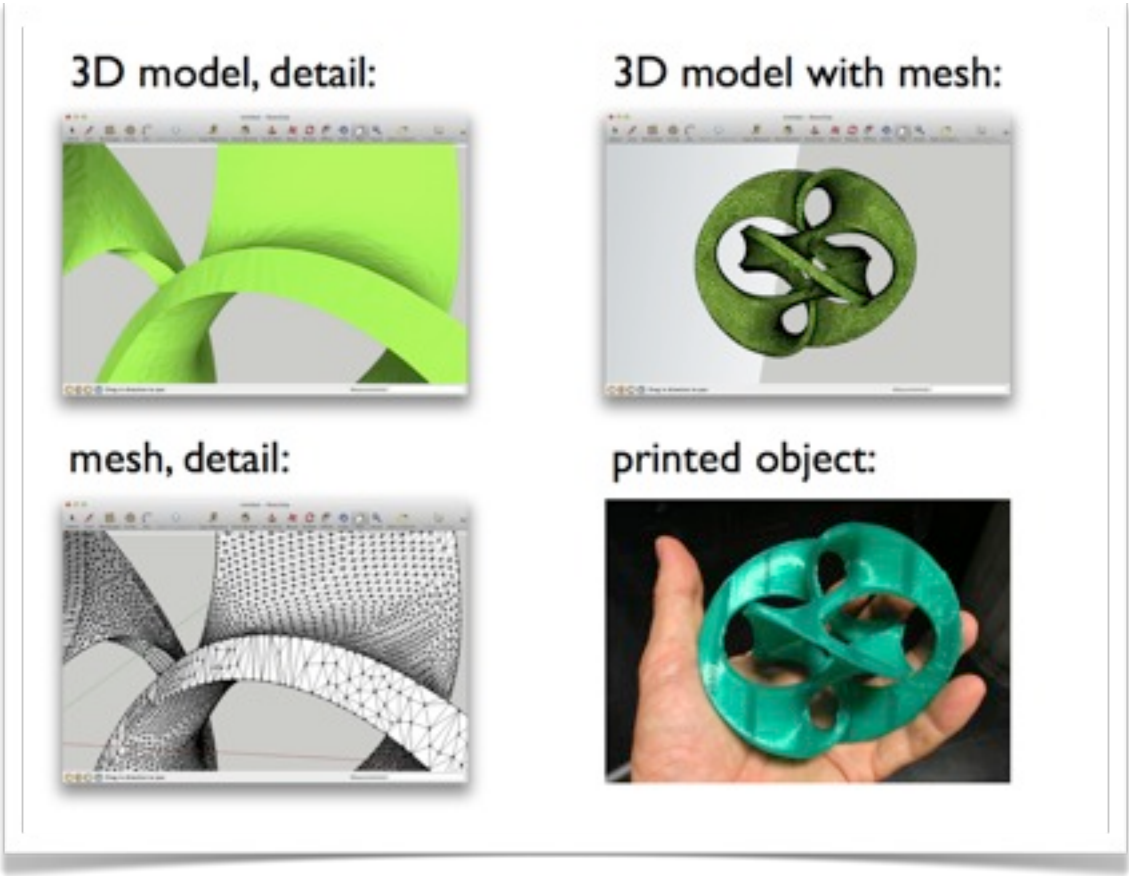
http://www.3ders.org/pricecompare/3dprinters/

It is certainly correct to estimate that in this moment there are more than a hundred different models of low-cost 3D printers available either as commercial products (that we can build on the local –or international– market) or as free designs made available on the Internet under an open hardware license (that we can build by ourselves).

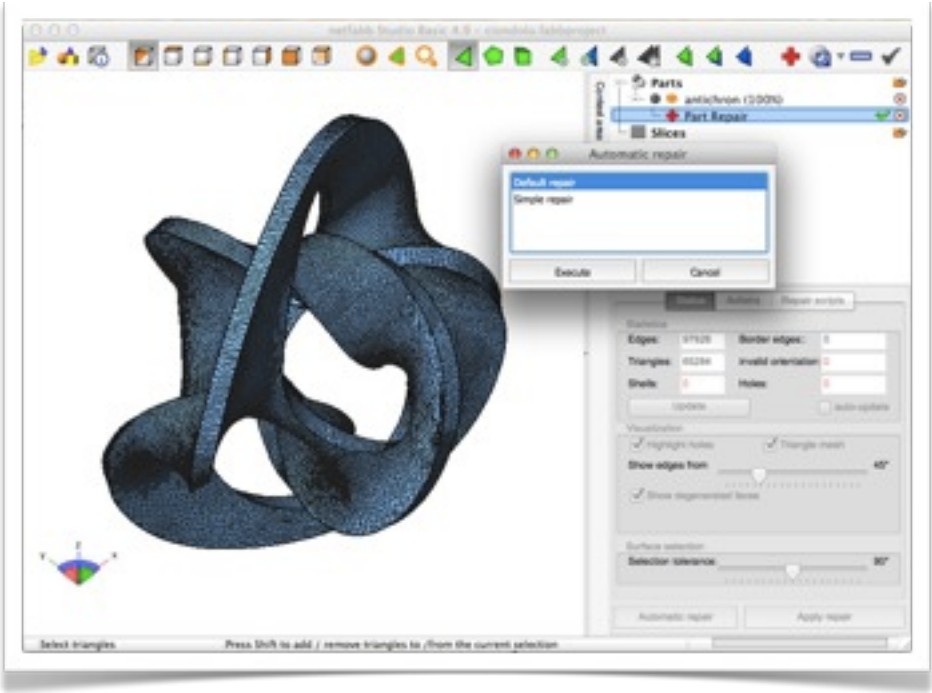
Repairing the mesh (thus avoiding a mess!)

The STL file that has been created by us (or by others) using some modeling software may not be yet ready to be printed, no matter how careful the creation process was. Even the best free software in the hands of an amateur designer can do little to avoid some mistakes to appear "mysteriously" on the surface of the objects, defects like *holes* or *reversed faces*. Those are typical problems that are almost unavoidable when we create complex models including cavities, intersections of faces or just curved surfaces.

Ideally a 3D printable model should be *watertight* (*i.e.* a *manifold*) and *solid*, not hollow. We can of course design objects like vases or "empty" bodies in general, but in fact they always have an inner part that is solid and full (even if it is just a thin "wall"). The watertightness of the object's body is the only situation that allows our slicing software (we will discuss its functioning in the following pages) to properly identify the inside and the outside of the object, in order to decide where and when to extrude plastic. But if there is even an invisible microscopic hole in the polygonal approximation of its surface (called *mesh*), the integrity of the object's external surface isn't guaranteed anymore, as well as the correct result of the slicing, and the print may end up with a messy bunch of plastic.

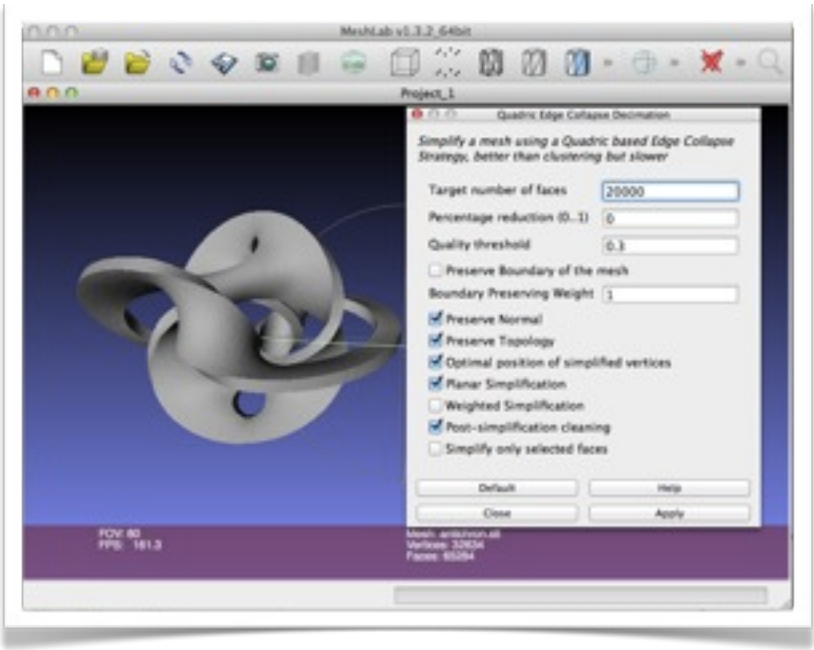


For this reason, it is always a good practice to check our models for similar problems before slicing, and this can be done with the free software **netfabb Studio Basic**[41], available for Windows, Mac and Linux.



If problems are found, they can be repaired going back to the modeling software or by using netfabb itself, either with an automatic[42] or manual[43] procedure.

An other very useful software is **MeshLab**[44], which can be used for the analysis and the manipulation of the object's mesh (*e.g.*, to reduce its complexity and number of elements[45]), and also to convert between STL and many other file formats. It has been developed by an italian research institute, ISTI - CNR, together with students of the University of Pisa, Italy, and it's available as open source for Windows, Mac and Linux.

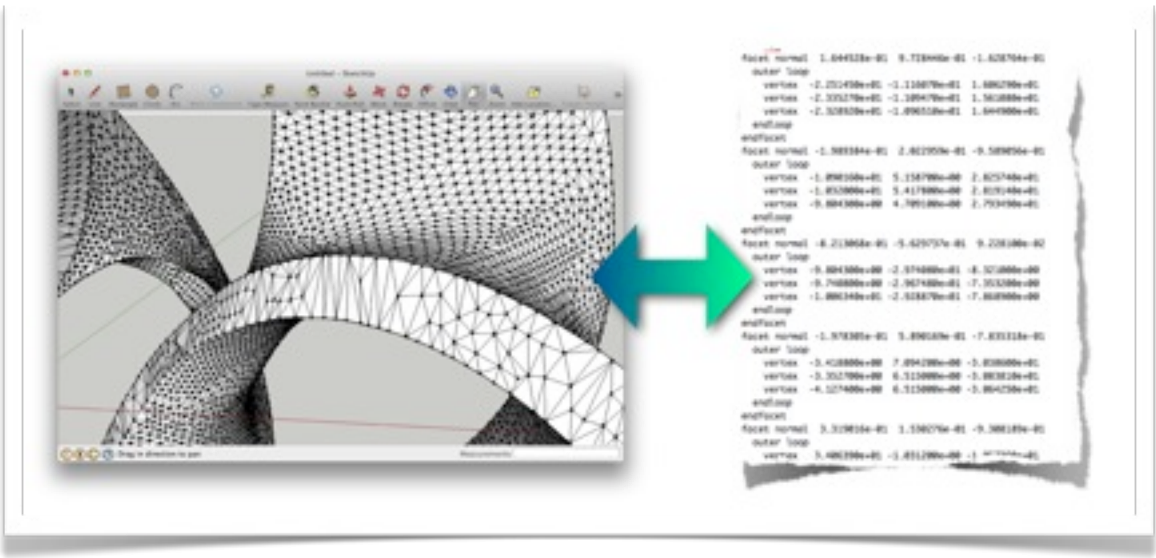


Slicing software

This step is maybe the most interesting one along the long process that goes from an idea to a real three-dimensional object, because it exposes clearly most of the subtle and intimate details of how a 3D printer works in order to convert some raw plastic filament into our beautiful creations. Preparing a 3D model for printing is a delicate combination of technical knowledge, science and art, and it requires some serious time to master this procedure.

In order to be printed, our model (saved or exported as an STL file) should be first converted into a set of instructions for the printer (a common format is called *g-code*): this task is called **slicing** (because the model is "sliced" in many thin horizontal layers that will be printed in sequence) and it's performed by complex computer programs called *slicers*.

In fact, the information contained inside an STL file is of little or no use for a printer, since it consists of just a long list of coordinates *<X,Y,Z>* identifying the vertexes composing the many polygonal faces of the object's mesh.

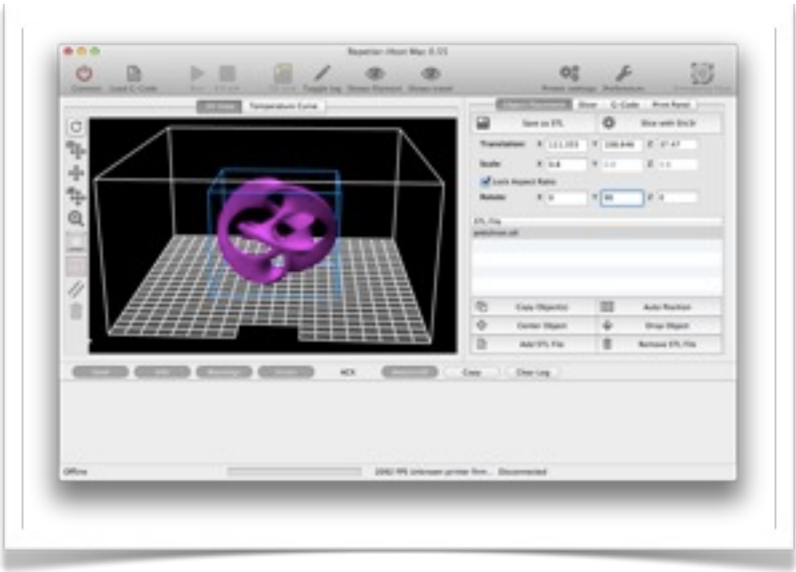


The printer needs very different information: the movements of the printing head and/or the platform in the various directions X, Y and Z, the amount of plastic to extrude and the precise time when it has to start and stop extruding, the temperature of both nozzle and printing platform, *and so on*...

This "conversion" between coordinates of vertexes and printing commands is a rather heavy task –computationally speaking– and cannot be handled in real time by the limited CPU of the printer itself, while printing, therefore it has to be done in advance on an external computer. Another reason for doing it in this way is that such slicing process requires quite a number of additional parameters that should be provided by the user (*e.g.,* the height of the layers –just to mention the most obvious, but the are many more), and the graphical interface of a real computer makes this task much easier than any of the small alphanumerical displays with a few buttons that are commonly found on 3D printers, if they are there at all (many printers don't have any interface with the user, except for the USB connection to a host computer and maybe a switch for powering on).

The standard procedure for slicing is therefore similar to this one:

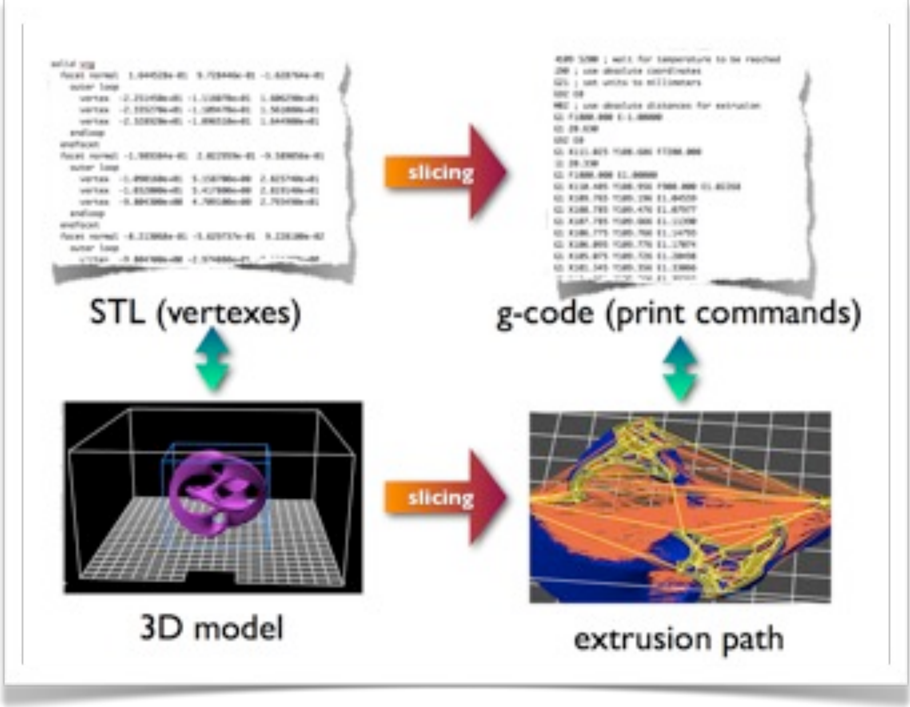
1. start the slicer program on a host computer;
2. load the STL file of the model;
3. translate/scale/rotate the model until is properly positioned on the printing platform;
4. input all the parameters that are needed for a correct print;
5. start the slicing process and wait until all the g-code is created;
6. send the g-code to the printer through a USB connection, or copy it inside a memory card (usually an *SD* or a *microSD card*) to be loaded into the printer.



The first two steps are quite obvious, but the third one may need some additional information. The slicing software is configured with all the characteristics of the 3D printer that will be used, so it knows the dimensions of the printing platform and can show the position of the model with respect to it. The user can reposition the model on the three axes until it's centered and lays exactly on the surface of the bed (it shouldn't be "suspended on air") and also rotate it if needed. The possibility to scale the dimensions of the model is also very useful, because in an STL file the unit of length is never specified, therefore it may happen that the modeling software uses centimeters while the slicer expect millimeters and the result is that the model appears 10 times smaller and needs to be rescaled of such factor. Another reason to slightly scale up the model (around

0.5% for ABS, even less for PLA) is to overcome the shrinkage of the plastic when it cools to room temperature (the thermal expansion coefficient of ABS is typically[46] about 75×10^{-6} °K^{-1}, assuming it solidifies at about 100°C and then cools to 25°C that would give a contraction factor of ~0.5%).

During the fifth step our 3D model is "cut" into many horizontal layers –it becomes a pile of slices– and each of them is processed separately to compute the best path for the nozzle to lay the melted plastic in the right places, mirroring the way the printing head is actually doing its job (*i.e.,* layer by layer).



This is the most critical part of the whole printing process, because the final quality of the printed object is determined almost entirely by the correct choice of the value for the many different slicing parameters. For this reason, the fourth step is really important, and we should learn the meaning of at least the most important slicing parameters. Unfortunately they are differently named and defined across the few different slicing programs that are available, of which we will discuss here the five most used (free) ones: *Skeinforge, Slic3r, KISSlicer, Cura* and *MakerWare* (all are available for Windows, Mac and Linux).

The best way to experiment with the slicing parameters is to follow a logical order, and probably the best one is the order used by **Slic3r**: there are parameters related to the printer model (and they are only changed when the printer is changed), others that are related to the plastic filament used, and finally parameters that may be tuned for a specific print.

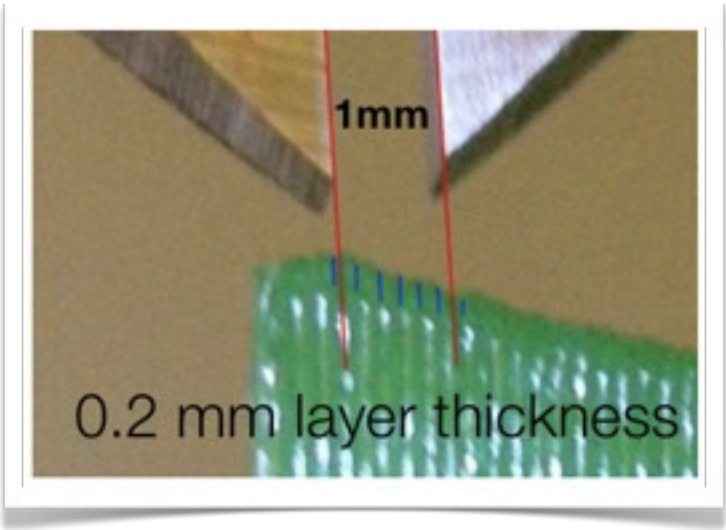
1. **Printer settings:**

- type of printer / firmware;
- size and offset of the printing platform, max Z height: a typical value for the printing envelope of common printers is 20x20x20 cm;
- number of extruders, diameters of their nozzles, other parameters for the extrusion.

2. **Filament settings:**

- diameter of the filament: it should be a precise actual measurement, the nominal value isn't good enough for the correct calculation of the length of plastic to extrude;
- proportionality factor (or multiplier or packing density): used to compensate the expansion of the plastic when is fused, it's 1 for PLA and 0.9 or less for ABS;
- extruder and bed temperature (may be different for the first layer);
- cooling fan.

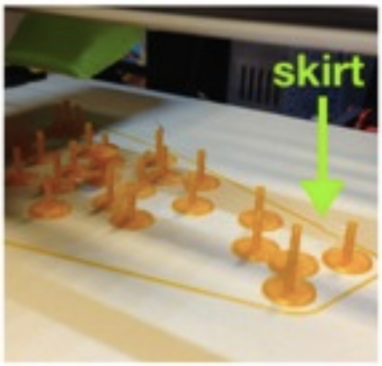
3. **Print settings:**



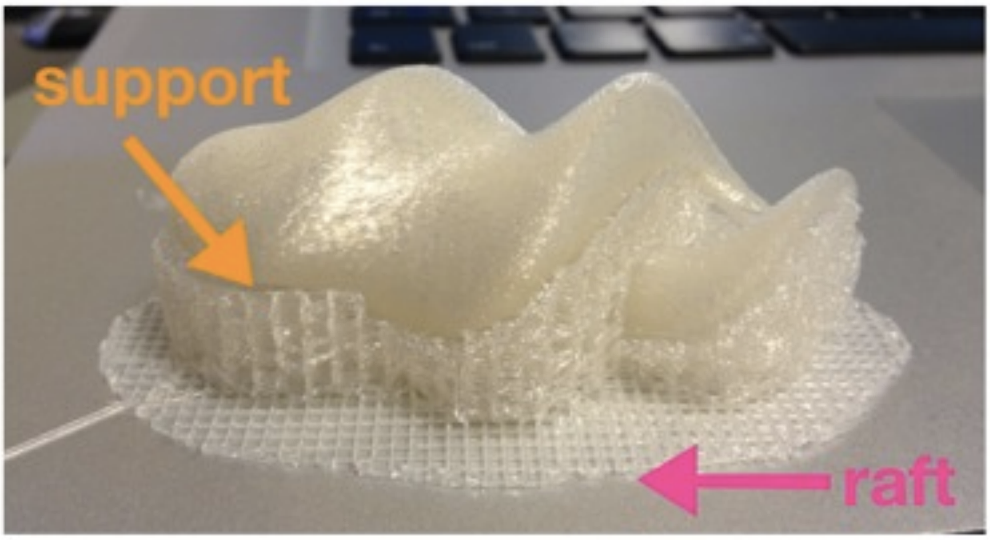
- **layer height** (may be different for the first layer): usually between 0.1 mm and 80% of the nozzle size, 0.25 mm is a typical value;
- number of shells/perimeters or thickness of the walls: increasing this value will make the object more robust;
- number/thickness of top/bottom layers: same as above;
- percentage of **infill**: amount of plastic to be used for the bulk of the object, it goes normally from 0% (hollow objects) to 50% (solid, very strong parts), more than 50% is rarely used, and typical values are around 10-20%;

- infill pattern: it's the pattern used to create the infill, commonly used are squares (rectilinear) or hexagons;

- printing speed (for the different tasks): this setting is very much related to the nozzle temperature, the type of filament and the quality of building of the printer (and the amount of lubrication used for axes and gears), a slow speed usually helps in getting better prints;
- **skirt** and brim: the skirt is the extra amount of plastic extruded before the actual printing in order to avoid to start printing with an empty nozzle, the brim is an extra thickness of the filament in the first layer, for the object to stick better to the bed;



- **raft** and **support**: the raft is another way to improve the adhesion of the object to the bed, by mean of one or two layers of a net of extra plastic filament, while the support is a special spongy structure of plastic built from below to support the parts of the object that wouldn't be printed otherwise, because of **overhangs**;
- other advanced settings.



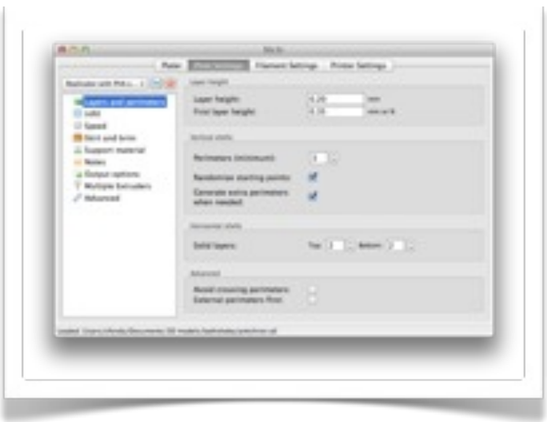
FDM-based 3D printers usually cannot produce stalactite-like structures as well as extreme overhangs, since they would be unsupported during the build. If these cannot be avoided, an extra thin **support** structure may be added into the object, which can be broken or cut away after the print process. Most slicing software can create automatically such support structure. Most printers generally handle overhangs *up to 45 degrees* well without special settings.

The 3D model should be rotated in order to minimize the parts with an overhang (before slicing), and a fan can be pointed at the part during the print, to cool the filament as soon as it comes out of the nozzle, before it has a chance to droop and ruin the print. Finally, the use of support material can be turned on in the slicing software, if necessary. This is a hassle because the process uses more plastic, takes longer to print, and you have to clean off the support material with a knife afterwards.

As mentioned before, the various slicing programs may have different names for the same setting, and they sometimes use parameters that defined quite differently (like number of perimeters/shells instead of wall thickness, *etc.*), so it is import to understand well the language and the definitions of the slicer you are going to use for your printer.

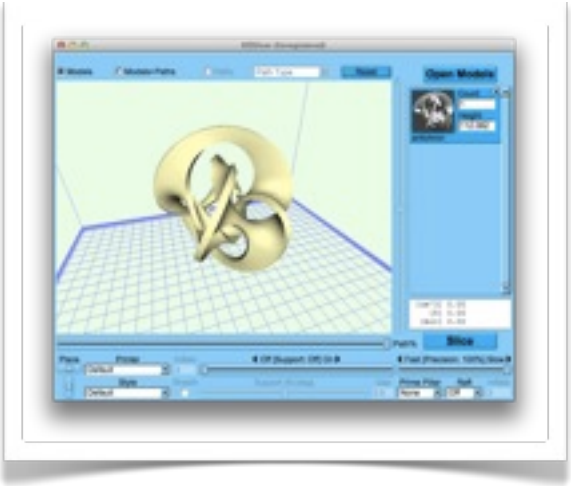
Now, let's have a quick overview of the five most used, free to download slicers:

- **Skeinforge**[47]: probably the oldest slicer, it's a set of scripts written in Python and released under a GPL license, it was the default slicing engine of the original Makerbot Replicator (embedded in the *ReplicatorG* software) and many RepRap 3D printers and it's still present as option in *MakerWare* (the program that took the place of ReplicatorG for controlling the most recent Makerbot printers) and the other common (free) program *Repetier-Host*. The user interface isn't friendly, and some settings are quite confusing.

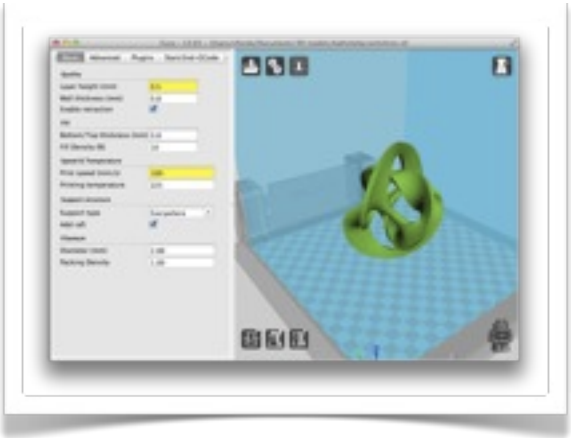


- **Slic3r**[48]: a modern, complete and actively developed open source slicing engine, it's widely supported by printer manufacturers and provided as primary option in *Repetier-Host*. It saves the user many troubles with its feature to record the various slicing parameters logically grouped within different presets.

- **KISSlicer**[49]: with a simple graphical interface and the claim to be quick and easy-to-use, it may be a good choice for the beginners of 3D printing. A "pro" version that adds support for multiple extruders and multiple objects (and a few other extra features) is also available for a price of $42 ($25 for "educational users").

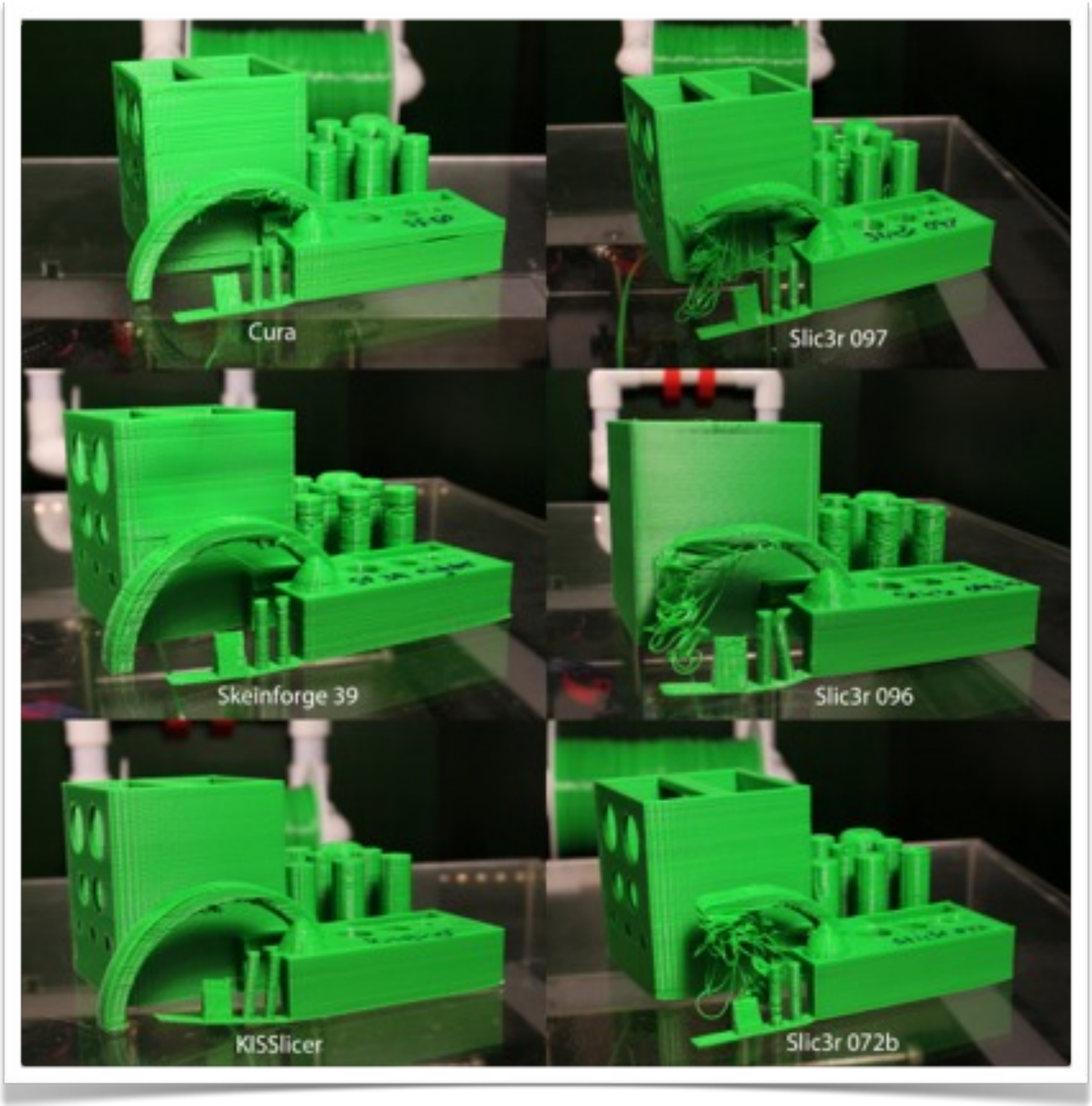


- **Cura**[50]: it's developed by Ultimaker with the goal to make 3D printing as easy and streamlined as possible. It includes everything that is needed to prepare a 3D file for printing and to print it, and it's fully preconfigured to work on the Ultimaker 3D printer.



- **MakerWare**[51]: pretty and simple to use software to control the Makerbot Replicator and Replicator 2 printers, it also provides its own slicing engine, optimized for stronger, faster and more consistent results. Additionally, Skeinforge can also be selected as embedded slicer engine.

The choice among the different slicer engines hasn't to do with just personal preferences or the list of features of the various options: some printers strictly require the use of only one specific slicer or two: an example is the Makerbot Replicator 2, its latest firmware can only use a new and backward-incompatible version of g-code called *.x3g*, thus requiring MakerWare or ReplicatorG, the only two slicers that can generate such files. In other cases, the manufacturers of the printer can make a strong recommendation to use specifically one slicer, like in the case of the Ultimaker with Cura. Finally, the choice of the slicer may be really left to the user with total freedom, and be possibly driven by a scientific and careful comparison of the actual results of various slicers when dealing with some complex models called *torture-tests*[52].



Plastic filaments

Currently (spring 2013) there are two different types of plastic widely used for low-cost 3D printing, and a few more that are less common. What is interesting is that more plastics are being developed and tested, that will offer a much wider range of physics, chemical and mechanical characteristics, thus paving the way to a number of new applications for 3D printing. Availability of new printing material may quickly change the filament market.

Plastic filaments are now produced in two standard diameters, 1.75 mm and 3.0 mm. The 3.0 mm filament is somehow an older standard and is slowly being upstaged by the 1.75 mm that can be pushed slightly more easily, controlled a little better and sometimes leaves fewer tails hanging off the sides of your object. Anyway, many current printers are still using 3 mm filament, and sometimes it's slightly less expensive than the 1.75 mm one.

PLA

The most common plastic filament is made of *Polylactic Acid* (or *Polylactide*, abbreviated with PLA[53]), a biodegradable and environment-friendly plastic derived from starch. Its melting temperature is within the range 180–230 °C. It doesn't smell badly when printing and the fumes aren't dangerous, therefore it doesn't require special safety precautions or forced ventilation.

It sticks well on the printing bed at room temperature (not requiring the more expensive heated bed option for the printer), but only if the platform is covered with blue tape (also an inexpensive product, that should be replaced from time to time –mostly because it gets sometimes damaged when removing the object from the platform).

Objects printed in PLA are robust but relatively brittle, and cannot be used when resistance to high temperature is needed (like for some parts of a 3D printer itself).

The PLA filament is rather inexpensive, averaging at 30 $ for 1 kg and it's usually sold in rolls of 0.5, 1 or 2.3 kilograms (but some manufacturers sell them also by the meter[54]). It is available as natural (translucent white) or in many bright colors, solid or half-transparent, and the printed objects have a beautiful smooth surface.

A special variant of PLA is the *soft* or *flexible PLA*, that should be extruded at lower temperature and very low speed, and can be used to print flexible joints, belts, tires, *etc.*

ABS

The second most common filament is made out of *Acrylonitrile Butadiene Styrene* –ABS[55] in short– a petroleum-based plastic used for many purposes and well known for the LEGO™ bricks. Its fumes are smelling badly and are even considered dangerous for the health, so it is highly recommended to use forced ventilation with fumes extraction when printing ABS for a long time. The melting temperature of ABS is 210–260 °C.

ABS filament costs more or less as PLA, and is also a rather common printing material, despite its more demanding requirements. An ABS object is usually printed on a heated bed (at around 100 °C) covered with *Kapton* tape in order to stick well, adding cost and complexity to the printer itself (for this reason, not all printers come with a heated bed as default, and some do not even have it as an option). A possible solution is to print ABS over a cold bed covered with a few layers of glue: cyanoacrylate, hair spray[56] or water-based glue like Vinavil®[57] have been proved to work well for this purpose. But the use of a heated bed is advised also because it helps reduce the warping of large printed objects.

The advantage of ABS over PLA is that the resulting objects are more robust and less brittle, and can resist at higher temperatures. ABS filament is commonly available in many colors, including glitter, glow-in-the-dark, gold and silver, and even color that changes with the temperature[58] (*e.g.,* blue/green below 30 °C and yellow/green above, making the objects printed with such filament sensitive to body temperature).

Nylon

Taulman[59] produces a *618 Nylon®* filament that has a few interesting characteristics, among them pliability, light weight and chemical resistance. It should be extruded at a higher temperature compared to PLA or even ABS (around 245 °C), but there isn't fumes production or odors, and it sticks well on blue tape. It is used for printing mechanical parts that need high resistance to breakage and a very low surface friction, but another very interesting potential use is for printing customized prosthetics and medical-related parts since nylon is inert to the body (but not officially FDA approved, at least yet). The cost of nylon filament is more than double than the cost of PLA or ABS, the only available color is white (natural) and the only source is Taulman.

PC

Polycarbonate[60] (PC), is a very strong and durable plastic material with high optical clarity and high melting temperature (around 270 to 300 °C). Despite being used in many industrial productions (for example CD and DVD are made of polycarbonate) the first tests with low-cost 3D printers started just in 2012[61] and there are only a few manufacturers of PC filament yet, selling it quite expensively at around 90 $/kg.

PVA

Polyvinyl Alcohol is a water-soluble plastic polymer that can be used for printing support structures for PLA and ABS objects that are easily dissolved in warm water, leaving a perfect surface of the object and simplifying the (usually quite tedious) process of removing the support. The printing temperature is around 170 °C and should never exceed 200 °C. The PVA filament is also rather expensive, selling at around 90 $/kg.

HIPS

High-impact Polystyrene[62] is a plastic filament soluble in Limonene, sometimes used to build support structures (specially for ABS) that can be easily removed without mechanical work. Limonene is a natural solvent extracted from the rind of lemons and other citrus fruits. Printing HIPS requires a temperature of around 230 °C. The cost of HIPS filament is around 40 $/kg.

Other types of plastic

LAYWOO-D3 is a wood-based filament recently produced[63] (technically a wood/polymer composite, containing recycled wood and binding polymers) and can be used to print objects that resemble real wooden pieces (even with the typical growth rings). All other characteristics are the same of PLA, but its price is still very high at around 100 $/kg and it requires some tricks[64] to change the color of the rings.

Finally, there have been a few experiments with *conductive plastic*[65], but the resistance is still quite high and no commercial product has been developed yet.

Printing

At this point, we should have at our disposal a carefully selected printer ready to be inaugurated, a filament with the right diameter for our printer and of the right type and color for the purpose of our design, and a g-code file produced by the slicing software, properly configured according to the properties that we would like to obtain for our object. It's the right time to switch on the printer and connect it to our host computer, and start the **calibration procedure**:

1. The first problem to solve will be to find out the correct parameters for the connections: most printers, despite being connected via USB, internally use a *USB-to-serial* chip to provide a serial data stream (*RS-232 style*) to the CPU, and this means that the speed of the serial line, the number of bits of start/stop and parity and the handshaking procedure have to match the correct values.
2. When –after some trials and errors– the connection is finally established, we can start sending *g-code* commands to the printer, to check if everything is working properly. A good calibration procedure should include the test of all end-stop sensors, temperature sensors and step motors.
3. When all these tests have been passed, we can do the leveling of the print bed: the ideal is to have a platform that is as flat as possible and perfectly parallel to the axes of the moving print head, in all directions. In order to reach this goal, the user has to move the head across all directions, comparing its vertical position with the one of the platform, and correct the level of the latter by mean of some screws, rising or lowering the four corners of the platform.
4. After the leveling, the platform should be carefully cleaned and covered with the proper kind of surface: it can be done with one or more layers of blue tape (for PLA) or Kapton tape (for ABS), or the proper material required for the other kinds of plastic.
5. If we are going to use ABS filament, we should now pre-heat the printing bed.
6. The next step require to load the filament: this will require the heating of the printing head (*i.e.* the nozzle) and the action of the extruder gear, either by hand or by the activation of the extruder step-motor. After extruding some plastic, we will be sure that the nozzle has been filled with plastic and it's ready for the actual printing.

7. We now have to load the g-code for the object we want to print, either by sending it through the USB connection or by saving the file on an SD (or microSD) card and then loading it on the printer (if it has an on-board card reader).
8. Finally, we can start the print. It has been a long journey and we deserve some relax, and maybe some coffee while we wait until the printer has finished and the object has been *created* out of the raw plastic filament.

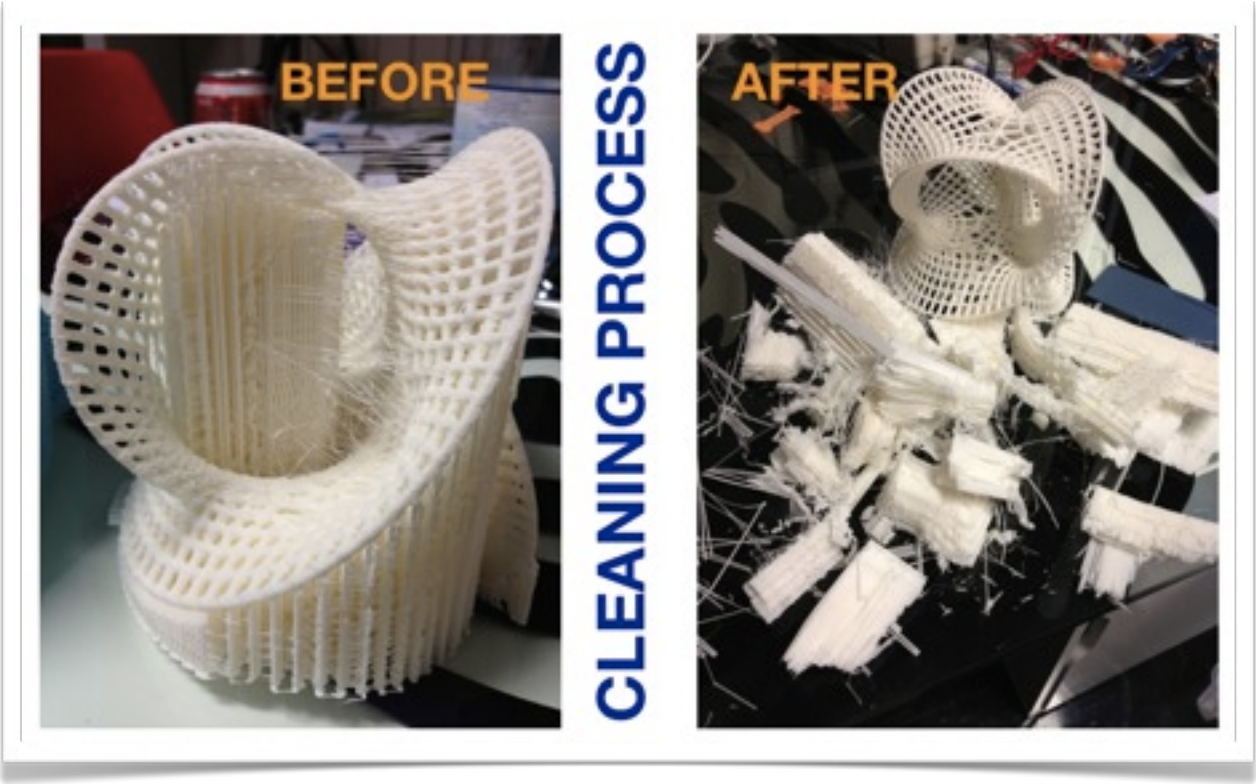
The time for printing a small hollow object that is a few centimeters wide can be around 10-20 minutes, while for an object the size of an apple the waiting time can increase up to 1 hour and even more (it depends on resolution, infill, and printer speed). The printing of bigger objects can easily take 10 hours, and if they are also complex or with a solid infill the time can rise to 50 and more hours...

As a word of caution, it may be dangerous to leave a 3D printer unattended when printing, because some of its parts will remain constantly at a temperature of 200ºC or more, melted plastic will be extruded by the nozzle, in presence of electricity, moving parts, running motors and often a wooden frame that has little protection against fire. When things go *really wrong*, a 3D printer can be as dangerous as a laser printer with all its hot parts.

Much more often, we just end up with a big mess of plastic that has little in common with our initial model[66]. And finally, most of times, we are rewarded with a successful printing of our idea that has now become a real 3D object, and from which we can continue with new experiments and even better results.

Finishing

After the printer has finished to print an object, it may be worth to give it a few minutes for all the parts to cool down, and in case of ABS it will be also much easier to detach it from the bed. You may then have to remove the raft and/or the support structures, with the help of a sharp knife or cutter blade.



As an additional step, and if a glossy finish is required, the object's surface can be further polished by using sandpaper (with caution, as this may even damage the smooth surface), or by using chemical solvents (*i.e.*, vaporized Acetone[67] for ABS and other solvents[68] for PLA –but be careful because some chemicals are very poisonous), heat (by mean of an hot air blower) or even a layer of transparent or opaque coating paint.

Conclusions

During the revision of this article, I've been told that a beginner who would read it without having first tried by himself to print an object in 3D with these low-cost technologies will be discouraged and would avoid trying it. The impression may be that this attempt is going to be hard and most likely end with a complete a failure, so I feel the need to correct this idea and encourage all the readers to embrace the challenge. I'm sure that it will be a success and will show them the real beauty of this technology, the fact that it is at reach of anyone that has a little bit of patience and willingness to learn something new.

3D printing at home, with inexpensive machines, and possibly in future with recycled plastic waste[69], is really a novelty even for today's technological world, but it is also a revolution in the way we will look at ourselves: by being able to *create* something *new*, only by mean of our *imagination* and with the help of some *affordable* and friendly mechanical assistants (they are our friends because we know all of their *inside* mechanisms), we will know that we can open the door to an incredible future of personal fabrication devices and new applications than we can't even imagine today. *A new world will start from us*.

Note: All prices and characteristics mentioned in this article have been checked at the time of writing (April 2013).

Acknowledgements

The author wish to thank Daniel Pietrosemoli for having introduced him first to the wonderful world of low-cost 3D printing; Ermanno Pietrosemoli for having facilitated the communication channel between me and Daniel; Enrique Canessa for his rich flow of ideas and new challenges and his faith in the power of scientific approach to solve technical problems encountered during the 3D printing of some rather difficult mathematical objects; Jonathan Gatti for his constant help and support for such prints; and –last but not least– Gaya Fior for her precious support and the many corrections she has made to my convoluted *italian*-english, for assembling (together with Jonathan and Ermanno) most of my printers when I was busy doing other stuff and for the research she has done on 3D modeling software and model repositories, which I've extensively used to write parts of this article.

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The Role of Open Source Software and Hardware in the 3D Printing Revolution

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We still don't know whether or not desktop 3D printing is the forerunner of the "Third industrial revolution" as Jeremy Rifkin[1] and Chris Anderson[2] have suggested. It is definitely one of the most interesting tech trends around and in the following we want to highlight the role of open software and hardware in its success.

Open Source

Open Source is an approach to design, development, and distribution offering practical accessibility to a product's source.

The term Open Source gained popularity with the rise of the Internet, which provided access to diverse production models, communication paths, and interactive communities. While the term applied originally only to the source code of software, it is now being applied to many other areas. The fundamental starting point of an open source project is the community.

Open source software

Open Source Software (OSS)[3] can be defined as computer software for which the human-readable source code is made available under a copyright license (or arrangement such as the public domain) that meets the Open Source definition[4]. This permits users to use, change, improve the software, and to redistribute it in modified or unmodified form. It is very often developed in a public, collaborative manner. Open Source software is the most prominent example of open source development and often compared to user-generated content.

Licensing

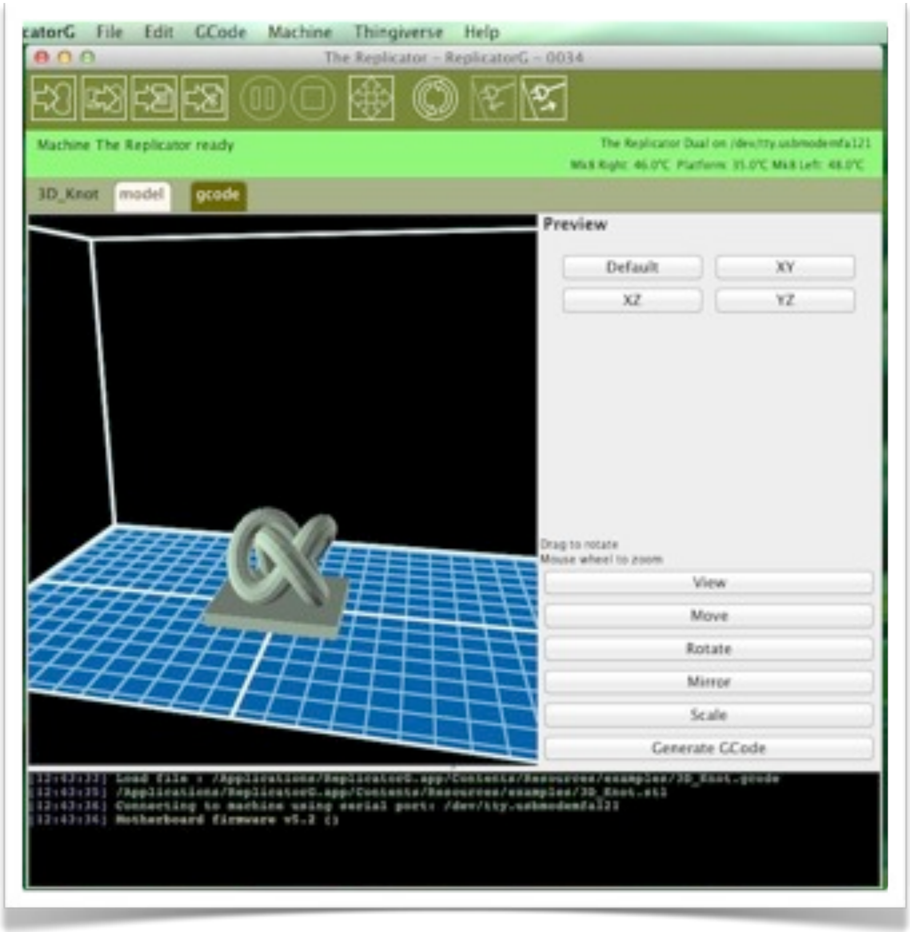
Open Source licenses define the privileges and restrictions a licensor must follow in order to use, modify or redistribute the open source software/hardware.

The GNU General Public License (GPL)[5] is the most pervasive license of Open Source. Of all the software to which it has been applied, none is better known than the Linux kernel. In fact, the GPL has been applied to a majority of those software modules that are included in the best known of the Linux distributions. Its wide appeal among the Open Source community stems from the fact that it falls into that category of Open Source licenses which obligate parties who wish to redistribute such software, either in original or modified (derivative) form, to do so under the terms of the license agreement under which such software was received. That is, having been granted the right to use, modify and redistribute the software under the GPL, the GPL requires the party to extend those same privileges under the same terms to others who receive the software.

A Creative Commons (CC) license[6] is used when an author wants to give people the right to share, use, and even build upon a work that they have created. Creative Commons provides an author flexibility. For example, they might choose to allow only non-commercial uses of their own work, and protects the people who use or redistribute an author's work, so they don't have to worry about copyright infringement, as long as they abide by the conditions the author has specified. There are several types of CC licenses. The licenses differ by several combinations that condition the terms of distribution.

Open software and 3D printing: the ReplicatorG example

ReplicatorG[7] is a simple, Open Source 3D printing program. This is the software being used by the MakerBot Replicator, Thing-O-Matic, CupCake CNC, RepRap machine, or generic CNC machine. It is able to process a GCode or STL file; it is cross platform (works on Mac, Windows and Linux); easy to install; it is based on the familiar Arduino / Processing environments. ReplicatorG is used by thousands of MakerBot Operators.



The ReplicatorG interface, based on the Arduino one

Thanks to the Open Source license, it is based on the Arduino GUI and provides an easy to use GUI for controlling and running RepRap compatible machines. It adopts the GNU GPL version 2. This is what the license preamble says:

> *When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things.*
>
> *To protect your rights, we need to make restrictions that forbid anyone to deny you these rights or to ask you to surrender the rights. These restrictions translate to certain responsibilities for you if you distribute copies of the software, or if you modify it.*
>
> *For example, if you distribute copies of such a program, whether gratis or for a fee, you must give the recipients all the rights that you have. You must make sure that they, too, receive or can get the source code. And you must show them these terms so they know their rights.*

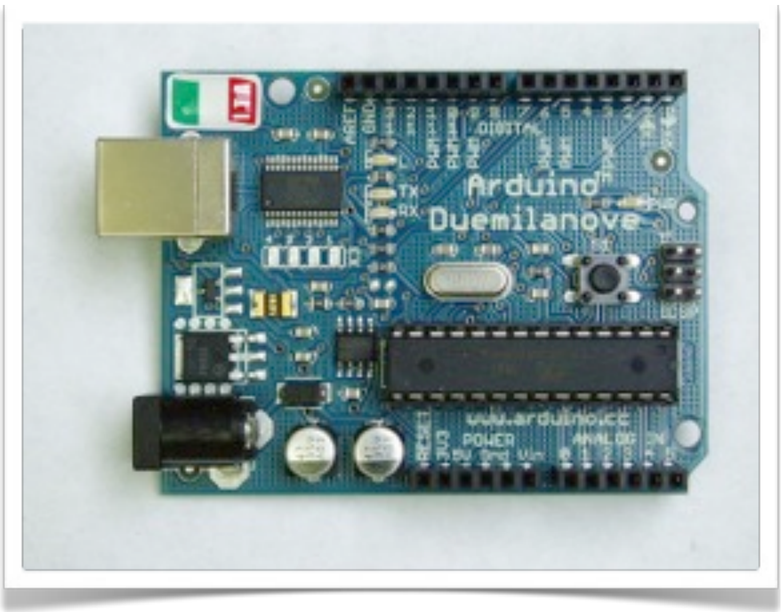
Open hardware

Open Source Hardware (OSH)[8] refers to computer and electronic hardware that is designed in the same fashion as Open Source software. Open Source hardware is part of the open source culture that takes the open source ideas to fields other than software. The term has primarily been used to reflect the free release of information about the hardware design, such as schematics, bill of materials and PCB layout data, often with the use of Open Source software to drive the hardware. In addition to existing software licenses, several new licenses have been proposed; these licenses are designed to address issues specific to hardware designs. One example is given by the Balloon license[9]. The license says that everyone has the right to manufacture, sell, and distribute Balloon boards unchanged, however populated, and for any price.

Arduino

The most popular open hardware example is the Arduino board[10]. Arduino is the brainchild of an international team of five engineers: Massimo Banzi and Gianluca Martino of Italy; David Cuartielles of Spain; and David Mellis and Tom Igoe of the USA. Arduino was developed by the Interactive Design Institute Ivrea (IDII) in Italy to help students there to actually build prototype objects that could react to their inputs.

Arduino's hardware is completely open sourced (under CC), with design files and specs available, as well as control software (under the GPL) and documentation (also under CC). The only thing non-free about Arduino is the trademarked name.



An Arduino board

An Arduino board, as the one showed on the left, consists of an 8-bit Atmel AVR microcontroller with complementary components to facilitate programming and incorporation into other circuits. An important aspect of the Arduino is the standard way that connectors are exposed, allowing the CPU board to be connected to a variety of interchangeable add-on modules known as shields. Some shields communicate with the Arduino board directly over various pins, but many shields are individually addressable via an I2C serial bus, allowing many shields to be stacked and used in parallel. Official Arduinos have used the megaAVR series of chips, specifically the ATmega8, ATmega168, ATmega328, ATmega1280, and ATmega2560.

A handful of other processors have been used by Arduino compatibles. Most boards include a 5 Volt linear regulator and a 16 MHz crystal oscillator (or ceramic resonator in some variants), although some designs such as the LilyPad run at 8 MHz and dispense with the onboard voltage regulator due to specific form-factor restrictions. An Arduino's microcontroller is also pre-programmed with a boot loader that simplifies uploading of programs to the on-chip flash memory, compared with other devices that typically need an external programmer.

Open hardware and 3D printing

Arduino's openness means that the micro-controller board can be found in the heart of a lot of Open Source hardware devices today, including 3D printers.

So far, the most popular desktop 3D printer has been an original Open Source design based on the original RepRap printer: the MakerBot's Replicator. Contrary to the non-commercial RepRap project, MakerBot (introduced in January 2012) is not focused on an end-goal of self-replication. The improved 3D printer has more than double the build envelope, includes a dual extruder allowing two-color builds, and upgraded electronics that include an LCD display and a control pad for direct user interaction without the need for a PC. The Replicator is only sold pre-assembled. In September 2012 Makerbot Industries introduced the Replicator 2.

The new version 3D printer again increased the build envelope and can print at 100 microns per layer. The dual extruder option was dropped, but the upgraded electronics, LCD display, and gamepad remain similar to the original Replicator. The firmware, desktop software and file formats were also changed in this version to support the additional accuracy and size. Unlike previous models, the Replicator 2 can only print PLA plastic, and does not include the heated build plate, extruder, or high-temperature settings for ABS plastic. The Replicator 2 is only sold pre-assembled. Around September 2012 the company stated that for their new Replicator 2 they "will not share the way the physical machine is designed or our GUI"[11]. This departure from the previous OSH model has been criticized by part of the community, including co-founder and now former employee, Zachary Smith. The move was said to be in response to the arrival of an almost identical clone of the Replicator called the Tangibot. MakerBot has not gone entirely proprietary, as the original Replicator is still open.

MakerBot's popular Thingiverse online store and hacker community remains free and open, unlike other online retail stores for 3D printing designs.

The LulzBot AO-100[12], from Aleph Objects, Inc., was the first hardware product to receive the Free Software Foundation's "Respects Your Freedom" certification[13]. This hardware product certification program encourages the creation and sale of hardware that will do as much as possible to respect your freedom and your privacy, and will ensure that you have control over your device. Aleph Objects was founded with the idea that people should be free to use, learn from, and improve the machines they use, and to share their improvements and innovations with collaborative communities. All of their printers ship with hardware designs, software, and documentation all under free licenses. You get it all —source code, design documents, and specifications— everything needed to control, tinker, fix, and improve upon every aspect of the printer.

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Plug'n'Play, Do-It-Yourself Kits and Pre-assembled 3D Printers

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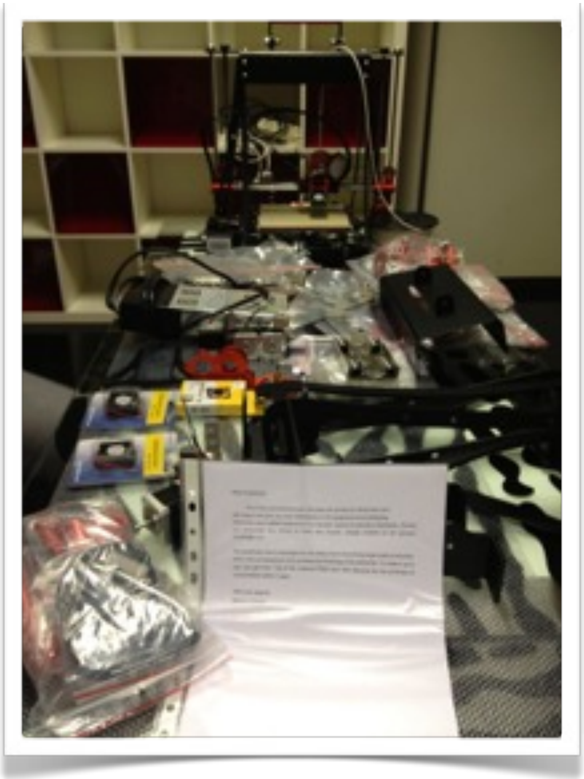
At the time of this writing (April 2013), manufacturers of low-cost 3D printers are feeding the market with an overwhelming number of options: there are literally a hundred of different models with different features and prices.

After pinpointing the one that suits our needs, we are in many occasions also given the choice to buy the printer either fully assembled or as a Do-It-Yourself kit, *i.e.,* as a set of motors, axes, gears, nuts, bolts and other hardware paraphernalia with some more or less detailed instructions for combining all together into an (hopefully) working device.



CB-printer DIY kit and assembled machine

The market also offers a third kind of low-cost 3D printer, friendly advertised as "Plug'n'play". This Plug'n'play label, once a privilege of very expensive "Pro" equipment, is in fact now making its appearance also in the low-cost range, with 3D printers priced lower than 1000€. These usually look much more refined than the other versions and are designed to reduce to the minimum all possible user's mistakes... but also most of his freedom. The interest in 3D printing is such that many *Kickstarter*[1] and *Indiegogo*[2] projects (crowd-financed kinds of project, hosted on two very popular websites) on this topic are getting funded with sums way higher than the expected goal. The RoBo 3D printer (410€) reached its funding goal with 1300% of the pledged sum[3] and is described as an *"Open source 3D printer that anyone* *can use, regardless of knowledge and skill level"* and *"Easy to use/Easy to assemble"*.

Cubify advertises[4] it's printer Cube (1.080€) as *"Plug and play simplicity: Voted MAKE magazine's "easiest to use" and "most reliable" 3D printer. Straight out of the box - you can get started immediately with the Cube's simple setup. Just plug it in and start. The only 3D printer certified for safe at-home use by adults and children."*

Up! by PP3DP (Up! mini 709€, Up! Plus 1183€) states[5] *"The UP! Mini is based on the simplicity of a traditional inkjet printer, with a snap-in printer head, slide-in build table and clip-in consumable roll. You are ready to start making your big ideas into 3-Dimensional usable models out of tough ABS+ plastic"*.

The downside of plug'n'play solutions is the limited possibility to modify the parameters of the print for a given object. These printers frequently come with a proprietary software aiming to simplify the user's experience by reducing to the minimum the settings adjustments. For example the Cubify client software[6] fixes the layer's thickness, print speed and infill support to factory presets and while these values may be ideal for printing the various objects proposed on the company's website, these restrictions will certainly be a limiting factor when the user moves after these initial simple objects.

In some cases plug-and-play printers also have proprietary filament cartridges, with prices much higher than the standard filament reels, and a reduced choice of colors.

If we set aside these plug'n'play printers (as I advise to do, if you think 3D printing will be more than a fancy for you) we are given a huge choice of machines, and many companies offer us also the possibility of choosing between a pre-assembled version and a DIY kit version of their printers.

What are the main differences?

Price

Obviously a pre-assembled printer will cost more than the same as a DIY kit, for the simple fact that the assembling requires a significant amount of labour.

The difference in price can be huge, from 13% to 42% more for the assembled and calibrated version in the examples we found. Choosing to buy the kit will make us save a consistent amount of money.

	DIY kit	assembled and calibrated	difference	percentage difference
Airwolf 3d	€ 1022	€ 1337	€ 315	31%
Ultimaker	€ 1194	€ 1699	€ 505	42%
Portabee	€ 387	€ 505	€ 118	30%
rapidbot	€ 699	€ 829	€ 130	19%
CB-printer	€ 1550	€ 1750	€ 200	13%
printrbot junior	€ 315	€ 394	€ 79	25%
MakerGear M2	€ 1163	€ 1400	€ 237	20%
Felix 2.0	€ 999	€ 1399	€ 400	40%

Comparison between the prices of 3D printers in kit or pre-assembled version.
Prices are for april 2013, taken from manufacturer's websites.

But more than saving a couple of 100$, building our own printer will really make us understand how it works and help us when (sooner or later) it will not give us the desired results. There are calibrations that need to be made regularly also in a perfectly working printer: the belts may need tensioning and the print bed has to be leveled with precision to ensure the object sticks on the surface and the print is not deformed.

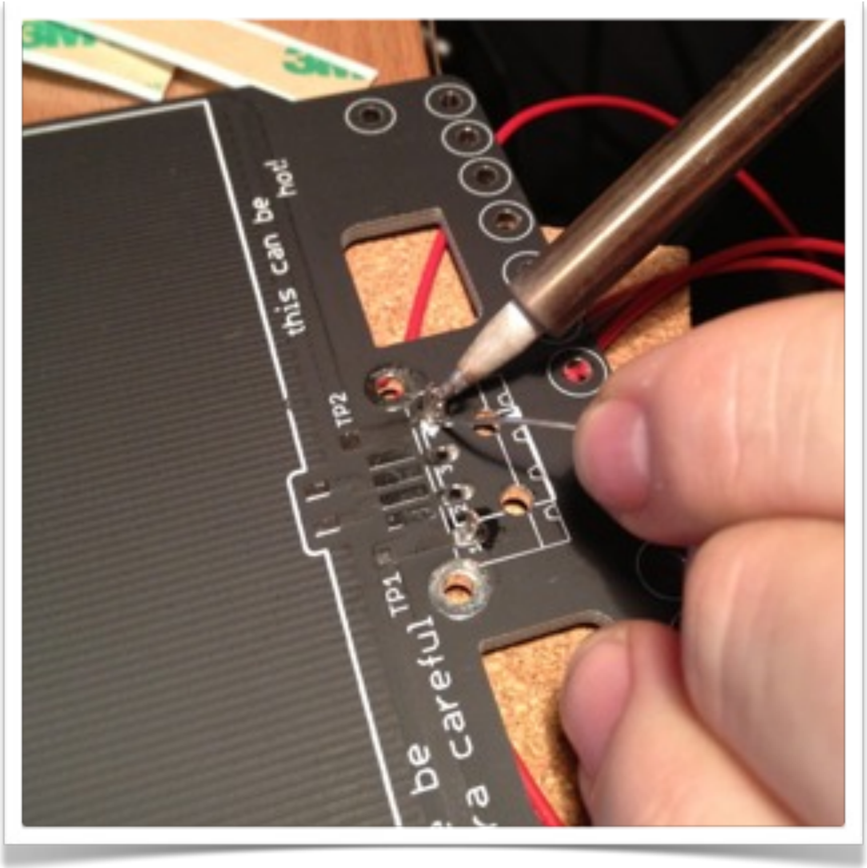
But there is also a wide array of adjustments that need to be made ever so often: the axes might need calibration, the extruder might clog or the mechanism that pushes the filament might need a fine tuning to provide a smooth feeding.

These and many other are standard problems[7] that might occur to all consumer-grade printers, also to those that state *"...we take the hassle out of 3D printing by shipping every machine fully assembled and ready to print -- right out of the box."*[8]

Buying an assembled and calibrated printer does not protect the users from these problems, because they might (will) happen along the way equally if we start out with an assembled or the equivalent kit version of the printer. Parsing through the web forums that almost all manufacturers provide to support their user community, you will certainly find out many of the problems (and luckily solutions) that your printer will encounter along the way, and have a better idea of what you might be expecting from this purchase.

Assembly time and technical difficulties

The kits usually come with all the electronic parts pre-soldered and require “only” for the mechanical parts to be assembled. Some kits ask for hand and power tools and in some cases even soldering skills. This might lead to some difficulties or at least the purchasing of a more complete set of tools. Most kits state clearly which are the tools needed for the assembling, and frequently include a few screwdrivers, Allen keys or wrenches of the needed sizes.



Soldering the heated bed of the PortaBee printer

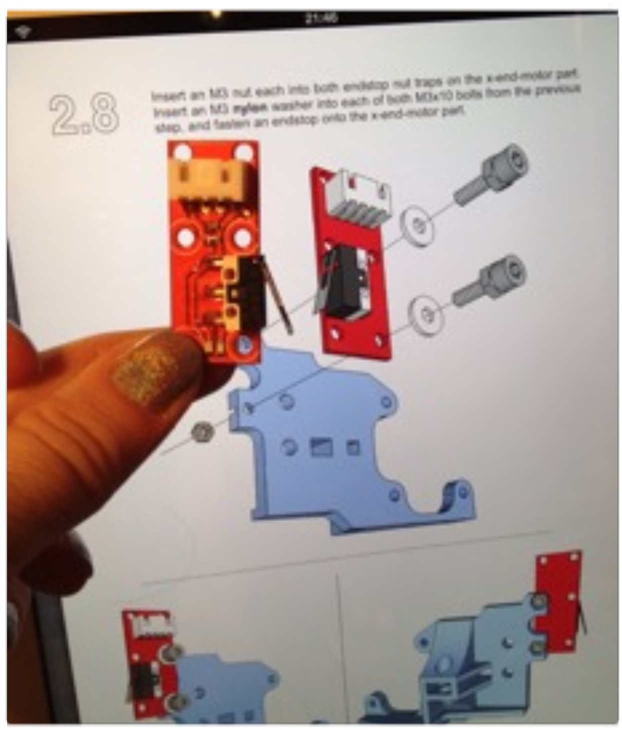
The earlier companies frequently have had the time to improve the assembly of the machine and provide a much easier user experience: to assemble the Ultimaker[9] (distributed since May 2011) you just need 2 hex keys (one is included in the kit), and an adjustable wrench. The “newer” CB-printer[10] (first prototypes in August 2012) instead requires a vast set of tools including hammer, pliers, a complete set of screwdrivers, hex keys and wrenches, riveter, files, glue… and fantasy to interpret the rudimentary instructions.

There is usually a great number of small steps required to complete the kits and these are often broken down in various sections of the assembling manual. In the best manuals also the time needed to complete each section is stated and the users are invited to send a feedback of their experience to further improve the estimates. The entire build task can usually be completed in 6-20 hours, depending on the complexity of the printer and on the technical abilities. To stay on the safe side I would recommend setting aside a full weekend for this task, keeping in mind the need for a big clean surface without disturbances. The number of small pieces to assemble is huge, and missing a key component because it has been easy prey of the house cat would be extremely frustrating.

Documentation

Some “older” companies like Ultimaker have very thorough wiki-based documentation[11] with photos and step-by-step instructions to build the machine. The possibility to read the comments that the other users have left and search for videos is a big help, as they frequently clear out the difficult spots in the procedure.

Unfortunately in many occasions the documentation is very precise for the first release of the printer, but is not upgraded when new versions of the kit are produced. This is terribly confusing because the components of the kit don’t match with the ones shown in the manual, and this might lead to a big waste of time trying to figure out the problem.



Differences between the documentation and the actual components

While well distributed machines will usually have a huge amount of official and unofficial documentation, emerging companies sometimes have had the time to concentrate only on the actual project and provide schematic step by step instructions with no consideration for the difficulties that the user will encounter. If a standard search on the web does not provide any insight regarding the assembly, and there are no reviews and opinions to be found, this might be a very worrying signal to keep in mind when choosing.

Recommendations

Often behind a new 3D printer there is a fairly new and unexperienced team of engineers and programmers that have little or no background in commerce. The customer service could be enthusiastic or extremely disappointing, but in any case it's very important to check carefully the contents of your purchase right after receiving it. Assembling the printer will certainly be time consuming e depending on the free time you have, it could take even a month to accomplish the task. In 2 different situations we found out, after more than 1 month since the arrival of the box, that there were missing parts. In one occasion the instructions were missing and there was no online documentation to replace them. The manufacturer sent us a CD-ROM by courier and a PDF via email. In another occasion there were a few missing components and the company pointed out their terms of service where it was stated that the user had 14 days after the deliver date to report any missing parts, forcing us to pay for purchasing again the parts, missing because of their mistake.

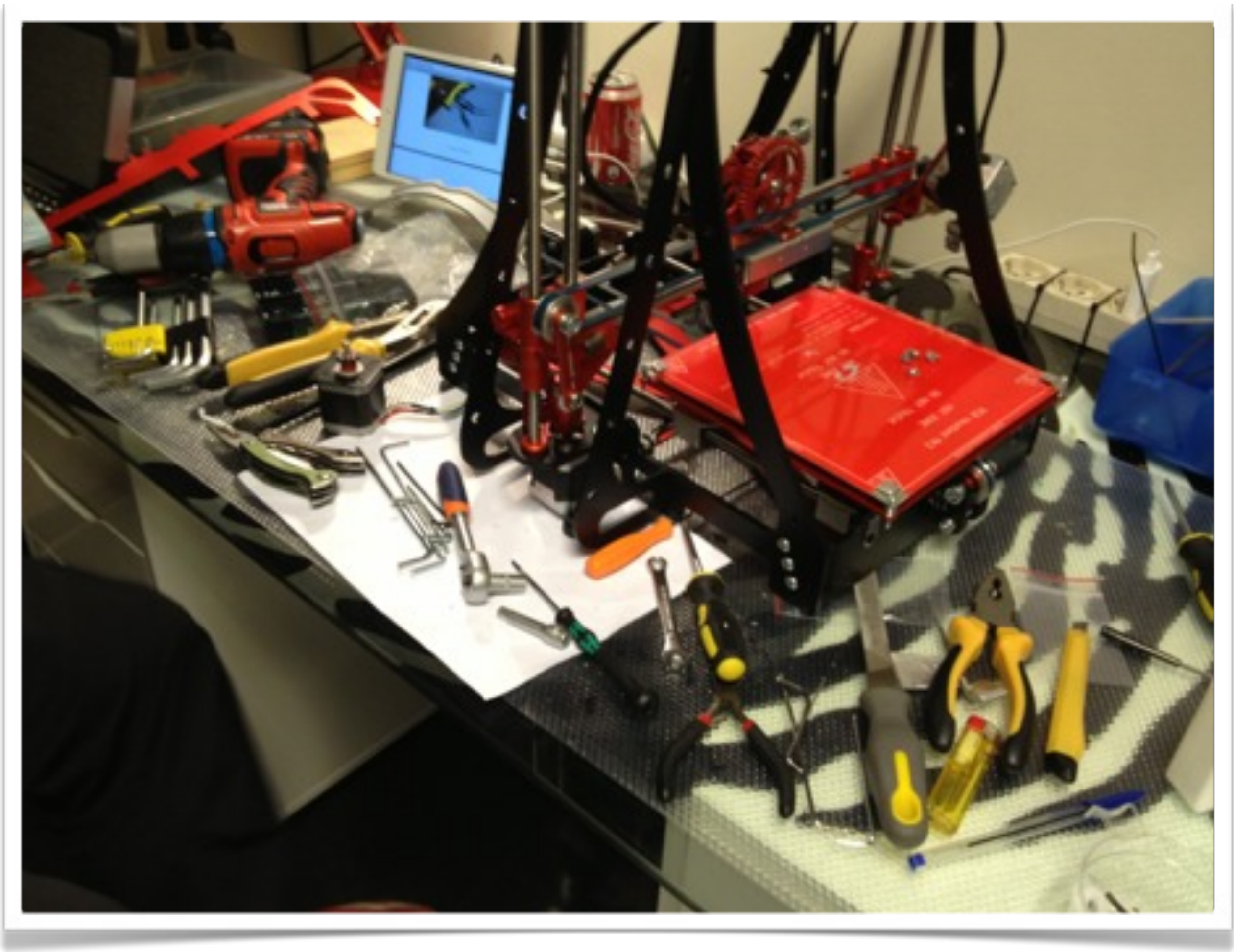
Checking the contents of the complete kit is extremely important and will save money and time when you will actually get down to assemble it.

Assembly of the Ultimaker

Conclusions

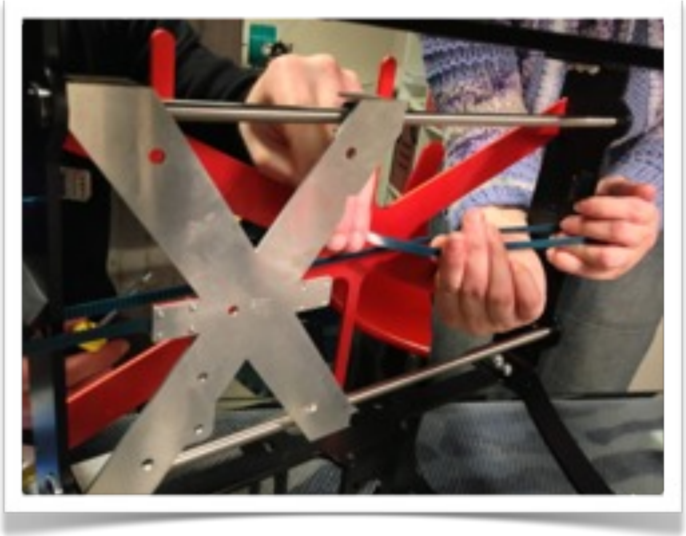
When the excitement of the unpacking fades away and in front of you there is a huge pile of pieces that should sum up to a working machine the sensation can be undoubtedly of fear, or at least of being inadequate. But if you just have the time and patience to build your 3D printer this would be the best choice in comparison to buying a pre-assembled model. The printer will probably need frequent tuning and adjusting, and occasionally substitution of components or maybe an upgrade of some parts. Building it by ourselves gives us the knowledge of the machine needed to tackle all these future problems, and will be a great help when we will decide to improve its feature set.

While buying a pre-assembled machine will certainly cut down the time before we start printing and make things easier in the beginning, it will certainly not help to solve all the future problems that will arise.



The large set of tools used to assemble the CB-printer

As a word of caution, if you are unsure of your assembling skills bear in mind that the manufacturer warranty might be different for the pre-assembled or user-assembled versions, as stated in one vendor's website[12]: *"Please understand that we can, and will not guarantee correct operation of the user-assembled end-product."*



When two hands aren't enough

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[2] http://www.indiegogo.com

[3] http://www.kickstarter.com/projects/1682938109/robo-3d-printer

[4] http://cubify.com/cube/

[5] http://www.pp3dp.com

[6] http://hothardware.com/Reviews/The-Definitive-3D-Printer-Roundup-Cubify-Up-Solidoodle/?page=2

[7] http://therealtonystark.blogspot.ca/2013/04/solidoodle-2-review.html

[8] http://www.solidoodle.com

[9] http://wiki.ultimaker.com/Mechanics_build_guide

[10] http://cb-printer.com/pl/

[11] http://wiki.ultimaker.com/Mechanics_build_guide

[12] Ultimaker kit disclaimer: https://shop.ultimaker.com/en/ultimaker-kits/ultimaker-kit-new.html?options=cart

Reprap, Slic3r and the Future of 3D Printing

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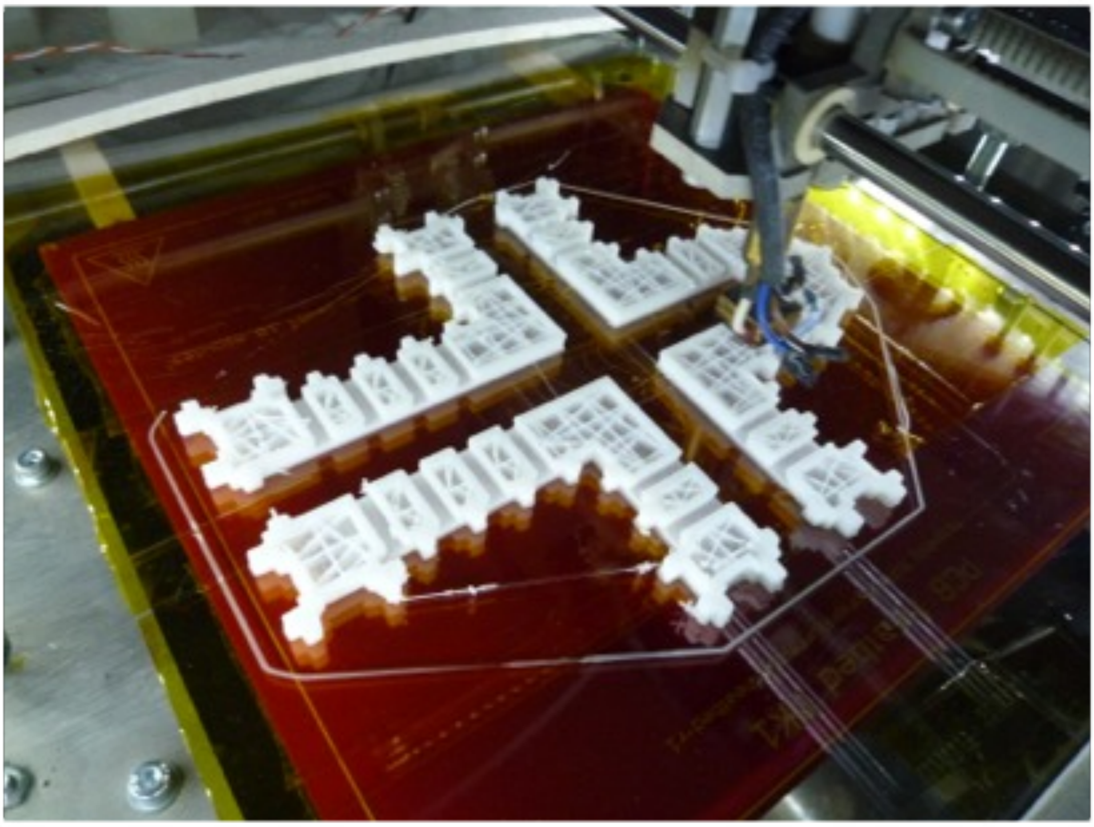
Brief chronology of the RepRap project

The RepRap project began in 2004, when Adrian Bowyer, senior lecturer at the University of Bath, proposed his idea of a self-replicating machine able to produce most of the parts required to build another similar one. The main challenge was to find a technology suitable for creating mechanical and structural parts as well as electronics and belts. Rapid prototyping technology had existed for many years and it required expensive, patented professional machines which used additive techniques for creating solid objects. However, the usage of such machines was only acceptable for creating the parts for the first machine, so the machine itself needed a low-cost and simple technology for doing the same and producing 'children' machines.

Bowyer's idea had great success and a small team started working on the project. They were mostly located physically at the University of Bath. Between 2006 and 2008 the first prototype was designed that was able to print its own parts: the RepRap Darwin. Other versions followed that one (the Mendel and the Huxley), but the context was changing. In 2010 there was a quite large community around the project, exchanging designs and feedback using the Internet. The RepRap project started evolving independently from the central team. People started experiments on several subcomponents of the machine: frame, electronics, software, printable materials, printable objects. The project didn't have a single direction anymore, and no more official machines were published by the original team.

This situation was actually the second, unofficial, goal of Dr. Bowyer: starting a natural, darwinian process of spontaneous and diffuse evolution. Each individual selected some items introduced in the project by other people and discarded other ones: this is an evolution process indeed. In modern 3D printers we could recognize the contributions of tens of people in each part –electronics, filament drive and everything else– spontaneously selected by quality, convenience, machining ease, resistance, versatility.

An important change happened in fall 2011, when the young Josef Prusa published his 'Prusa Mendel' printer. He said it was the 'Ford Model T' of 3D printing, because it provided a strong simplification of frame parts. The Prusa Mendel mostly required items commonly available at local stores and quickly became the most famous printer in the world.



A RepRap printer printing an architectural model in ABS

The RepRap project today

The effects of the quick spread of the RepRap project in the world are great and affect much more than the strict community involved in the project itself. The availability of such low-cost machines allowed other projects to start, inspired the 'makers' movement, helped the diffusion of fablabs and prototyping boards such as the Arduino, and it even started an economy: parts or filament manufacturers, assembled printers or kits vendors, on-demand print services, support centers, courses, and even shops.

Tens, or even hundreds, of printers exist today. They're all derived from the RepRap project by the darwinian evolution described above. Some of these are sold by companies, others are totally open source and are thus available for anyone who wants to source the parts locally and build them.

The RepRap project at large is very active thanks to thousands of active people, but it totally lacks any kind of centralization, or guidelines, or common goal, or official designs. The IRC chat (#reprap on FreeNode) and the official forum are the preferred communication channels, while the project blog continues to document some of the main news coming from the community. Even the wiki, despite being one of the most collaborative tools, doesn't contain enough documentation to track every development happening in the RepRap area.

RepRep doesn't really identify a project anymore, but an ecosystem where many subjects act following the open hardware principle and using the free, open, copyleft licenses to exchange knowledge.

Characteristics of RepRap 3D printers

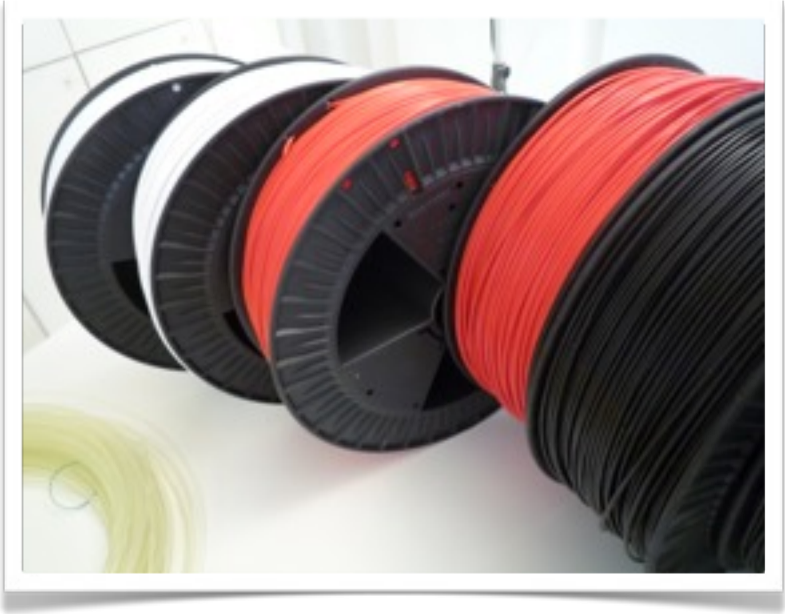
The RepRap printers are based on the Fused Filament Fabrication technology, which identifies the process of melting plastic filament and applying the fused material on top of other layers made of the same material. These printers are very similar in terms of hardware. A tool is moved in space by a cartesian or non-cartesian system able to reach any XYZ point inside the build volume. This tool is an extruder that melts thermoplastics and pushes them through a small orifice to build the object layer by layer. These machines usually work on 20-30cm^3 build volumes, although is not very difficult to build larger ones to print larger objects. However, there are a few issues with larger prints: thermal shrinkage tends to crackle or warp large objects, especially with ABS, and printing times would reach several days which is often a risk since any failure would lead to restarting the whole print. Operators usually split larger objects in handier chunks that can be assembled together.

While the base principle is common to all printers, the mechanics was developed according to any possible combination: fixed build plate, or sliding along one axis, or moving along two axes or even three. Cartesian bots, having a motor for each axis, are sometimes being replaced with the new 'delta robot' concept that was introduced recently where three arms at 120° are joined with universal joints.

A large variety of electronics is also available: there are many mature choices, including Arduino-based solutions and ad-hoc boards based on Atmel or ARM chips. The main goals of the research about electronics have been several so far: cost, thermal optimization, ease of self-manufacturing, support for LCD displays or SD card readers, support for many extruders, modularity, computing power.

Most available boards are open source and their development is usually supported by companies selling them.

Materials used in Fused Filament Fabrication are under constant evolution too. Several thermoplastics are available, including PLA (derivative of corn starch or sugarcane), ABS (well-known plastic used in most industrial products), nylon, polycarbonate. A 'wood' filament is also available. These materials have different physical and mechanical properties, and their melting temperatures span from 170°C to 300°C, according to material, color, manufacturer. Note that the evolution of printable materials is driven by industrial investments of commercial companies serving the 3D printing market. Community is not involved in such experiments, and almost no open source philosophy is applied to material manufacturing.

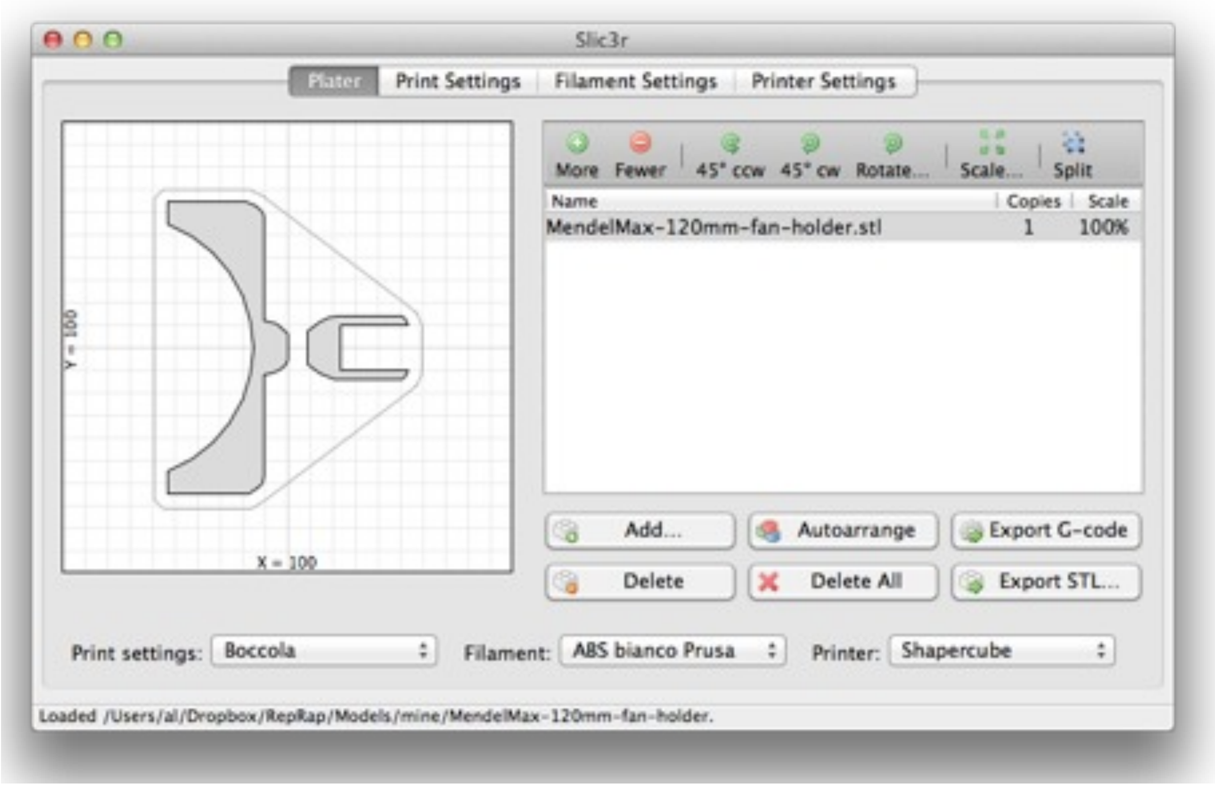


Spools of 3mm PLA for RepRap printers

The birth of Slic3r

While mechanics and electronics are fundamental parts of 3D printing and affect its speed, capabilities and precision, software is an essential complement. Without software, such machines could not move or do anything. Machine logic resides in software, as it defines the needed strategy for coordinating motors, extruder, fans in order to produce the desired result. Software is responsible for making the final result match the expectations of the operator.

Slic3r was born at the end of 2011 as an effort to replace the existing software, not suitable anymore for the development of the RepRap project. A better tool was needed to match the ease of use and real-world applications of the general user base, which included many people not belonging to the strict community, and to match the speed of development of mechanics of electronics. Software was the bottleneck as it didn't allow to fully benefit from new developments. One example was the processing speed: while the evolution of other components (belts, motors, stepper drivers, bushings) already led to a high precision and good regular filaments were already available for purchase, processing a detailed print (for example, at 0.1mm layer height) took several hours. This required long waits between one test and the next one, discouraging good calibration. The lack of good software caused a missed evolution on the side of high-resolution printing. Note that processing speed wasn't actually among the first goals of Slic3r; however it proved to be fast enough (about 100x the previous one) and community started to benefit from it to test their printers with high-resolution prints, thus raising the quality bar.



The graphical interface of Slic3r. After positioning models on the build plate, the operator selects the profiles to apply to the slicing job

The main goal driving Slic3r development was to have a well-written software and not the result of patches; clean commented code, as well as a test suite, would have been the basis for faster development and testing of new ideas, thus matching the evolution on the hardware side. Ease of use was among the original goals too, as users needed a clean interface with only a limited number of options to print well regardless of the large variety of hardware setups. Slic3r did reach this goal, making 3D printing easy and accessible for most people: good results were achievable by just setting some values that were easy to understand and measure. However, the need for more configuration options arose lately to support new features and match the growing expectations of the user base (stimulated by the existence of Slic3r itself).

The impact of Slic3r in 3D printing world went beyond the reduction of processing time. Several original features enabled community to work on new ideas, such as machines equipped with two extruders or more. This technique allows to make multicolor or multimaterial objects; using multiple materials in single print allows for a more removable support material. One more application of the multiextruder features is the usage of a nozzle with small orifice for external visible details and a nozzle with a larger orifice for faster internal infill.

More original features of Slic3r include the ability to save time and material. Printing time can be saved by printing internal infill at thicker layer height but still using low layer heights for visible parts. Material usage can be reduced by configuring Slic3r in order to only put infill where required to support the ceiling of the object. One more feature was added lately to enable combining multiple distinct layer heights in the same object.

Last but not least, Slic3r includes an integrated cooling strategy which controls both cooling fans (whose speed is calculated according to the needs) and dynamic printing speed (automatically reduced in little regions).

How Slic3r works

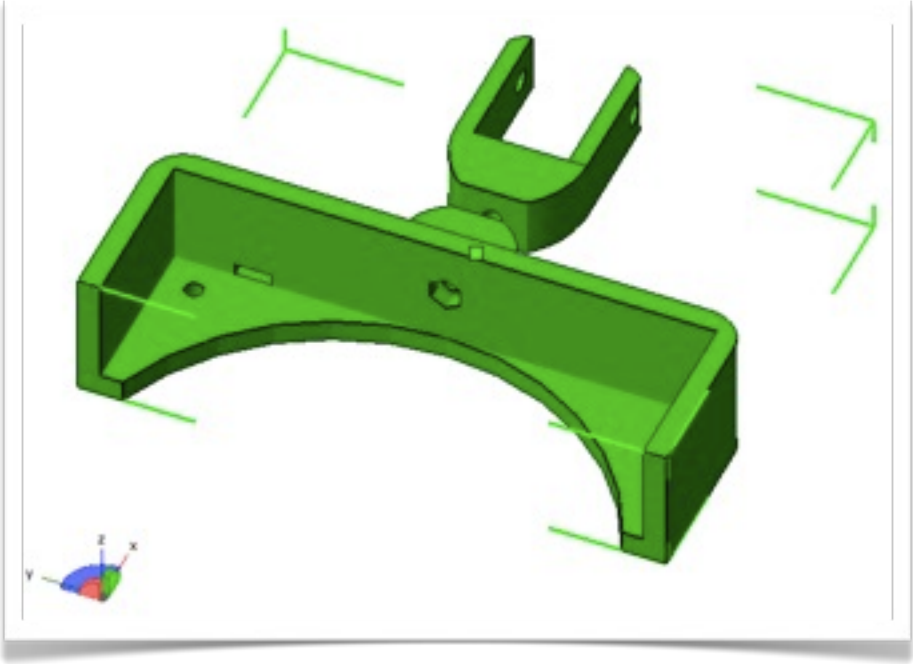
Slic3r belongs to the CAM (Computer Aided Manufacturing) software category, which is the complement to CAD (Computer Aided Design). The object is designed in CAD and then processed with CAM to generate the machining instructions. CAM software knows the characteristics of the single machine and of the specific material being used. Each manufacturing technique requires its own CAM: mills, lathes, 3D printers, *etc*.

The fundamental concept of rapid prototyping technology, included our Fused Filament Fabrication, is the layer. The object is discretized in horizontal layers according to the specified layer height. Thinner layers allow for more resolution (think about the less visible steps on a sloping surface) but require longer printing times. The layer concept enables additive techniques to make any shape, including concave shapes or even closed volumes containing other solids inside; subtractive CNC machines wouldn't be able to make these objects.

After generating the slices of the object, as a set of horizontal section cuts, Slic3r generates the toolpaths for each layer. Also, for each toolpath Slic3r calculates how much material is needed and what speed should be used, as well as how much cooling is required.

Toolpaths are configurable according to several options affecting the wall thickness and internal solidity, expressed in a density factor (a 40% density, thus leaving 60% of volume occupied by air, gives very good mechanical strenght). Other options are also available to affect internal infill, speed, characteristics of support material, temperatures.

Slic3r reads the STL, OBJ and AMF formats which represent solid triangulated meshes. It is important that the input models are valid and two-manifold (this means that their topology must represent a correct and not ambiguous solid, without holes or self-intersections). The output of Slic3r is a G-code file that will drive the machine components.



An STL model of a mechanical part ready to be printed

Community and funding models

The Slic3r project is open source and based on the AGPLv3 license. Development is open and it makes use of collaborative platforms such as an IRC chat channel and a repository on the GitHub platform where each problem or task is tracked. Community provides an excellent distributed smoke-testing system, as hundreds of people test all the changes and report their results back with details and pictures. Errors can be identified and fixed quickly.

The project benefits from crowd-funding happening on two distinct tracks: on one side there are spontaneous donations from end users, while on the other side there are formal sponsorship agreements. Printer vendors and filament manufacturers (most notably LulzBot, who are funding on a monthly basis, but also including TrinityLabs, SeeMeCNC, RepRapDiscount, Wasp and others) contribute to the project funding. Such companies consider the existence of the Slic3r project a critical item of their business, and sponsoring it as open source is a way to lower the financial effort as developing in-house solutions would be more expensive and would not be shared among several subjects. Also, an open source project benefits from the spontaneous contribution of the community.

Open issues and future developments

Support material is one of the highest priorities of the Slic3r project, since in this field professional/commercial 3D printers are still able to produce better results. Support material is the scaffolding that is automatically generated to support overhanging geometries, which wouldn't be printable otherwise without any support below them. For example, the balconies of a building or a human nose in a bust need support material. A dual extruder machine allows to print support with a distinct material (for example, the water-soluble PVA filament or the wood filament which is brittle and easily removable). However, support material is very often generated using the same material as the object: in this case the software needs to find the best compromise between the support effectiveness and its removability. The goal is to be able to remove support with hands and no tools without leaving any visible seam on the printed object.

Speaking of more future goals, Slic3r needs to be optimized for better performance on embedded platforms. The roadmap also comprises a proper and complete graphical environment (IDE) where the operator can change and preview the toolpaths visually. Other goals include support for arcs and NURBS, as well as the support for more rapid prototyping technologies such as DLP and SLS (still not much tested in the open source world, but this is also because of the lack of software for them). Some experiments are also planned to make objects more isotropic by better interlacing layers and to reduce warping problems. One more open issue affects dimensional accuracy: because of several factors, including the different thermal shrinkage of used materials, dimensional errors are often significant, especially for holes having a small diameter. Better models are needed for compensating the thermal behavior.

3D Modeling with OpenSCAD - *Part 1*

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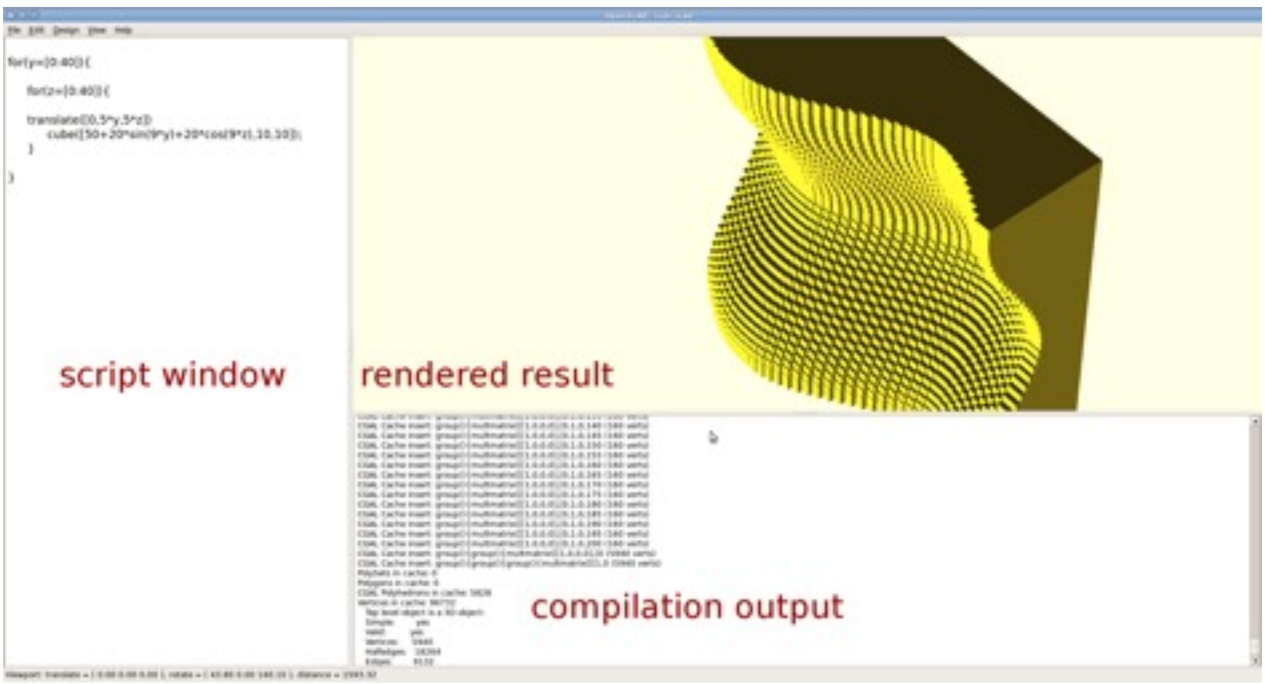
On the way from idea to finished 3D print, there are a number of different steps to perform. Starting with the design of a CAD file or the capture of an existing object, followed by the conversion to an STL file, possibly some post-processing/repair work, and finally to the conversion to a printer-executable gcode file.

Your first steps in 3D printing might be based on 3D designs found on the internet, but when you are getting serious, you will want to design your own, or improve existing designs, rather than just replicating the work of others. We will focus on the design step here –*i.e.*, the production of 3D models and export of STL files.

There are many software tools available, and the following two URLs are good starting points for learning about them:

- http://www.reprap.org/wiki/Useful_Software_Packages
- https://en.wikipedia.org/wiki/Comparison_of_3D_computer_graphics_software



Designing in OpenSCAD

The most popular free and open source software are Blender, POV-Ray, Wings3d and OpenSCAD. OpenSCAD is suitable for anything which may be calculated and generated by code and logic rather than by freehand, mouse moves or light tracing. For the latter ones, Blender or POV-Ray might be your choice.

So when the task is to design objects of which you know the precise measures, or objects that would be cumbersome or impossible to draw, but are readily described by formulas, parameters or series, OpenSCAD is the right tool for you. Its approach to 3D design is based on mathematics and programming.

Quoting from its website http://openscad.org:

> *"Unlike most free software for creating 3D models (such as the famous application Blender) it does not focus on the artistic aspects of 3D modeling but instead on the CAD aspects. Thus it might be the application you are looking for when you are planning to create 3D models of machine parts but pretty sure is not what you are looking for when you are more interested in creating computer-animated movies."*

OpenSCAD is free software, available for Linux/UNIX, MS Windows and Mac OS X, under a GNU GENERAL PUBLIC LICENSE Version 2.

In OpenSCAD, there are two basic modeling techniques:

1. Constructive solid geometry (CSG) is the construction of full 3-dimensional objects, element by element, from script.

2. Extrusion of 2D outlines on the other hand takes existing 2-dimensional shapes, *e.g.* in the form of a DXF file or a simple 2-dimensional shape, and derives the 3D object from this, for example by rotation or elevation.

The resulting 3D file may then be exported in file formats STL or OFF.

STL stands for STereoLithography. It is a format available for export in most CAD programs. An STL file represents an object that you may call "watertight": an object without holes or singularities. While more adventurous objects of course can be imagined and drawn, only a "watertight" object, an object that can be filled with matter, can be printed in real life.

It should be mentioned that exporting to STL can be a problematic process, and it is always a good idea to check results by means of a post-processing and repair tool like Meshlab.

The basic syntax elements of OpenSCAD are variables, modules, functions, inclusions and requirements.

Variables are declared like

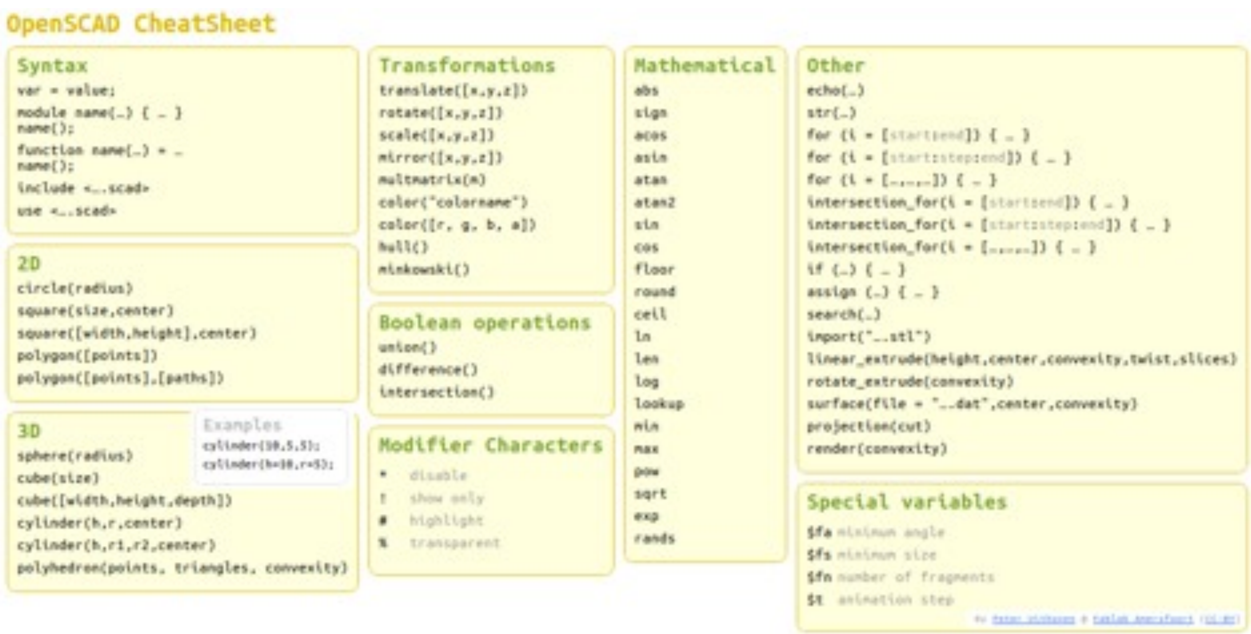
```
myVar = 5+4
```

and may be grouped into vectors/points like this:

```
myVector = [5,4,8];
```

Variables are set once at compile time, and will not change at runtime.

OpenSCAD knows scalar arithmetic operators, relational operators, boolean logic operators and a long list of common mathematical functions. You can create 2D (circle square, polygon) and 3D (cubes, spheres, cylinders) primitives, all of which take parameters like the points introduced above as input, often complemented with resolution/facet parameters and additional instructions.



The OpenSCAD cheatsheet at http://www.openscad.org/cheatsheet/ gives a good summary of all OpenSCAD language elements

The following example code shows the translate transformation and the three basic boolean operations:

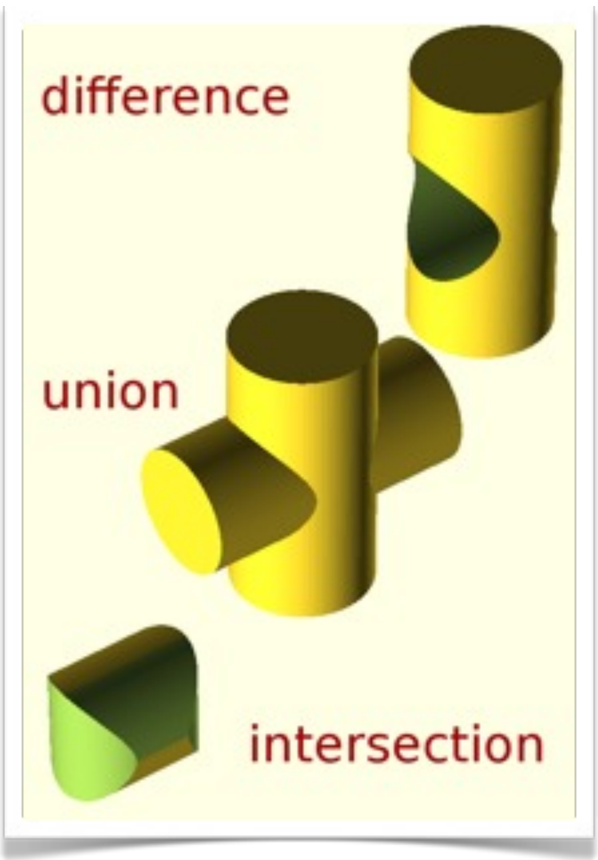
```
union (objects joined together),
difference (cutting one object out of the other);
intersection (the shared space of two objects).
```

Example code of 3 basic transformations:

```
union() {
        cylinder (h = 4, r=1, center = true, $fn=100);
        rotate ([90,0,0]) cylinder (h = 4, r=0.9, center = true, $fn=100);
}

translate([0,3,3])
difference() {
        cylinder (h = 4, r=1, center = true, $fn=100);
        rotate ([90,0,0]) cylinder (h = 4, r=0.9, center = true, $fn=100);
}

translate([0,-3,-3])
intersection() {
        cylinder (h = 4, r=1, center = true, $fn=100);
        rotate ([90,0,0]) cylinder (h = 4, r=0.9, center = true, $fn=100);
}
```



Basic boolean operations

A detailed OpenSCAD User Manual is hosted on wikibooks:

http://en.wikibooks.org/wiki/OpenSCAD_User_Manual

and it supplies all the information you will need in order to design complex objects.

Note: *All URLs in this article visited April 2013.*

3D Modeling with OpenSCAD - *Part 2*

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Some words from the author

OpenSCAD grew out of the RepRap community, more exactly out of the 3D printing activities at the Metalab (http://metalab.at), a hackerspace in Vienna, Austria.

The idea of OpenSCAD was born because we lacked a free software design tool for rapidly and iteratively creating mechanical parts. The existing tools at the time were too time-consuming to use and changing details often required full remodeling. Commercial CAD tools which solve these problems do exist. However, apart from them being prohibitively expensive, they weren't Open Source and we felt that the world needed a better Open Source design tool.The basic idea of OpenSCAD was to allow people to describe their 3D models beginning with basic building blocks, and iteratively build from there. Additionally we wanted it to be possible to parametrically describe shapes and positions in order to facilitate customizations and adaptations without having to go through time consuming and boring remodeling tasks.

Early on, we realized that OpenSCAD would have severe limitations in terms of creating geometric shapes, so we decided to enable users to model more complex building blocks in their software of choice. OpenSCAD can then and import these files for further modeling, while you at any time can go back and change the basic geometry without having to redo the work already done in OpenSCAD. Keeping source code as the user interface also has an important emergent property in that people are enticed to share their designs, as well as their design intentions. This also makes it possible to change, reuse, or in other ways build on the existing ideas and designs of other people.

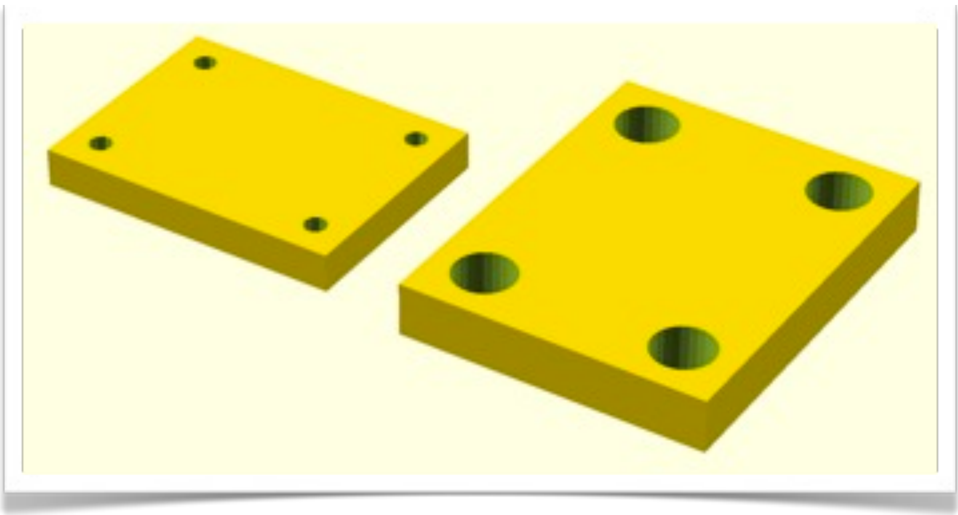
Parametric designs

One of the primary strengths of OpenSCAD is that it supports parametric designs. Parametric in this context means that you can create logical building blocks, which take certain parameters and in return create a 3D component satisfying those parameters. Examples of parameters can be *Object sizes*, *Nut and bolt holes*, *Object descriptors* (*e.g., number of teeth in a gear*) or *Design elements* (text to emboss onto a design).

In OpenSCAD, building blocks are called modules. A module is a type of template, which is defined once and can then be used multiple times with different parameters. The following code defines a module, *TopPlate*, which describes a parametric plate with four screwholes. The module parameters are plate dimensions and screw size. The *TopPlate* module is then instantiated twice:

```
module TopPlate(size, screwsize)
{
  margin = 3;
  offset = screwsize/2 + margin;
  difference() {
    cube(size);
    for (xoffset = [offset, size[0] - offset], yoffset = [offset, size[1] - offset])    {
      translate([xoffset, yoffset, -0.5]) cylinder(r=screwsize/2, h=size[2]+1);
      }
    }
}

TopPlate(size=[40,50,3], screwsize=8);
translate([50,0,0]) TopPlate(size=[40,30,5], screwsize=3);
```



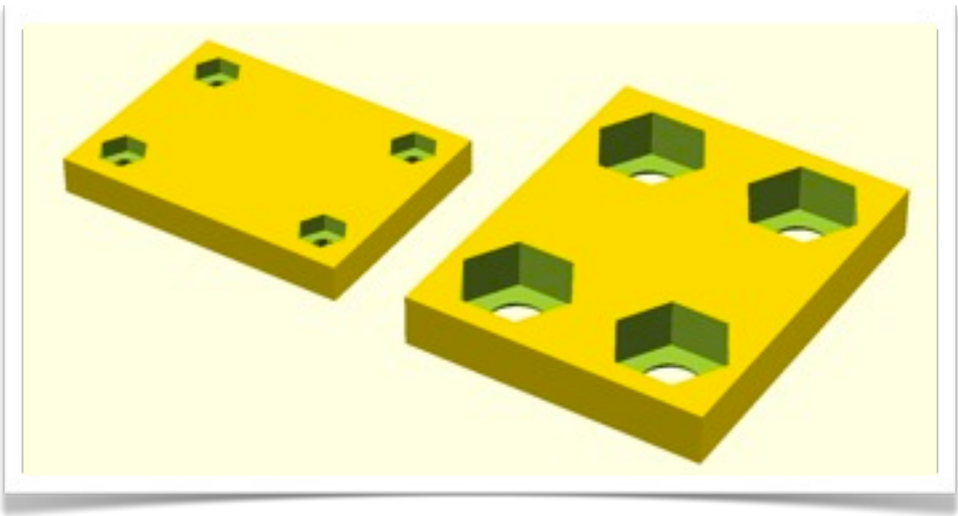
Libraries

A lot of modeling tasks, especially when creating mechanical parts or assemblies, consist of repetitive use of standard elements like fasteners, holes, slots etc. In addition to defining modules that facilitate reuse of component within one design it is also possible to use external *libraries*. OpenSCAD includes a collection of common components in a library called MCAD.

The following example builds on the previous one by adding captive nuts to the existing screw holes, and uses the MCAD library's **nuts_and_bolts** module to get the correct dimensions of the nut corresponding to the screw size:

```
include<MCAD/nuts_and_bolts.scad>
module screwhole(screw, depth)
{
  translate([0,0,-0.5]) cylinder(r=screw/2, h=depth+1);
  translate([0,0,-0.01]) nutHole(size=screw);
}
module TopPlate(size, screwsize)
{
  margin = 2;
  offset = METRIC_NUT_AC_WIDTHS[screwsize]/2 + margin;
  difference() {
    cube(size);
    for (xoffset = [offset, size[0] - offset], yoffset = [offset, size[1] - offset]) {
      translate([xoffset, yoffset, 0]) screwhole(screwsize, size[2]);
    }
  }
}

TopPlate(size=[40,50,7], screwsize=8);
translate([50,0,0]) TopPlate(size=[40,30,5], screwsize=3);
```



As a result of the nature of OpenSCAD designs, libraries are shared simply by sharing the source code of your modules. Many modelers have created component libraries, and have shared them online. There is a number of OpenSCAD libraries on Thingiverse:

http://www.thingiverse.com/search?q=openscad+library

Usage examples

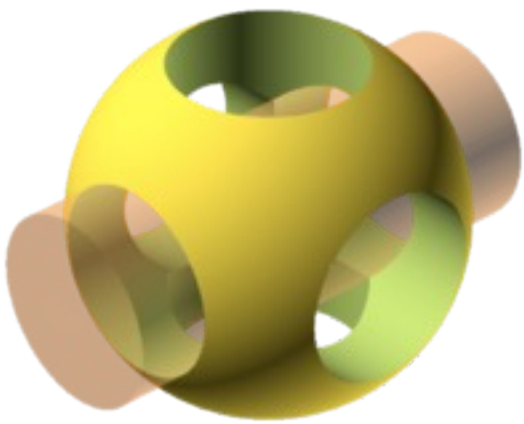
Since OpenSCAD grew out of the early 3D printing and RepRap movement, the user base is still by far the strongest within these communities. As a result, some of the most prominent examples of OpenSCAD usage is the design of 3D printers themselves.

Some examples are:

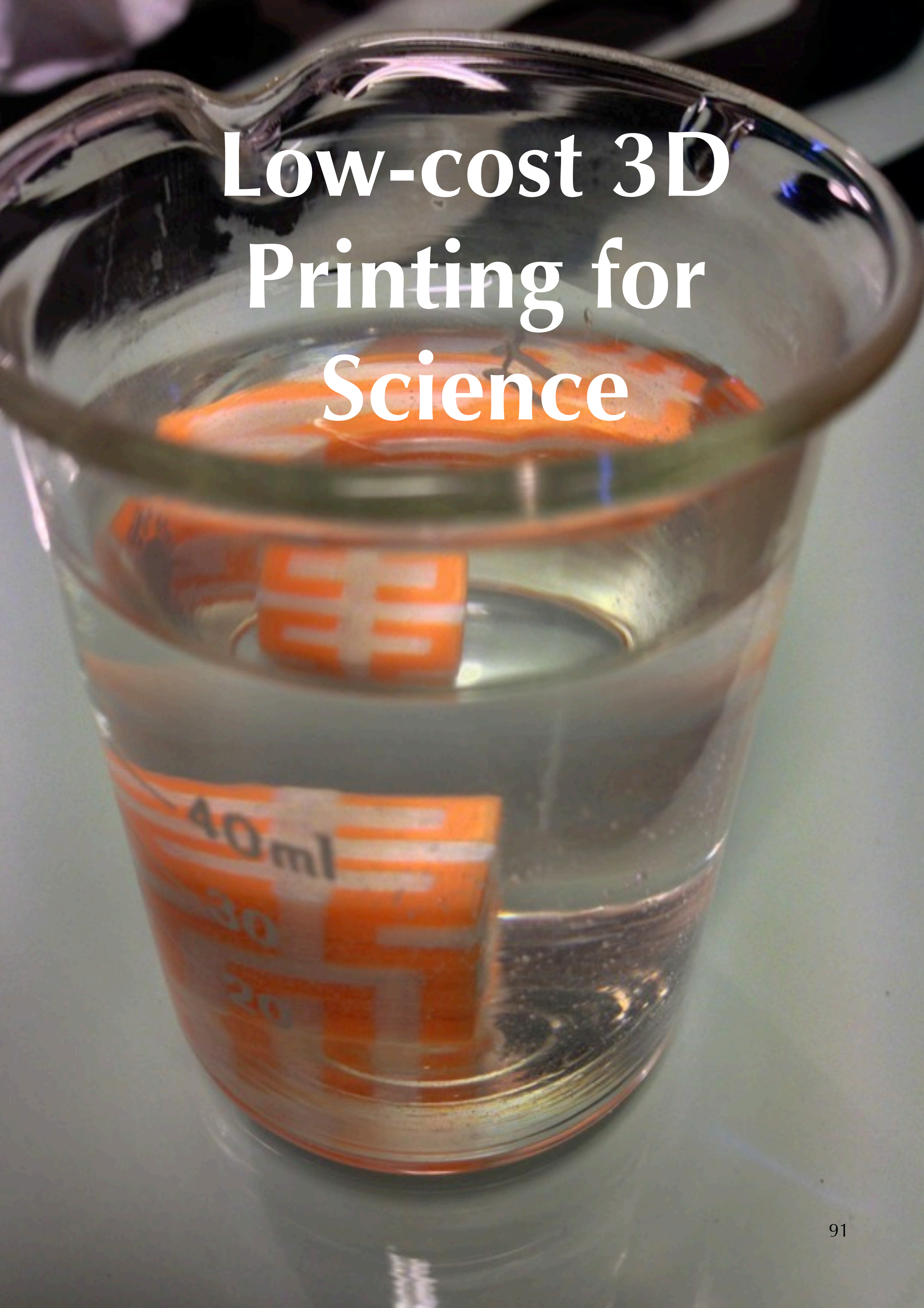
- RepRap Prusa iteration 3:
  https://github.com/josefprusa/Prusa3
- Lulzbot AO-100 (partially):
  http://download.lulzbot.com/AO-100/hardware/printed_parts/source/
- Lulzbot TK-0:
  https://github.com/mswillia/TK-0
- RepRap Mendel90:
  http://hydraraptor.blogspot.co.uk/2012/12/mendel90-updates.html

To find OpenSCAD designs online, the largest repository is Thingiverse:

http://www.thingiverse.com/tag:openscad



Low-cost 3D Printing for Science



Illustrating Mathematics using 3D Printers

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Visualization

Visualization has always been an important ingredient for communicating mathematics. Figures and models have helped to express ideas even before formal mathematical language was able to describe the structures. Numbers have been recorded as marks on bones, represented with pebbles, then painted onto stone, inscribed into clay, woven into talking knots, written onto papyrus or paper, then printed on paper or displayed on computer screens. While figures extend language and pictures allow to visualize concepts, realizing objects in space has kept its value. Already in ancient Greece, wooden models of Apollonian cones were used to teach conic sections. Early research in mathematics was often visual: figures on Babylonian Clay tablets illustrate Pythagorean triples, the Moscow mathematical papyrus features a picture which helps to derive the volume formula for a frustum. Al-Khwarizmi drew figures to solve the quadratic equation. Visualization is not only illustrative, educational or heuristic, it has practical value: Pythagorean triangles realized by ropes helped measuring and dividing up of land in Babylonia. Ruler and compass, introduced to construct mathematics on paper, can be used to build plans for machines. Greek mathematicians like Apollonius, Aristarchus, Euclid or Archimedes mastered the art of representing mathematics with figures[1].

While pictures do not replace proofs –Kline[2] gives a convincing visual proof that all triangles are equilateral– they help to transmit intuition about results and ideas[3] [4]. Visualization is especially crucial for education and can lead to new insight. Many examples of mechanical nature are in the textbook “The Mathematical Mechanic”[5]. As a pedagogical tool, it assists teachers on any level of mathematics, from elementary and high school over higher education to modern research[6] [7] [8]. A thesis of Slavkovsky[9] has explored the feasibility of the technology in the classroom. We looked at work of Archimedes[10] using this technology.

Visualizations helps also to showcase the beauty of mathematics and to promote the field to a larger public. Figures can inspire new ideas, generate new theorems or assist in computations; examples are Feynman or Dynkin diagrams or Young tableaux. Most mathematicians draw creative ideas and intuition from pictures, even so these figures often do not make it into papers or textbooks. Artists, architects, film makers, engineers and designers draw inspiration from visual mathematics. Well illustrated books like [11] [12] [13] [14] [15] [16] advertise mathematics with figures and illustrations. Such publications help to counterbalance the impression that mathematics is difficult to communicate to non-mathematicians. Mathematical exhibits like at the science museum in Boston or the Museum of Math in New York play an important role in making mathematics accessible. They all feature visual or even hands-on realizations of mathematics. While various technologies have emerged which allow to display spacial and dynamic content on the web, like Javascript, Java, Flash, WRML, SVG or WebGl, the possibility to **manipulate an object with our bare hands** is still unmatched. 3D printers allow us to do that with relatively little effort.

3D printing

The industry of rapid prototyping and 3D printing in particular emerged about 30 years ago [17] [18] [19] [20] [21] and is by some considered part of an **industrial revolution** in which manufacturing becomes digital, personal, and affordable [22] [23] [24]. First commercialized in 1994 with printed wax material, the technology has moved to other materials like acrylate photopolymers or metals and is now entering the range of consumer technology. Printing services can print in color, with various materials and in high quality. The development of 3D printing is the latest piece in a chain of visualization techniques. We live in an exciting time, because we experience not only one revolution, but two revolutions at the same time: an information revolution and an industrial revolution. These changes also affect mathematics education [25]. 3D printing is now used in the medical field, the airplane industry, to prototype robots, to create art and jewelry, to build nano structures, bicycles, ships, circuits, to produce art, robots, weapons, houses and even used to decorate cakes. Its use in education was investigated in [9]. Since physical models are important for hands-on active learning. 3D printing technology in education has been used since a while[26] and considered for [27] sustainable development, for K-12 education in STEM projects[28] as well as elementary mathematics education[29]. There is no doubt that it will have a huge impact in education [30] [31].

Printed models allow to illustrate concepts in various mathematical fields like calculus, geometry or topology. It already has led to new prospects in mathematics education. The literature about 3D printing explodes, similar as in the computer literature when PCs entered the consumer market. Examples of books are [32] [33] [34]. As for any emerging technology, these publications might be outdated quickly, but will remain a valuable testimony of the exciting time we live in.

Bringing mathematics to life

To illustrate visualizations using 3D printers, our focus is on mathematical models generated with the help of **computer algebra systems**. Unlike **3D modelers**, mathematical software has the advantage that the source code is short and that programs used to illustrate mathematics for research or the classroom can be reused. Many of the examples given here have been developed for classes or projects and redrawn so that it can be printed. In contrast to “modelers”, software which generate a large list of triangles, computer algebra systems describe and display three dimensional objects mathematically. While we experimented also with other software like “123D Design” from Autodesk, “Sketchup” from Trimble, the modeler “Free CAD”, “Blender”, or “Rhinoceros” by McNeel Accociates, we worked mostly with computer algebra systems and in particular with Mathematica [35] [36] [37] [38] [39]. To explain this with a concrete example, lets look at a **theorem of Newton on sphere packing** which tells that **the kissing number of spheres in three dimensional space is 12**. The theorem tells that the maximal number of spheres that can be placed around a given sphere is twelve, if all spheres have the same radius, touch the central sphere and do not overlap.

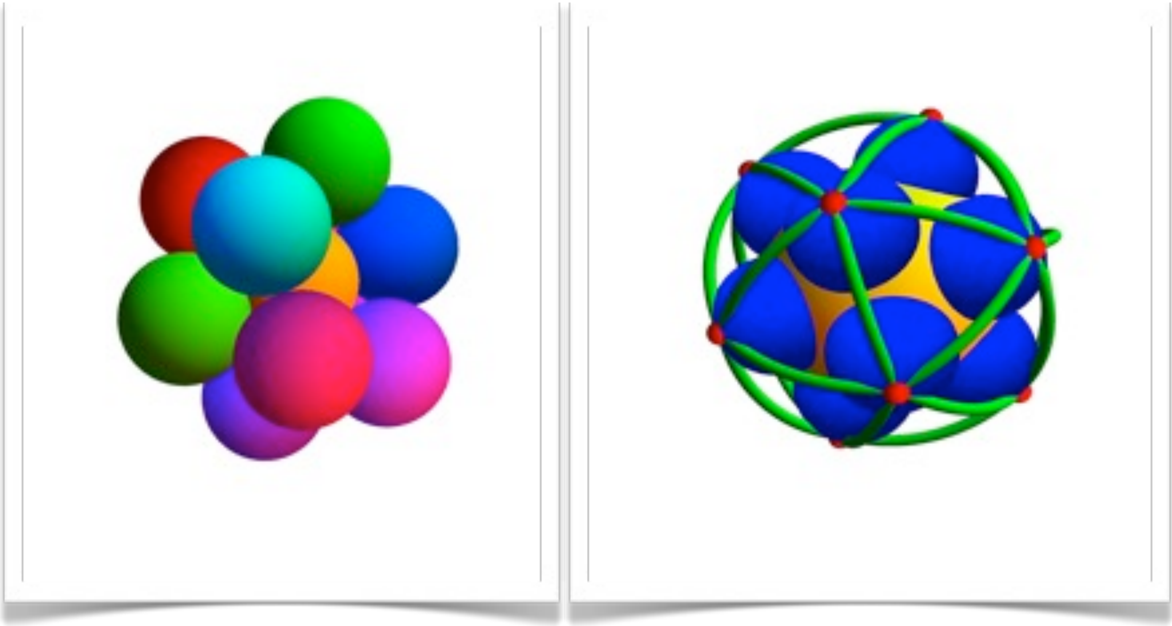
While Newton's contemporary Gregory thought that one can place a thirteenth sphere, Newton believed the kissing number to be 12. The theorem was only proved in 1953[40]. To show that the kissing number is at least 12, take an icosahedron with side length 2 and place unit spheres at each of the 12 vertices then they kiss the unit sphere centered at the origin. The proof that it is impossible to place 13 spheres[41] uses an elementary estimate[42] for the area of a spherical triangle, the Euler polyhedron formula, the discrete Gauss-Bonnet theorem assuring that the sum of the curvatures is 2 and some combinatorics to check through all cases of polyhedra, which are allowed by these constraints. In order to visualize the use of Mathematica, we plotted 12 spheres which kiss a central sphere. While the object consists of 13 spheres only, the entire solid is made of 8640 triangles. The Mathematica code is very short because we only need to compute the vertex coordinates of the icosahedron, generate the object and then export the STL file. By displaying the source code, we have **illustrated the visualization**, similar than communicating proof. If fed into the computer, the code generates a printable “STL” file.

Sustainability considerations

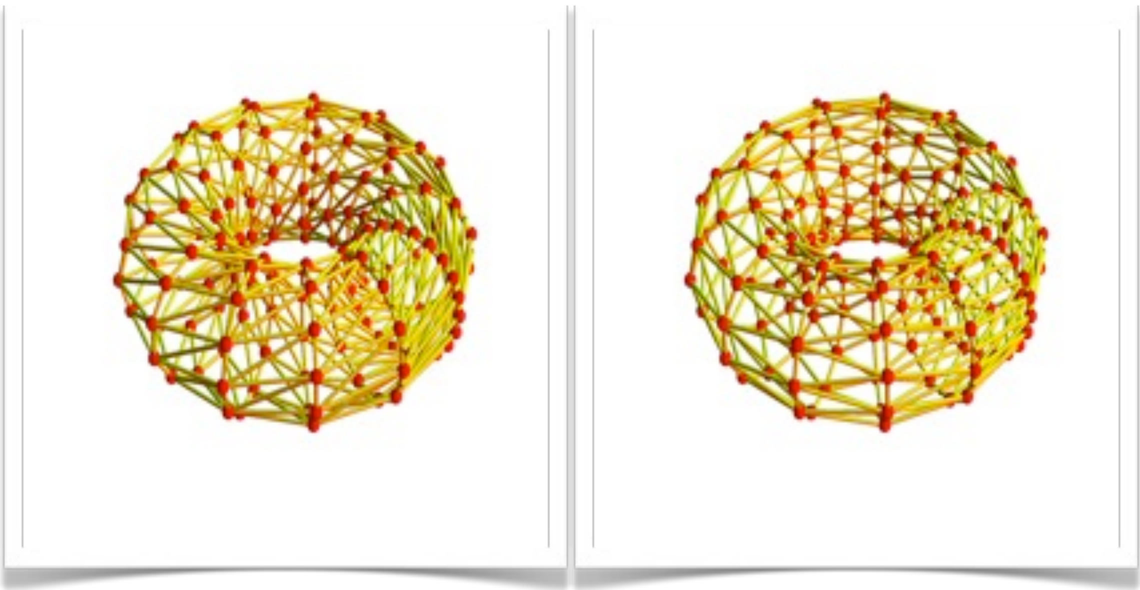
Physical models are important for hands-on active learning. Repositories of 3D printable models for education have emerged[26]. 3D printing technology has been used for K-12 education in STEM projects[28], and elementary mathematics education[29]. There is optimism that it will have a large impact in education[30]. The new technology allows everybody to build models for the classroom -in principle. To make it more accessible, many hurdles still have to be taken. There are some good news: the STL files can be generated easily because the format is simple and open. STL files can also be exported to other formats. Mathematica for example allows to import it and convert it to other forms. Programs like "Meshlab" allow to manipulate it. Terminal conversions like "admesh" allow to deal with STL files from the command line. Other stand-alone programs like "stl2pov" allow to convert it into a form which can be rendered in a ray tracer like Povray. One major point is that good software to generate the objects is not cheap. The use of a commercial computer algebra system like Mathematica can be costly, especially if a site license is required. There is no free computer algebra software available now, which is able to export STL or 3DS or WRL files with built in routines. The computer algebra system SAGE, which is the most sophisticated open source system, has only export in experimental stage[43]. It seems that a lot of work needs to be done there.

Many resources are available however[44] [45] . The following illustrations consist of Mathematica graphics which could be printed. This often needs adaptation because a printer can not print objects of zero thickness.

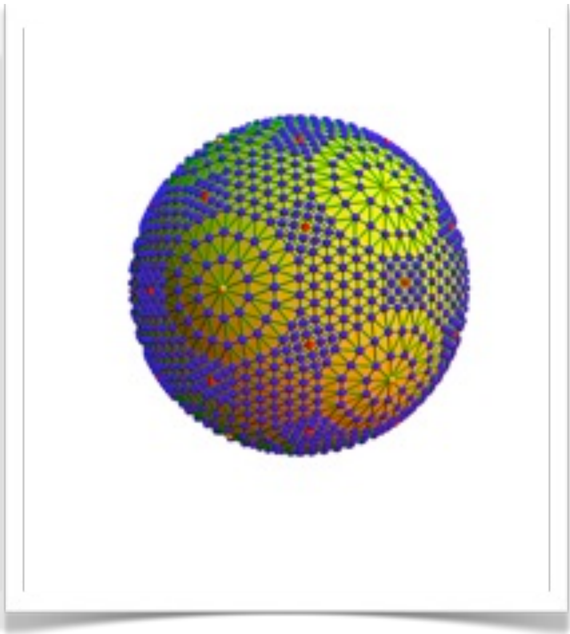
Illustrations



This figure aims to visualize that the kissing number of a sphere is ≥ 12. The Mathematica code producing this object is given in the text. It produces a file containing tens of thousands of triangles which the 3D printer knows to bring to live. The printed object visualizes that there is still quite a bit of space left on the sphere. Newton and his contemporary Gregory had a disagreement over whether this is enough to place a thirteenth sphere.

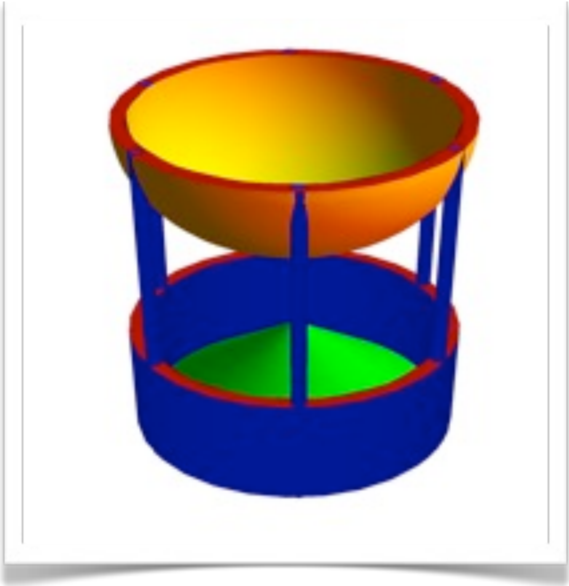
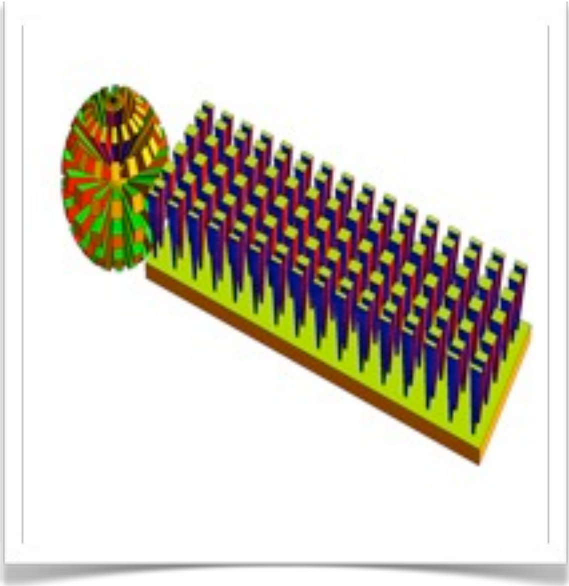


A Dehn twisted at torus and an untwisted torus. The left and right picture show two non-isomorphic graphs, but they have the same topological properties and are isospectral for the Laplacian as well as for the Dirac operator. It is the easiest example of a pair of nonisometric but Dirac isospectral graphs.

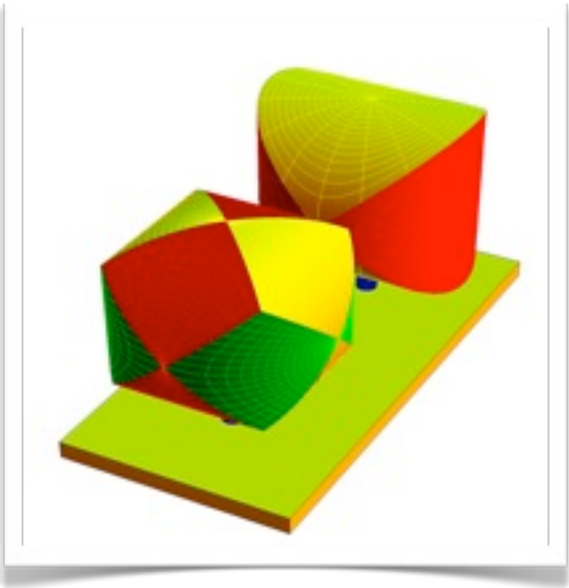


All 26 Archimedean and Catalan solids joined to a "gem" in the form of a DisdyakisDodecahedron. The right figure shows a Great Rhombicosidodecahedron with 30 points of curvature ⅓ and 12 points of curvature -⅔. The total curvature is 2 and agrees with the Euler characteristic. This illustrates a discrete Gauss-Bonnet theorem[46].

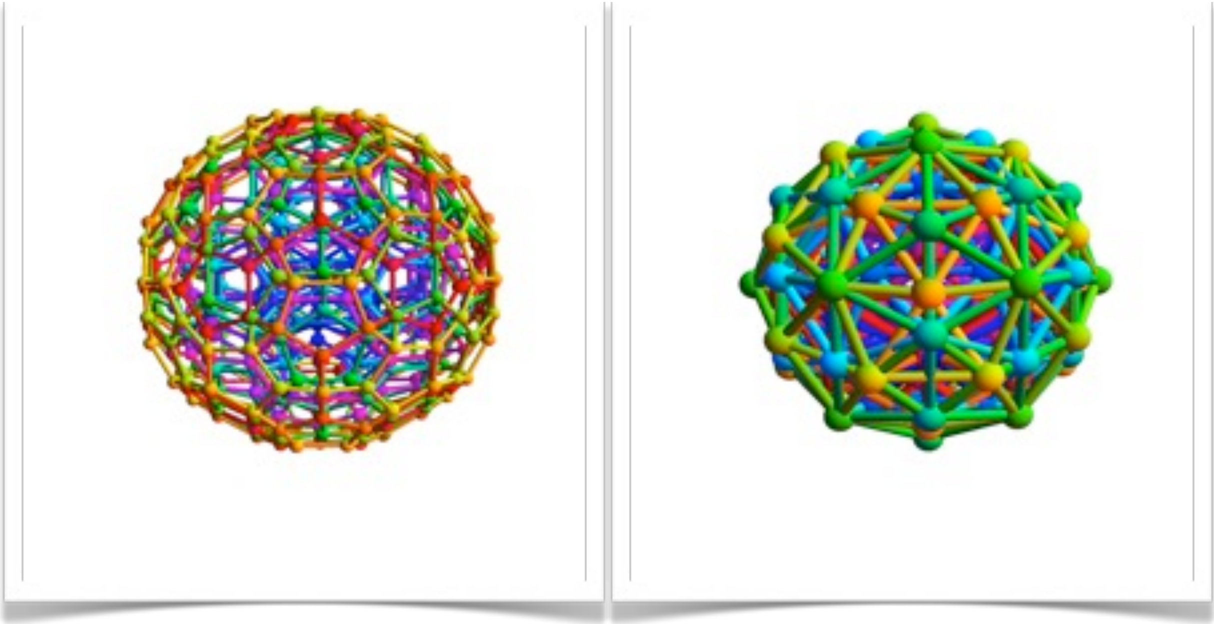
The Antoine necklace is a Cantor set in space whose complement is not simply connected. The Alexander sphere seen to the right is a topological 3 ball which is simply connected but which has an exterior which is not simply connected. Alexander spheres also make nice ear rings when printed.

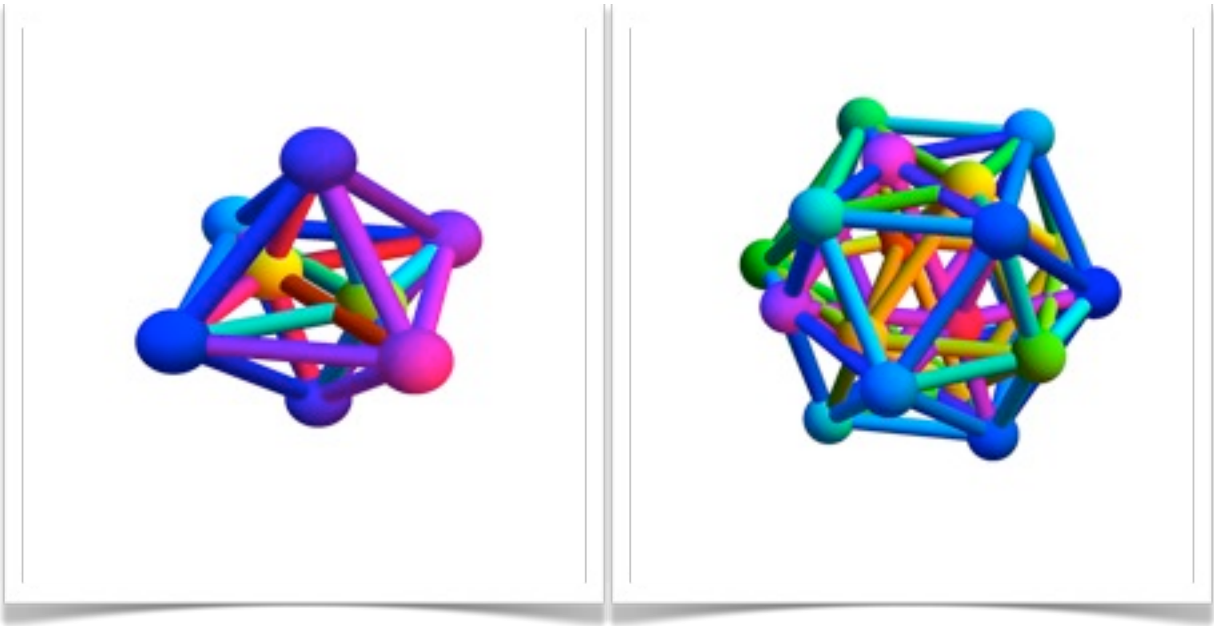
Two Archimedes type proofs that the volume of the sphere is 4π/3 [47] [48] [49]. The first one assumes that the surface area A is known. The formula *V = Ar/3* can be seen by cutting up the sphere into many small tetrahedra of volume *dAr/3*. When summing this over the sphere, we get *Ar/3*. The second proof compares the half sphere volume with the complement of a cone in a cylinder.

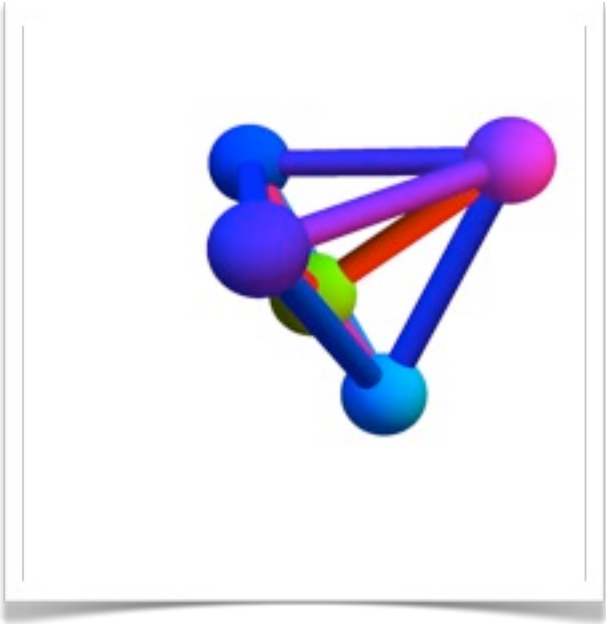
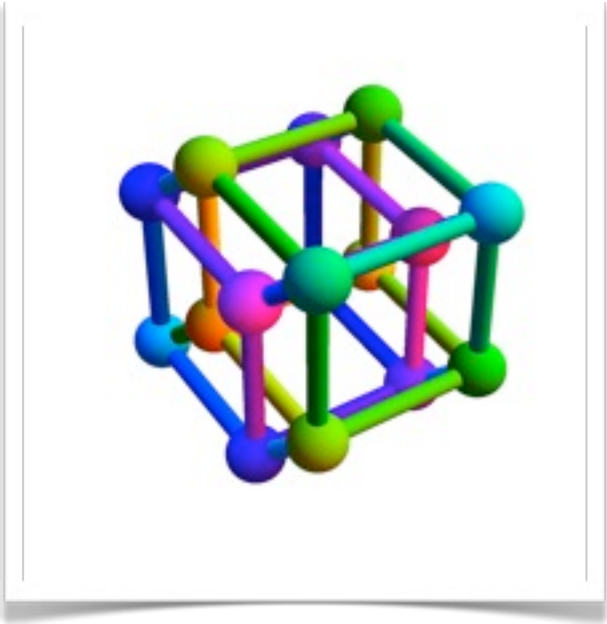
The hoof of Archimedes, the Archimedean dome, the intersection of cylinders are solids for which Archimedes could compute the volume with comparative integration methods[50]. The hoof is also an object where Archimedes had to use a limiting sum, probably the first in the history of humankind[51].



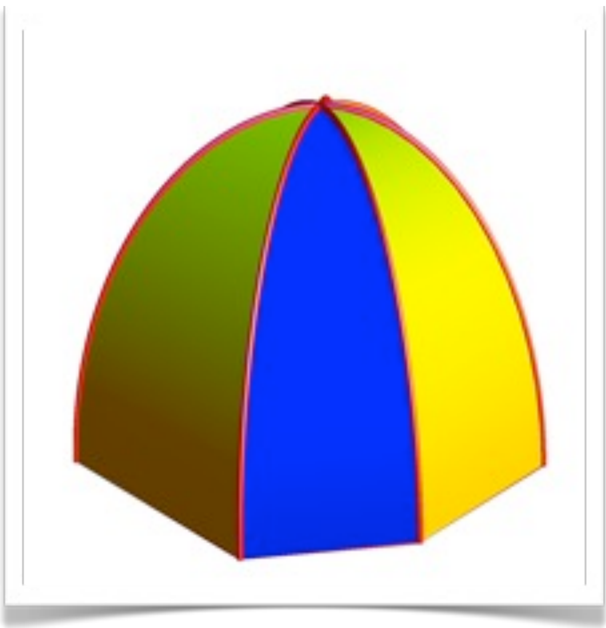
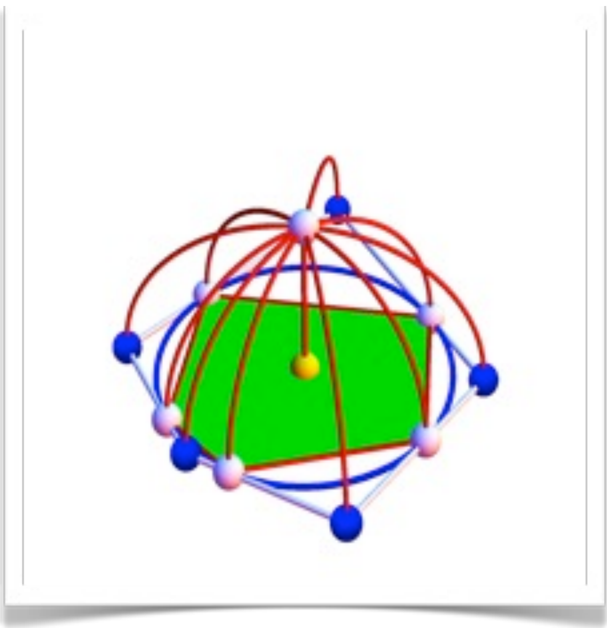
Two of the 6 regular convex polytopes in 4 dimensions. The color is the height in the four-dimensional space. We see the 120 cell and the 600 cell.



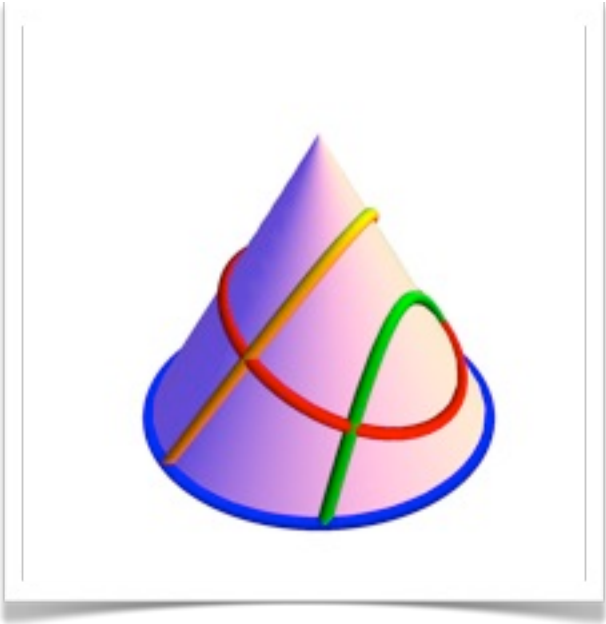
An other pair of the 6 regular convex polytopes in 4 dimensions. The color is the height in the four-dimensional space. We see the 16 cell (the analogue of the octahedron) and the 24 cell. The later allows to tessellate four-dimensional Euclidean space.

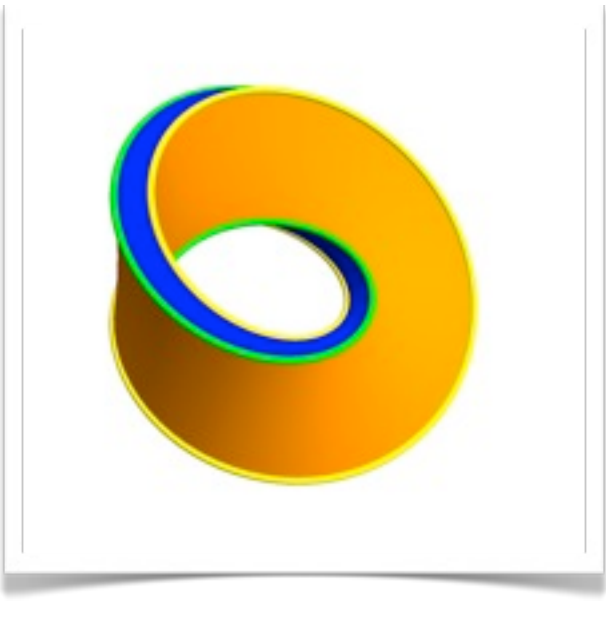
The 5 cell is the complete graph with 5 vertices and the simplest 4 dimensional polytop. The 8 cell to the right is also called the tesseract. It is the 4 dimensional analogue of the cube.

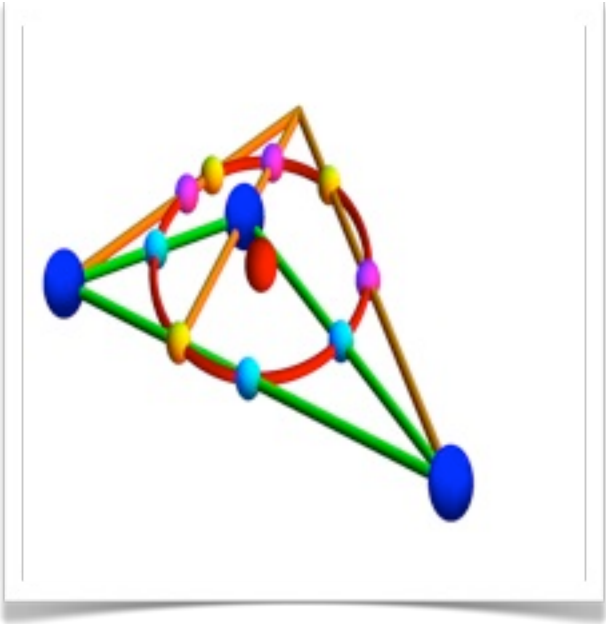
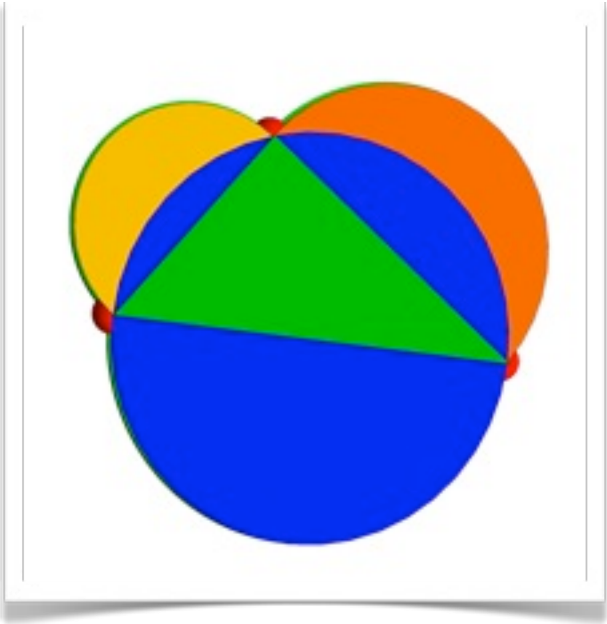
The Archimedean domes are half of Archimedean spheres. They have volume equal to ⅔ of the prism in which they are inscribed. It was discovered only later that for Archimedean globes, the surface area is ⅔ of the surface area of a circumscribing prism[50].



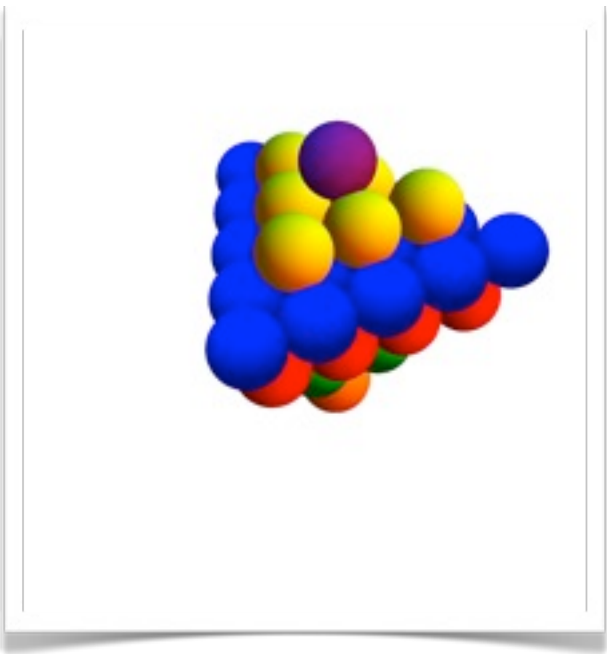
An Apollonian cone named after Apollonius of Perga is used to visualize the conic sections. Wooden models appear in school rooms. The right figure shows an icon of Chaos, the Lorentz attractor[52]. It is believed to be a fractal. The dynamics on this set is chaotic for various parameters.



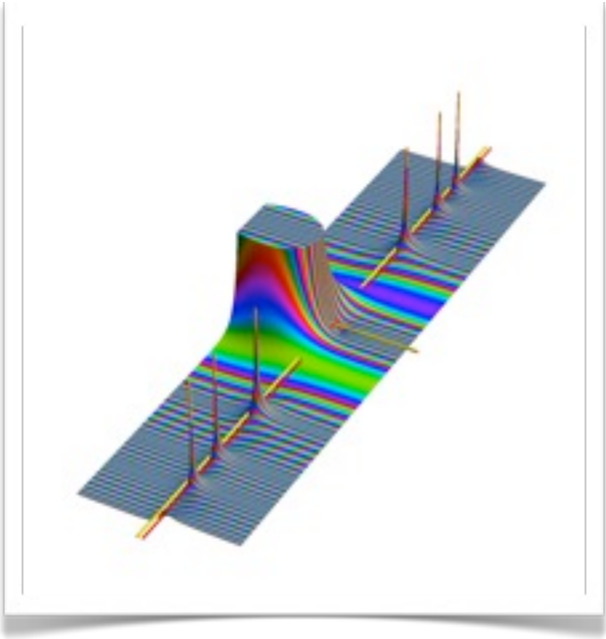
The Möbius strip was thickened so that it can be printed. The right picture shows a Möbius strip with self intersection. This is a situation where the computer algebra system shines. To make a surface thicker, we have have to compute the normal vector at every point of the surface.

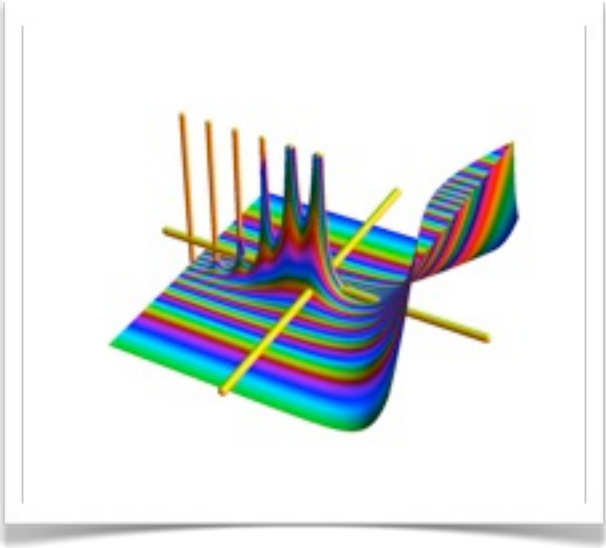
 

The nine point theorem of Feuerbach realized in 3D. The right figure illustrates the theorem of Hippocrates, an attempt to the quadrature of the circle. The triangle has the same area than the two moon shaped figures together.

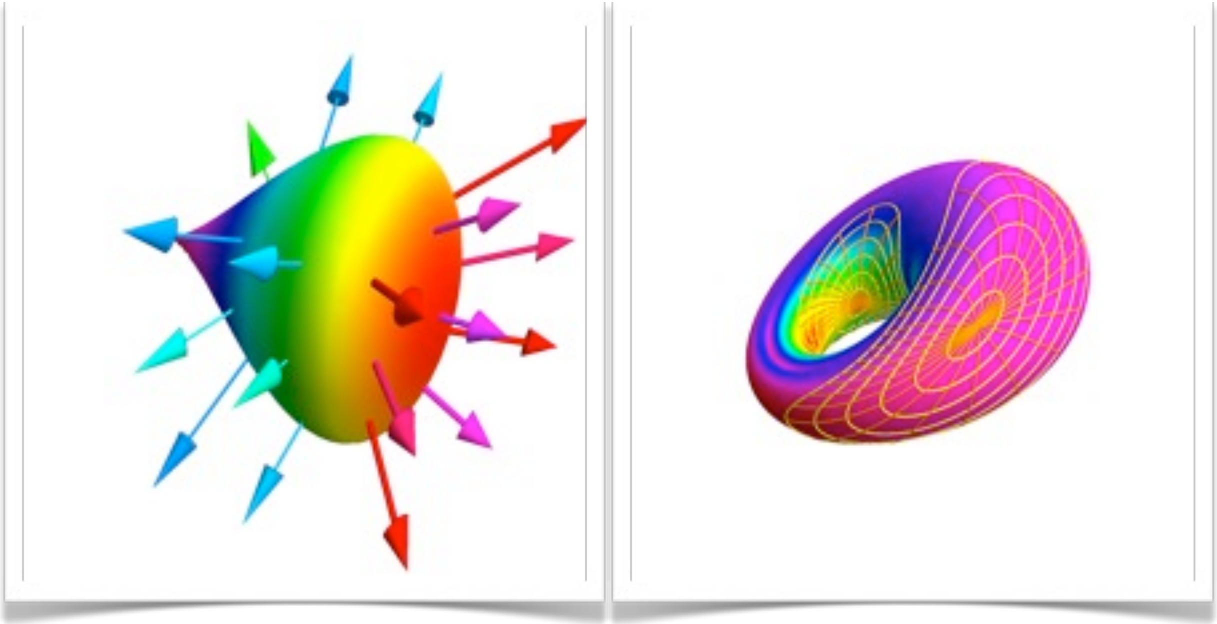
The left figure shows the Soddy's Hexlet. One needs conformal transformations, Möbius transformations in particular to construct this solid. The right figure hopes to illustrate that there are in infinitely many densest packings in space. While there is a cubic close packing and hexagonal close packing, these packings can be mixed.



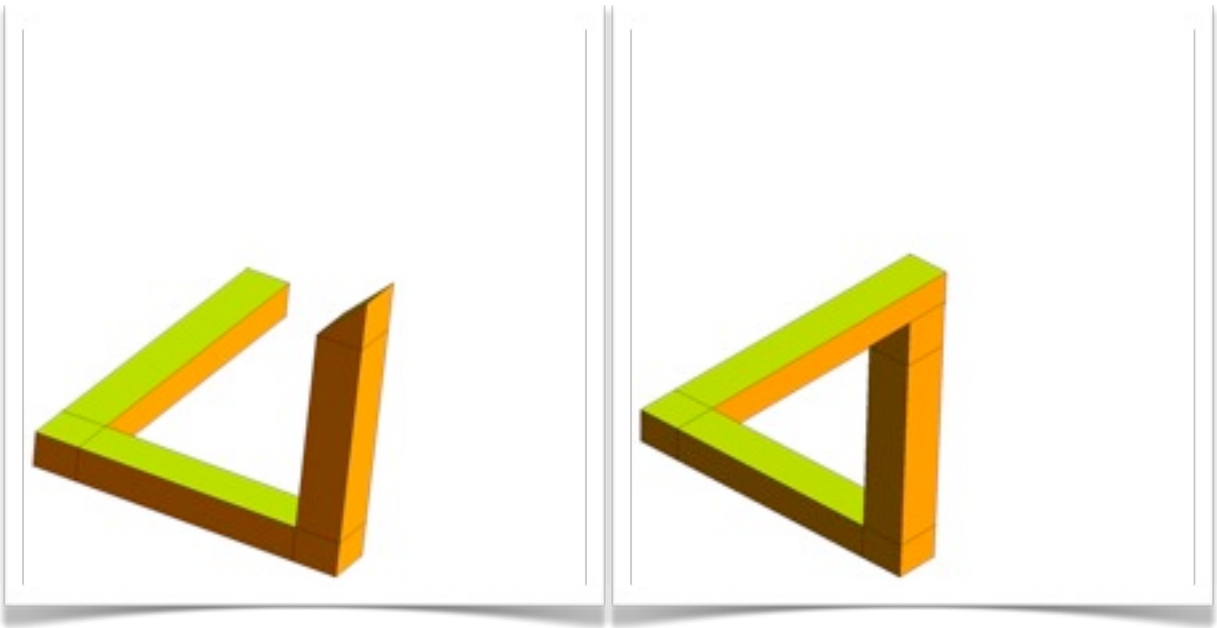


The graph of $1/|\zeta(x+iy)|$ shows the zeros of the zeta function $\zeta(z)$ as peaks. The Riemann conjecture is that all these roots are on the line $x = ½$. The right figure shows the Gamma function which extends the factorial function from positive integers to the complex plane $\Gamma(x) = (x - 1)!$ for positive x. These graphs are produced in a way so that they can be printed.

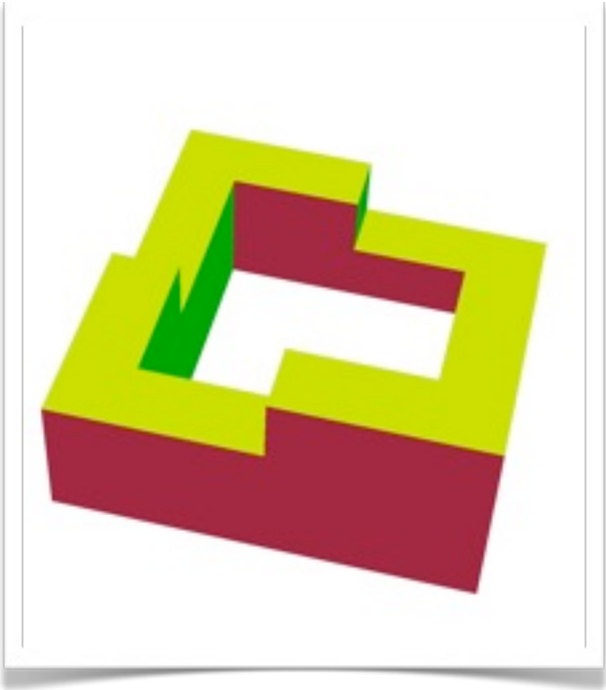
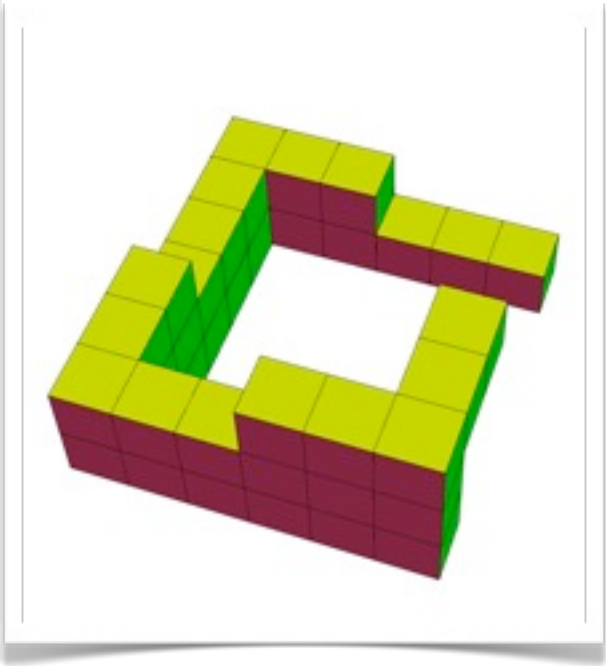
Two figures from different areas of geometry. The first picture allows printing an aperiodic Penrose tiling consisting of darts and kites. To construct the tiling in 2D first, we used code from [37] section 10.2. The second figure is the third stage of the recursively defined Peano curve, a space filling curve.



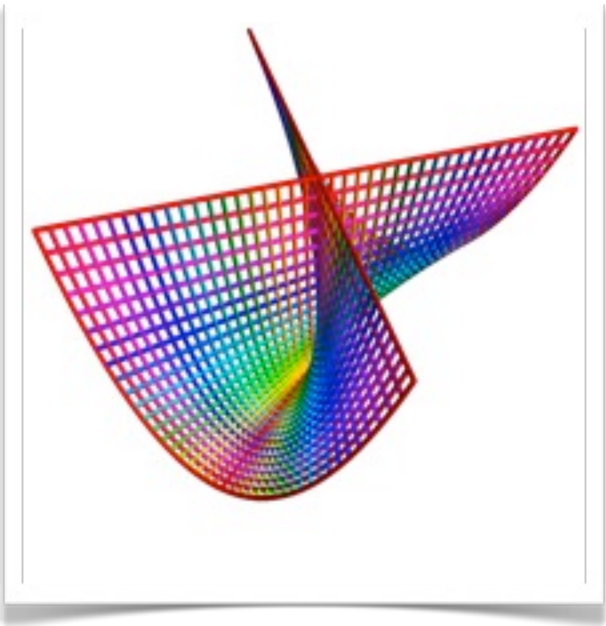
An illustration of the theorem in multivariable calculus that the gradient is perpendicular to the level surface. The second picture illustrates the exponential map in Riemannian geometry, where we see wave fronts at a point of positive curvature and at a point of negative curvature. The differential equations are complicated but Mathematica takes care of it.



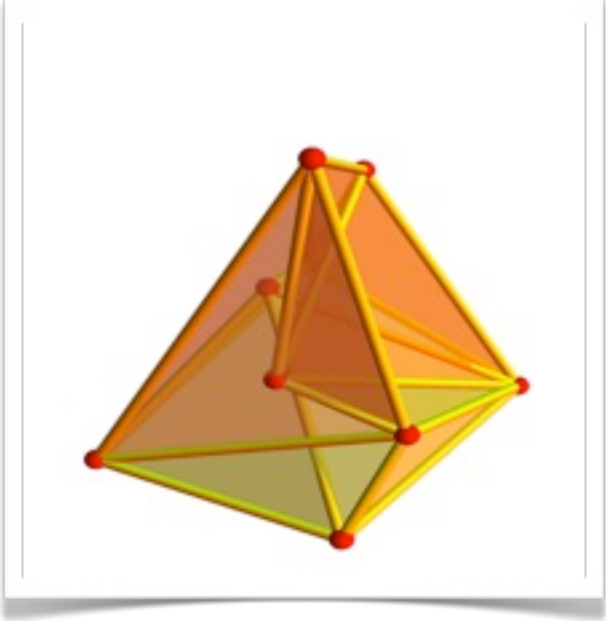
Printing the Penrose triangle. The solid was created by Oscar Reutersvard and popularized by Roger Penrose[53]. A Mathematica implementation has first appeared in [36].

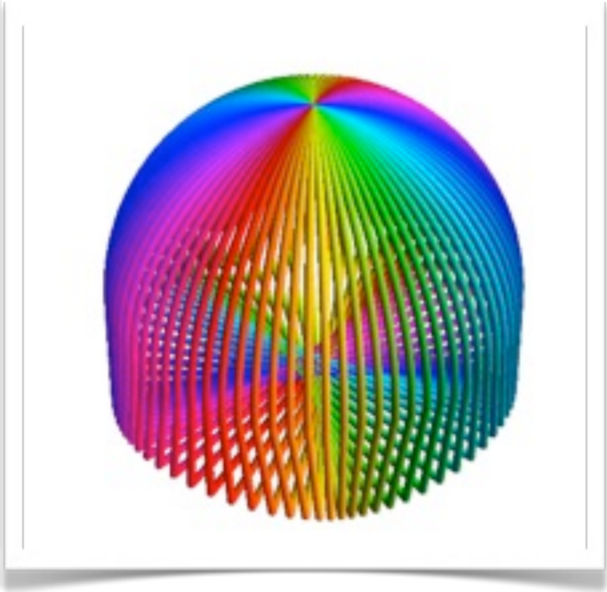



Printing a simplified version of the Escher stairs. If the object is turned in the right angle, an impossible stair is visible. When printed, this object can visualize the geometry of impossible figures.

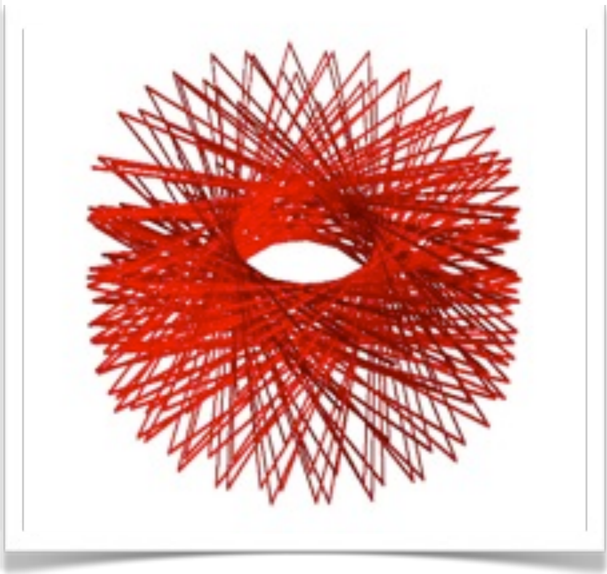



The Whitney umbrella is an icon of catastrophe theory. This is a typical shape of a caustic of a wave front moving in space. To the left, we see how the surface has been thickened to make it printable. On the right, the grid curves are shown as tubes. Also this is a technique that is printable.

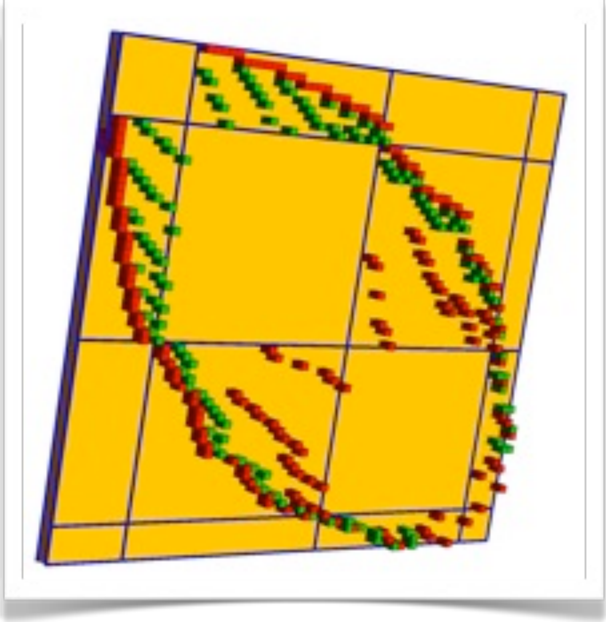




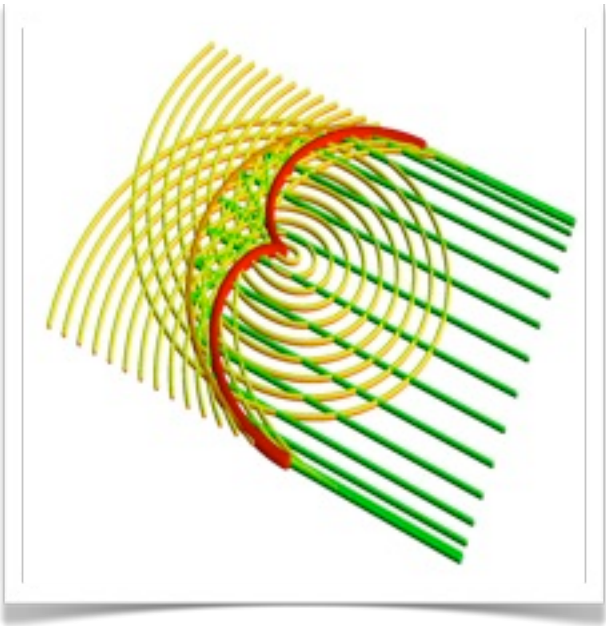
The left figure shows the Steffen polyhedron, a flexible surface. It can be deformed without that the distances between the points change. This is a surprise, since a theorem of Cauchy tells that this is not possible for convex solids[54]. The right picture illustrates how one can construct caustics on surfaces which have prescribed shape.



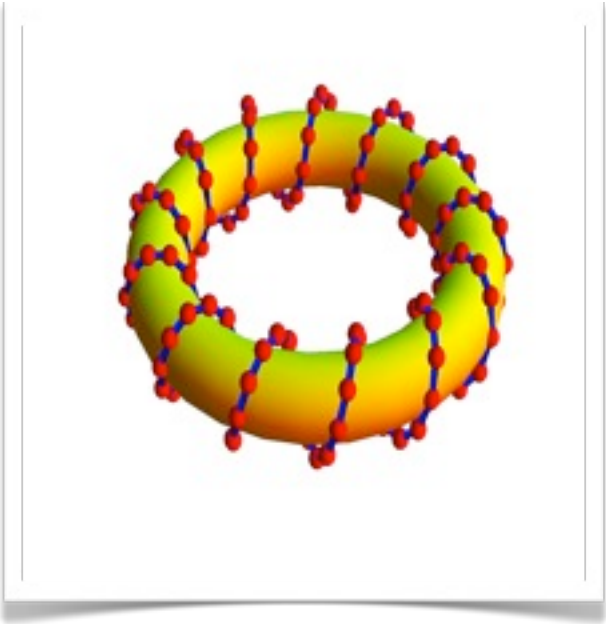
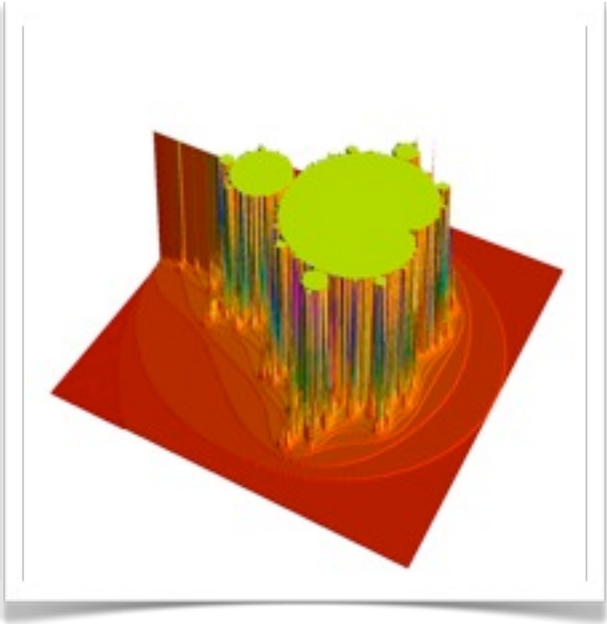
The first pictures illustrates a falling stick, bouncing off a table. We see a stroboscopic snapshot of the trajectory. The second picture illustrating the orbit of a billiard in a three dimensional billiard table[55].



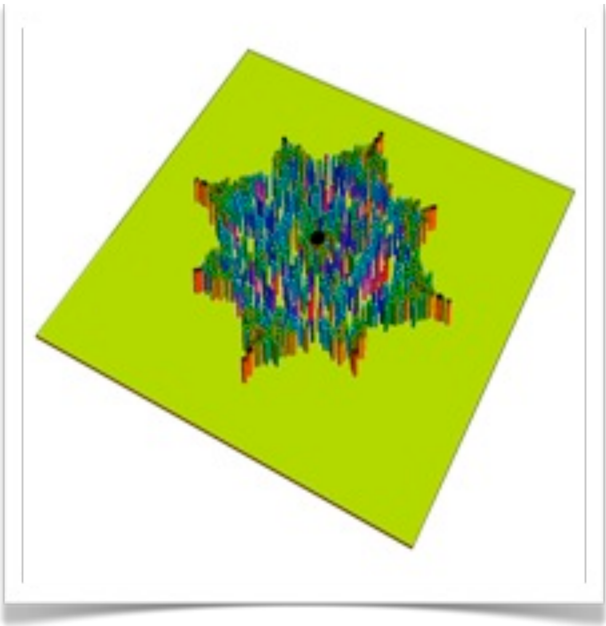
The left picture shows two isospectral drums found by Gordon-Webb. The right picture shows a printed realization of a Dirac operator of a graph[56].



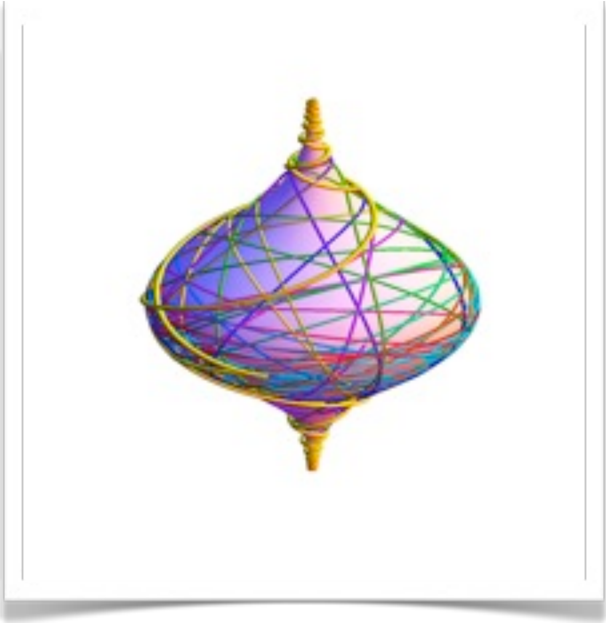
The left picture shows the coffee cup caustic. It is an icon of catastrophe theory. The right picture shows the Costa minimal surface using a parametrization found by Gray[57].

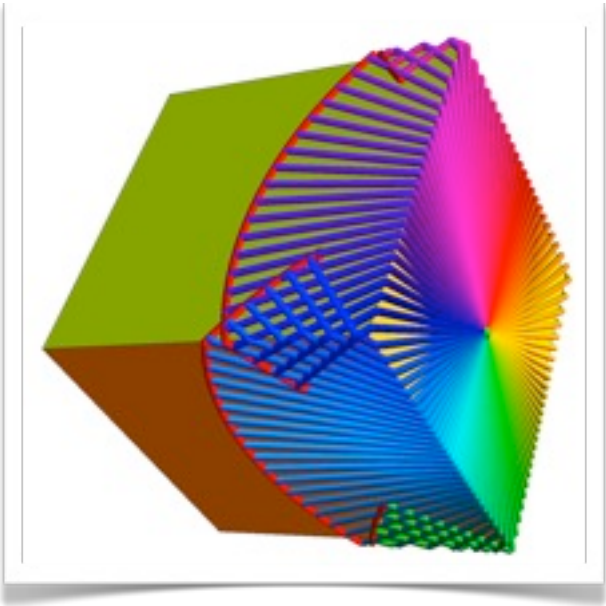
The left picture illustrates a torus graph, the right picture shows the Mandelbrot set in 3D. Fantastic computer generated pictures of the fractal landscape have been produced already 25 years ago[58].

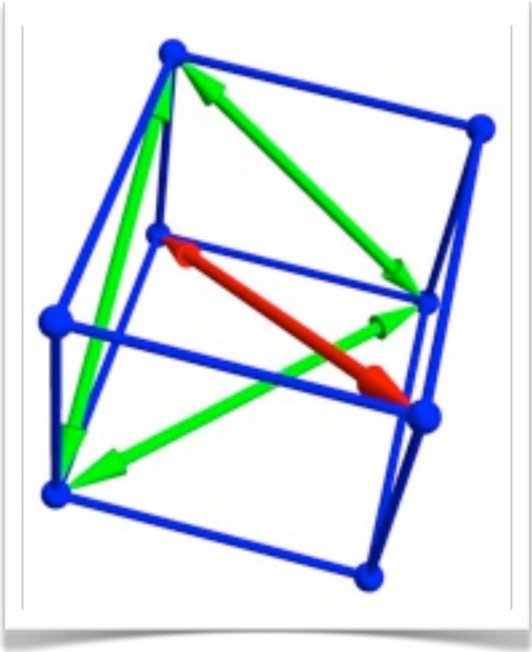
The left picture illustrates the spectrum of a matrix, where the entries are random but correlated. The entries are given by the values of an almost periodic function. We have observed experimentally that the spectrum is of fractal nature in the complex plane. The picture could be printed. The right example is a decic surface, the zero locus $f(x, y, z) = 0$ of a polynomial of degree 10 in three variables . We show the region $f(x, y, z) \leq 0$.

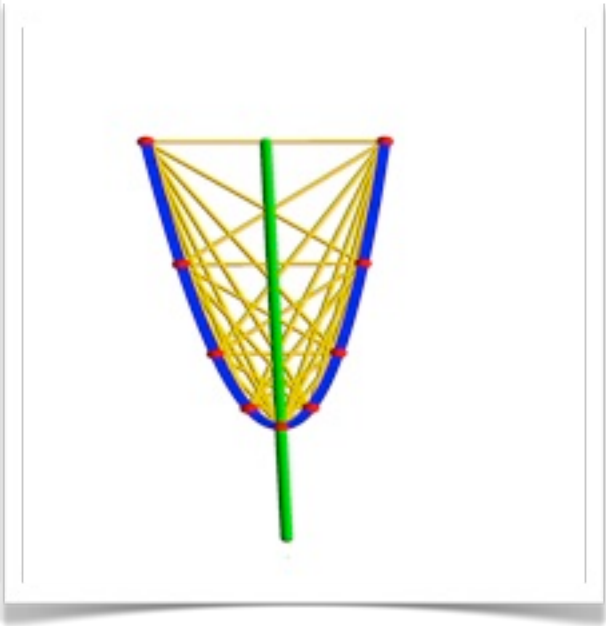


The left figure shows the geodesic flow on an ellipsoid without rotational symmetry. Jacobi's last theorem -still an open problem- claims that all caustics have 4 cusps. The right picture shows some geodesics starting at a point of a surface of revolution.



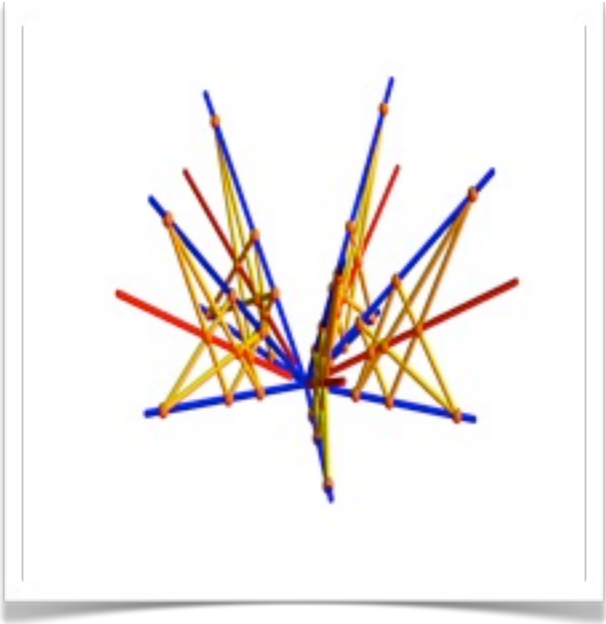
A wave front on a cube. Despite the simplicity of the setup, the wave fronts become very complicated. The right figure shows an approximation to the Menger sponge, a fractal in three dimensional space. It is important in topology because it contains every compact metric space of topological dimension 1.

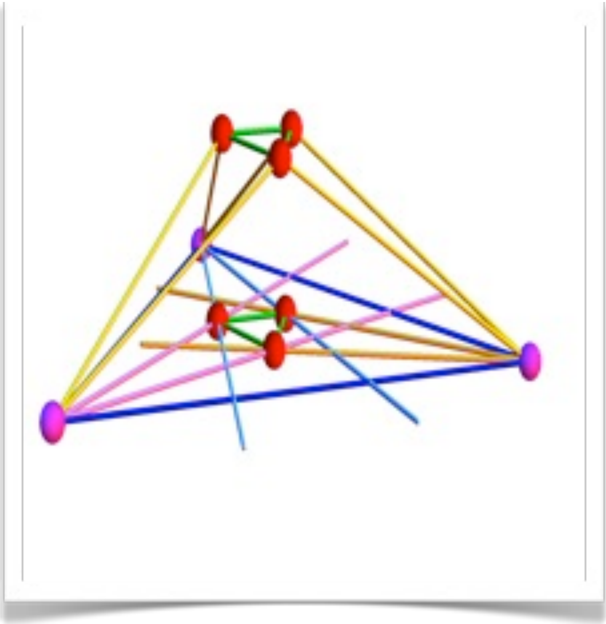




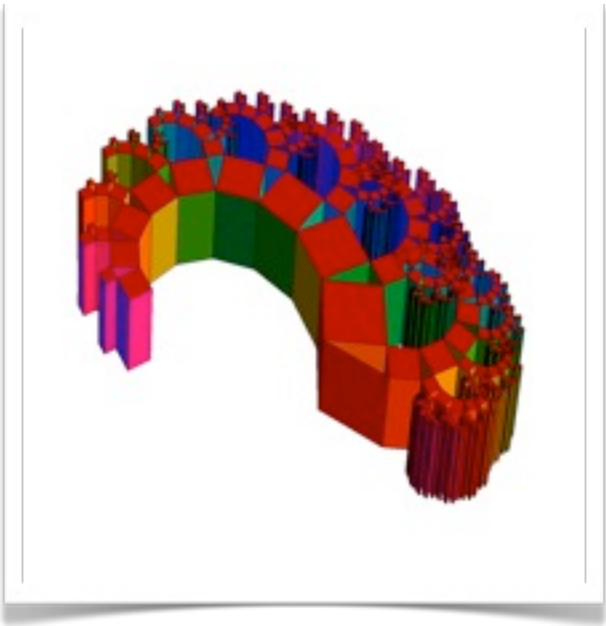
The left figure illustrates an Euler brick. It is unknown whether there is a cuboid for which all side lengths are integers and for which also all face and space diagonals are integers. If all face diagonals have integer length, it is called an Euler brick. If also the space diagonal is an integer it is a perfect Euler brick. The right figure shows how one can realize the multiplication of numbers using a parabola.

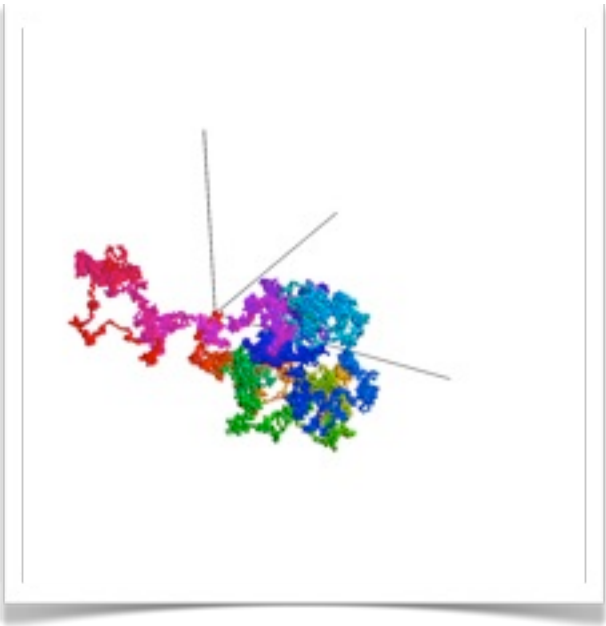
The left figure illustrates the proof of the Pythagoras theorem[59]. The right figure is a proof that a pyramid has volume one third times the area of the base times height.





A theme on the Pappus theorem to the left and an illustration of the Morley theorem which tells that the angle trisectors of an arbitrary triangle meet in an equilateral triangle.





The left figure shows a fractal called the "tree of pythagoras". The right picture shows the random walk in three dimensions. Unlike in dimensions one or two, the random walker in three dimensions does not return with probability 1 [60].

Tables and code snippets

A) **Revolutions**. The first table summarizes information and industrial revolutions.

Information revolutions		Industrial revolutions	
Gutenberg Press	1439	Steam Engine, Steel and Textile	1780
Mechanical Computer	1642	Automotive, Chemistry	1850
Personal Computer, Cell phone	1973	Personal Computer, Rapid Prototyping	1969

.

For industrial revolutions, see [61] page 3, for the second industrial revolution [62] page 2, for the third one see [21] page 34 [23].

B) **Change in communication, perception and classroom.** This table gives examples of breakthroughs in communication and in the classroom. The middle number indicates how many years ago, the event happened.

Communication			Perception			Classroom		
Alphabet	20K	Ishango bone	Projection	1K	Camera obscura	Models	2K	Greeks
Figures	6K	Clay tablet	Eye glass	730	Aalvina Armate	Abacus	1.5K	Abacus
Models	2K	Apollonius	Microscope	420	Janssen	Blackboard	1K	Tarikh Al-Hind
Books	560	Gutenberg	Telescope	400	Kepler	CAS	50	Schoonship
Photo	170	Photographia	Xrays	110	Roentgen	Calculator	40	Busicom
Film	130	Kineograph	MRI	60	Catscan	Powerpoint	30	Presenter
3D-Print	30	Stereolithog.	3D scan	25	Cyberware	3D-Models	15	Makerbot

.

Early computer algebra systems (CAS) in the 1960ies were Mathlab, Cayley, Schoonship, Reduce, Axiom and Macsyma[63]. The first author was exposed as a student to Macsyma, Cayley (which later became Magma) and Reduce. We live in a time when even the three categories start to blur: cellphones with visual and audio sensors, possibly worn as glasses connect to the web. In the classroom, teachers already today capture student papers by cellphones and have it automatically graded. Students write on intelligent paper and software links the recorded audio with the written text. A time will come when students can print out a physics experiment and work with it.

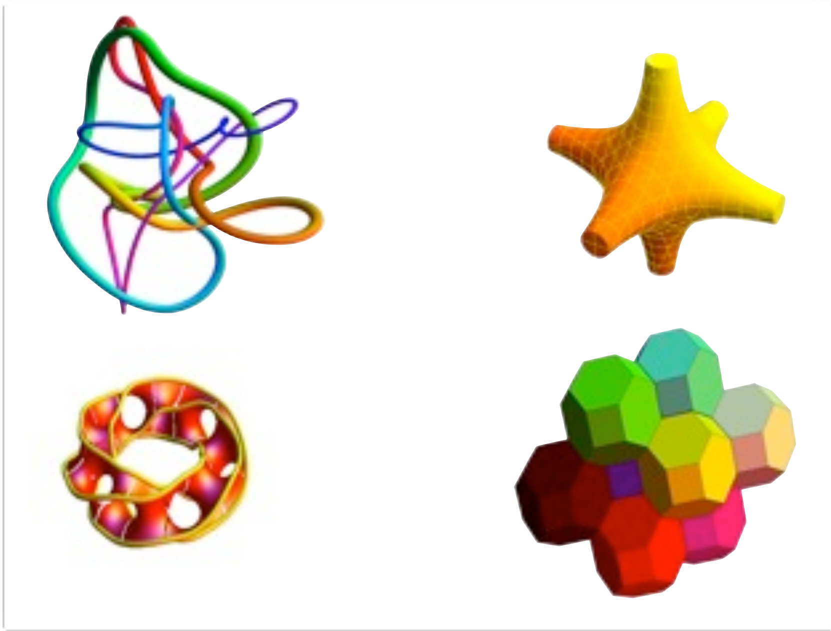
C) **Source code for exporting an STL file.** The following Mathematica lines generate an object with 13 kissing spheres.

```
s=Table[{0,n,m*GoldenRatio},{n,-1,1,2},{m,-1,1,2}];
s=Partition[Flatten[s],3]; s=Append[s,{0,0,0}];
s=Union[s,Map[RotateRight,s],Map[RotateLeft,s]];
S=Graphics3D[Table[{Hue[Random[]],Sphere[s[[k]]]},{k,12}]]
Export["kissing.stl",S,"STL"]
```

D) **The STL format.** Here is top of the file kissing.stl converted using "admesh" to the human readable ASCII format. The entire file has 104'000 lines and contains 14'640 facets. The line with "normal" contains a vector indicating the orientation of the triangular facet.

```
solid  Processed by ADMesh version 0.95
 facet normal  2.45300293E-01 -3.88517678E-02  9.68668342E-01
  outer loop
   vertex  1.64594591E-01  0.00000000E+00  9.86361325E-01
   vertex  1.56538755E-01 -5.08625247E-02  9.86361325E-01
   vertex  3.08807552E-01 -1.00337654E-01  9.45817232E-01
  endloop
 endfacet
```

E) **Mathematica Examples.** Here are examples of basic "miniature programs" which can be used to produce shapes:



- E1) Addition of some "knots":

```
u = KnotData[{"PretzelKnot",{3, 5, 2}}, "SpaceCurve"];
v = KnotData[{"TorusKnot", {5, 11}}, "SpaceCurve"];
Graphics3D[Tube[Table[3u[t]-4v[t],{t,0,2 Pi,0.001}],0.3]]
```

- E2) A region plot:

```
RegionPlot3D[
 x^2 y^2+z^2 y^2+x^2 z^2<1 && x^2<6 && y^2<6 && z^2<6,
 {x,-3,3},{y,-3,3},{z,-3, 3}]
```

- E3) A Scherk-Collins surface[64], which is close to a minimal surface:

```
T[{x_,y_,z_},t_]:={x Cos[t]-y*Sin[t],x Sin[t]+y*Cos[t],z};
W[{x_,y_,z_},t_]:={(x+3)Cos[t],(x+3)Sin[t],y}; A=ArcTan; L=Log;
f[z_]:=Module[{p=Sqrt[2Cot[z]],q=Cot[z]+1,r=Re[z]/3},
W[T[Re[{u(L[p-q]-L[p+q])/Sqrt[8],v*I(A[1-p]-A[1+p])/Sqrt[2],z}],r],r]];
Show[Table[ParametricPlot3D[f[x+I*y],{x,0,6Pi},{y,0,6}],{u,-1,1,2},{v,-1,1,2}]]
```

- E4) A polyhedral tessellation: At present, Mathematica commands “Translate” and “Rotate” or “Scale” produce STL files which are not printable. This requires to take objects apart and put them together again. Here is an example, which is a visual proof that one can tesselate space with truncated octahedra.

```
T[s_, scale_, trans_] := Module[{P,E},
    P = Table[scale*s[[1,k]] + trans,{k,Length[s[[1]]]}];
    E = s[[2,1]]; Graphics3D[Table[{Polygon[Table[P[[E[[k,l]]]],
    {l,Length[E[[k]]]}]]},{k,Length[E]}]]];
P=PolyhedronData["TruncatedOctahedron","Faces"];
Show[Table[T[P,1,{k+l+2m,k-l,3m/2}],{k,-1,1,2},{l,-1,1,2},{m,0,1}]]
```

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Science and Art: Periodic Tessellations

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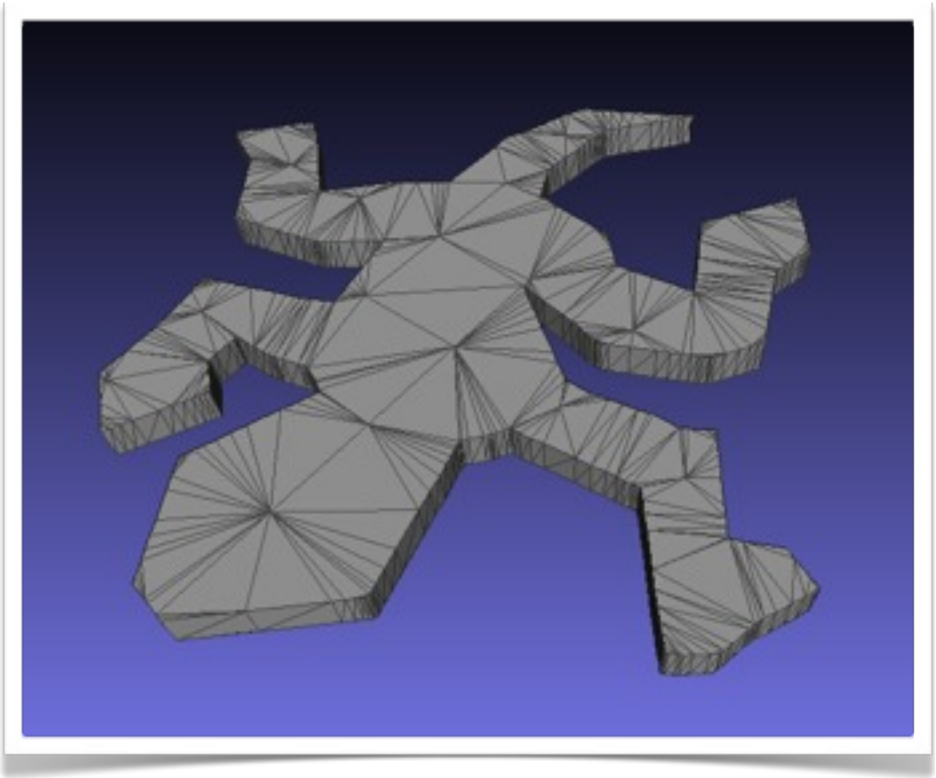
There are strict relations between science and art. This fact is quite natural: on the one hand many living organisms exhibit innumerable and wonderful symmetry aspects which, in turn, have significantly influenced the artistic practice. On the other hand scientists have realized that one of the most efficient ways of unveiling the laws which govern the universe is to make resort to symmetry considerations.

Escher's plane-filling tilings reproduced in a low-cost 3D printer

So, first of all, many artists have paid a specific attention to symmetry even making of it, in various instances, the canon which has guided them in their artistic production. A typical example is given by music, which, in general, is pervaded and regulated by symmetry principles and which, in some cases, has made of the symmetry requests the basic rule informing a composition. The most typical and sublime examples of this is represented by the late works of J.S. Bach: *The art of Fugue and The Musical Offering*.

An analogous process has characterized many creations of visual arts, from architecture, to sculpture and painting. One could make a detailed list of the cases in which symmetry criteria became fundamental structural elements of visual compositions, but, for sure, the most paradigmatic example is represented by the graphic work of the great Dutch artist M.C. Escher. Actually, he has made a systematic resort to the problem of the tessellation of the plane, *i.e.*, the identification of elementary tiles which allow, when they are put side by side, a continuous covering of the whole plane.



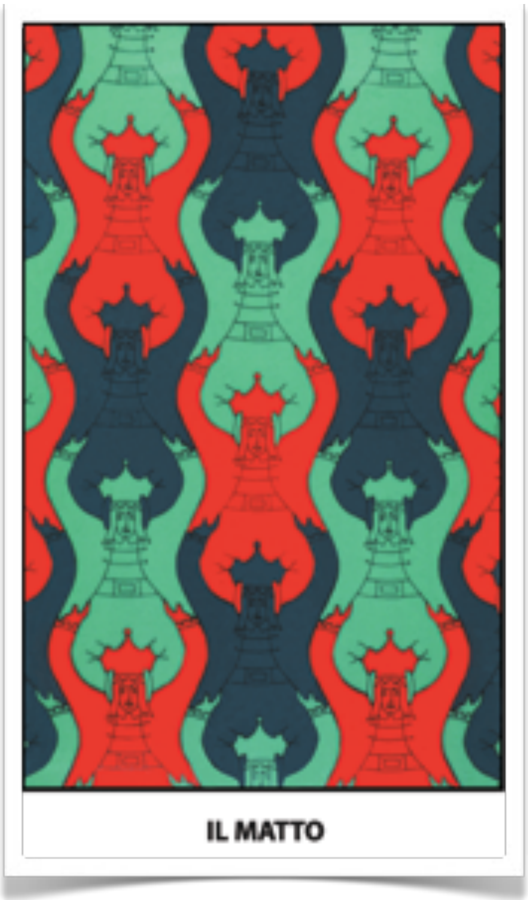
3D model of the previous tile by M.C. Escher

The same problem has represented a stimulating challenge for mathematical investigations. Actually, it has been just the elaboration of group theory, one of the basic formal instruments of this discipline, which has allowed to prove that, if one takes the perspective of looking at the symmetries (obviously quite different images can exhibit the same symmetry) characterizing the tiles which allow a tessellation, there are only 17 different ways to actually implement such a result.

The purpose of this lecture is to make understandable how it happens that symmetry considerations imply extremely strong constraints which all possible tilings must satisfy, and, as a consequence they drastically limit their number.

In spite of the fact that this book deals with the fundamental and extremely promising subject of *"Low-cost 3D Printing"*, and in spite of the fact that the 3-dimensional regular organization of crystals is strictly related to the problem of the tessellation of the 3–dimensional space, I will confine my considerations almost exclusively to the 1 and 2 dimensional cases, *i.e.* to periodic friezes and tessellations of the plane by identical tiles. As seen already in the 2-dimensional case, to identify all possible tilings is an extremely complex problem. Passing to 3 dimensions the complexity increases incredibly. Actually, while there are only 7 types of periodic linear structures, and, as already anticipated, 17 types of plane tessellations, in the 3-dimensional case the possible different tilings, from the point of view of their symmetry structure, become 230.

A few conclusive remarks. I have been invited to deliver a talk addressed to a general public and which deals with non specifically scientific problems. Now, it happens that, many years ago, I have been involved, just for fun, in the same problem which has inspired Escher, *i.e.* in carrying out tessellations of the plane, and since I believe that the images that I have produced have some interest, I will conclude by mentioning the reasons for which I took the challenge of producing more than 30 tesselating images. Actually, the peculiar purpose which has guided me has been that of producing a Tarot Deck in which all the standard images appearing in the popular cards decks have been shaped in such a way to allow a tessellation. I consider it appropriate to add few word on the process which has led me to do what I did.



Since my high school times, I have been interested in Freud's position about our psychological evolution. Much later I read an exciting book by the famous italian writer Italo Calvino: *The castle of crossed destinies*. Calvino's idea is very simple: to test that the symbolic value of an image depends on the context in which it is inserted. In the novel, many people, having had terrible experiences have lost the capacity to speak. So, when they arrive at the Castle and they find on the table a Tarot deck, one of them starts displaying a sequence of cards which summarizes his history. Then the game goes on with other guys up to when one has a full disposition of all cards in a quite big rectangular area. Any sequence which one meets going through the rectangle in various ways (horizontally, vertically, along the diagonals, *etc.*) is a fascinating story (Hamlet, Aedipus, *etc.*), and these stories, *i.e.* the destiny of their heroes, literally intersect one another.

This is how I started being interested in Tarots. And I discovered that there are all sorts of interpretations for them, from the most stupid ones like their use for fortune telling, to investigations by serious people, *e.g.*, by Jung and Reichenbach. For me it became quite obvious that any image of the tarots has a clear significance in a Freudian perspective (typically, The Emperor is the image of the father, The Empress of the exigent mother, The Popess the one of the good, sensitive mother, The Lovers symbolize the choice between the principle of pleasure and the one of reality, *etc.*). If one takes this point of view, then one is naturally led to the following idea: each image represents a crucial moment of the individual psychological evolution. But when one is the victim of a "complex", let us mention for instance the Aedipus' complex, it pervades all his universe.

For somebody who knew and loved Escher, the suggestion was obvious and intellectually challenging: since the universe of the cards is two dimensional, in order to represent the pervasive role of the relevant psychological moments depicted in the cards, the associated images had to fill the two dimensional universe of the cards themselves. In this way the Periodic Tarot Deck had its origin.

Printable ALICE 3D Models at CERN

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Understanding a concept is the beginning of understanding science. Without conceptual understanding, you cannot bring the idea of what you are aiming to achieve to a wider audience. Without interesting a wider audience, you will never inspire the next generation of scientists and researchers on whom future science will rely.

When concepts can be demonstrated easily, such as in chemistry or biology, then the effects of science can be easily introduced to a wider audience who may not have the prior knowledge of the reaction taking place. Such dramatic effects are visually exciting and immediately interesting, and hold people's attention so the science behind it can be explained.

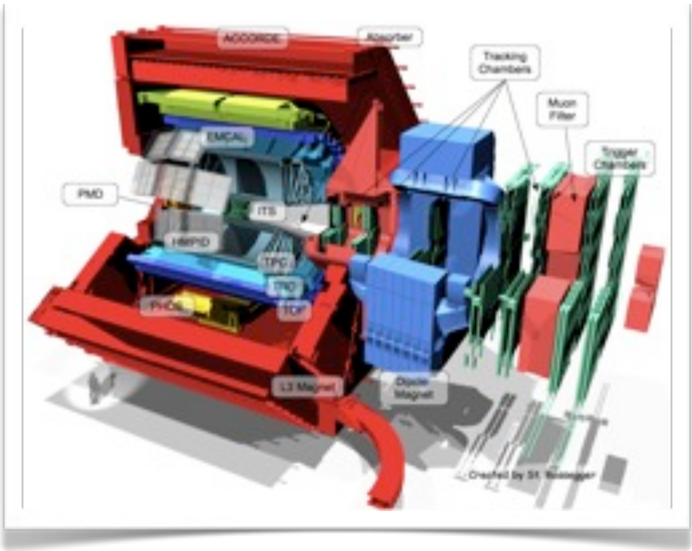
The difficulty for particle physics, which is studied and tested at CERN, is that we deal in reactions which cannot be directly observed. Particles are created within the collisions in the Large Hadron Collider (LHC), the largest particle accelerator in the world. Their paths and properties are measured through their interactions in our detectors, computer tracking and later mathematical modeling. Because of the complexity of the scientific experiments and their conceptually challenging nature of particle physics, explaining exactly what the LHC does in a simple manner presents massive challenges. These reactions are almost beyond the imagination of a general audience.

Therefore, you have to find other conceptual methods to engage people. 3D models are such attempts to explain how a particle detector looks, how they work and what happens during a collision. First, a little bit of background about CERN and the ALICE experiment and our efforts to keep peoples interest.

CERN began in the 1950s as the European Organization for Nuclear Research. Today it is also known as the European Laboratory for Particle Physics. It is one of the world's most prestigious research centers headquartered in Geneva, Switzerland. Its business is fundamental physics - finding out what makes our Universe work. At CERN, some of the world's biggest and most complex machines are used to study nature's tiniest building blocks, the fundamental particles. By colliding these minute particles of matter, physicists unravel the basic laws of nature. The Laboratory provides state-of-the-art scientific facilities for researchers to use. These are accelerators that accelerate tiny particles to a fraction under the speed of light and detectors that behave like electronic eyes, making the particles visible.

CERN is currently running a new accelerator called the Large Hadron Collider (LHC). This machine is a new tool for the world's physicists to probe deeper than ever into the heart of matter. The LHC plays host to a range of experiments run by collaborations of physicists from around the world. These physicists build particle detectors at their home institutes and bring them to CERN to record the results of particle collisions. The LHC provides four experiments with collisions. The experiments are called ATLAS, CMS, LHCb and ALICE.

ALICE, the experiment I am working on, stands for “A Large Ion Collider Experiment”. In contrast to the other experiments at the LHC, we study heavy nuclei collisions, which are as close as we can get to the very early stage of the universe, the Big Bang. It has been designed and built to measure, in the most complete way possible, the particles produced in such collisions which take place at its center so that the evolution of the system in space and time can be reconstructed and studied. To do so, many different detectors have to be used, each providing a different piece of information to physicists. To understand such a complex system, one needs to observe the phenomenon from different points of view, using different instruments at the same time.



ALICE - A Large Ion Collider Experiment

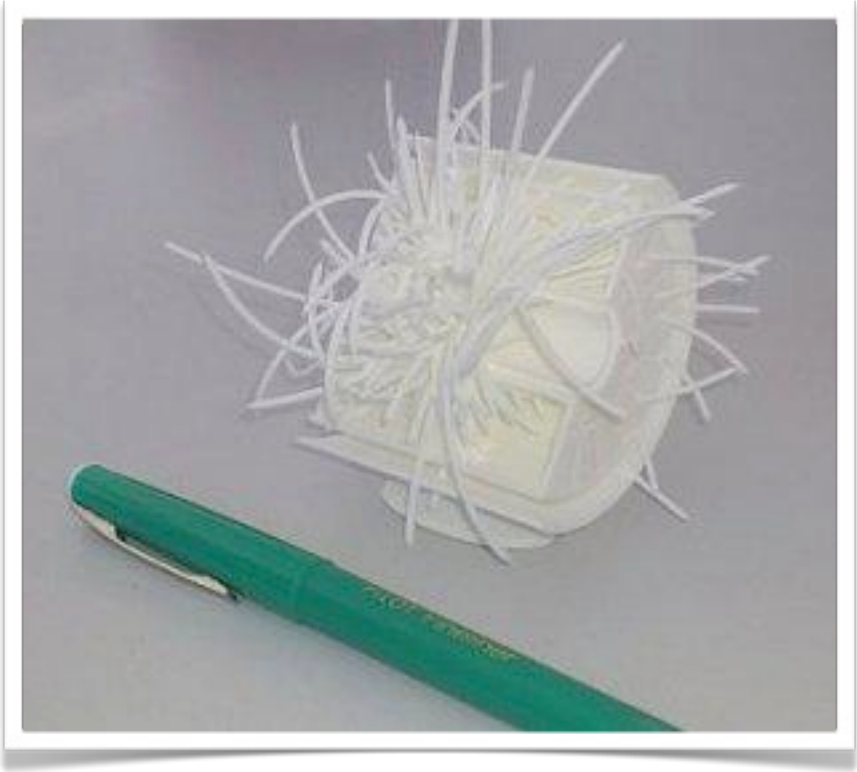
An ensemble of cylindrical detectors (from inside out: Inner Tracking System (ITS), Time Projection Chamber (TPC), Transition Radiation Detector (TRD)) measures at many points (over 100 just the TPC) the passage of each particle carrying an electric charge, so that its trajectory is precisely known. The ALICE tracking detectors are embedded in a magnetic field bending the trajectories of the particles: from the curvature of the tracks one can find their momentum. The ITS is so precise that particles which are generated by the decay of other particles with a very short life time can be identified by seeing that they do not originate from the point where the interaction has taken place (the “vertex” of the event) but rather from a point at a distance of as small as a tenth of a millimeter.

ALICE also wants to know the identity of each particle, whether it is an electron, or a proton, a kaon or a pion. In addition to the information given by ITS and TPC, more specialized detectors are needed: the Time Of Flight (TOF) measures, with a precision better than a tenth of a billionth of a second, the time that each particle takes to travel from the vertex to reach it, so that one can measure its speed and the TRD measures the special radiation very fast particles emit when crossing different materials, thus allowing to identify electrons. Muons are measured by exploiting the fact that they penetrate matter more easily than most other particles: in the forward region a very thick and complex absorber stops all other particles and muons are measured by a dedicated set of detectors, the muon spectrometer.

3D model of the first heavy ion collision

Because of the previously mentioned conceptual difficulties of explain the science behind the LHC and its experiments, CERN uses many different methods to bring the interior of the experiments to life. One of the methods that CERN uses is to visualize the paths of the particles generated in collisions on normal computer screens. A collision looks very similar to fireworks for an amateur's eye. The visualization demonstrates the paths of particles as they are tracked after a collision. We do this using AliROOT, a specially designed software package that not only visualizes the tracks but also is able to read the raw data from the detectors, does the tracking and pattern recognition and is used for the final analysis of the data. Apart from that, this display is the centerpiece of our visitor's center, the Globe, and the ALICE exhibition.

The 3D model which we printed with rapid prototyping methods is a pure static visualization of one of the first heavy ion collision measured by one of our sub-detectors, the TPC, back in the year 2010, which was an historic event. The 3D model of the TPC as well as the tracks were created with the open source modeling software Blender, using a python plug-in in order to load the reconstructed particle properties from the previously mentioned AliRoot package. Shapeways, a commercial company available to everybody, then printed this as seen in the picture in the next page.



3D print out of the first heavy ion collision

The creation of this 3d model allows us to demonstrate the reactions in a way that is visually interesting without being too conceptual. As for example, lines/tracks with a strong curvature represent particles with a low momentum. The longest lines/tracks are traveling basically with the speed of light; shorter ones are heavier and therefore slower, and so on.

This model is only the first step towards an exhibition where we try to show and explain our detector and the science behind it for a wider audience.

Large Scale 3D Printing: from Deep Sea to the Moon

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Introduction

The interest of the scientific and technical community toward large scale Three Dimensional (3D) printing technologies is ever and ever increasing in the last few years, due to the wide variety of potential applications both for direct construction of portion of buildings, complete buildings and other complex structures with virtually any kind of shape. Since their birth, which dates back to the 90ies, these construction scale rapid manufacturing techniques have now reached a quite mature stage and are now currently used in the production of walls, large sculptures design elements especially for external environments. Figure 1 depict three exemplar objects, while Fig. 2 depicts a small complete house.

Fig. 1: A sculpture for outdoor environments, the "Radiolaria" sculpture and a "chaise longue" for garden

Fig. 2: A complete house

All the artifact reported in Fig.s 1 and 2 have been realized through a technology called **D-shape**, invented and patented by Eng. Enrico Dini from Monolite UK. This technology differs from the most widely known competitors (for instance Freeform Construction[1] developed at the Rapid Manufacturing Research Group in Loughborough and Contour Crafting[2]), for the particular feature of selectively catalyzing materials within a layer of pre-deposited sand substrate through the ad-hoc injection of a liquid "ink", while the other techniques exploits the extrusion of the building material already premixed with the associated binder or catalyst. This characteristic make the D-Shape capable of printing work pieces at a very large-scale, as the only limit dimension is given by the size of the printing area: the most updated version of printer (a giant plotter with a linear spraying head moving along two frames in the x-y axis space), which is depicted in Fig. 3, has a printing area of 6×6 meters and reaches an height of 3 m.

Realization of building blocks for a Lunar Outpost

Due to its unique features, the D-Shape technology has been selected within the project entitled *"3D Printed building Blocks Using Lunar Soil"* funded by the European Space Agency (ESA) which aimed at developing concepts for the construction of habitations for stable human residence on the Moon[3].

Fig. 3: The D-Shape printer

The establishment of human settlements on the Moon is of great interest to conduct scientific experiments, to make observation campaigns on some remote portion of the space without the shield of the atmosphere and as a base for deep space exploration missions. Like any colonization of the human history, even the lunar one must exploit local material for the basic structure of the "houses", but on the Moon only sandy soil and a small amount of icy water are available. The lunar sand is called *regolith* and the first part of the above-cited project was devoted to the search of a suitable material to duplicate the main features of regolith. Afterwards, vacuum tests have been performed to prove that the D-shape technology is applicable also in absence of atmosphere an at reduced gravity, *i.e.* in conditions similar to the ones that can be found on the Moon.

These experiments have been conducted in one of Alta SpA vacuum chambers. The D-shape technology has also been adapted to the operations on such a harsh environment with very limited support from human operators (the possibility to hold remote operations without human supervision has also been considered). Scuola Superiore Sant'Anna investigated in this direction: the printer has been equipped with a camera taking images of each printed layer and with image processing algorithms capable to compare the printed surface with its ideal shape and to find eventual defects. The control logic has also been adapted in order to autonomously detect and repair malfunctioning and printing defects. Finally the whole structure of the printer had been preliminarily re-designed in a way that it can be –in the future– more flexible, adaptable to the irregular lunar ground and, most of all, capable to move and interact with other autonomous or semi-autonomous cooperating vehicles, which could for instance accumulate regolith for the printing operations.

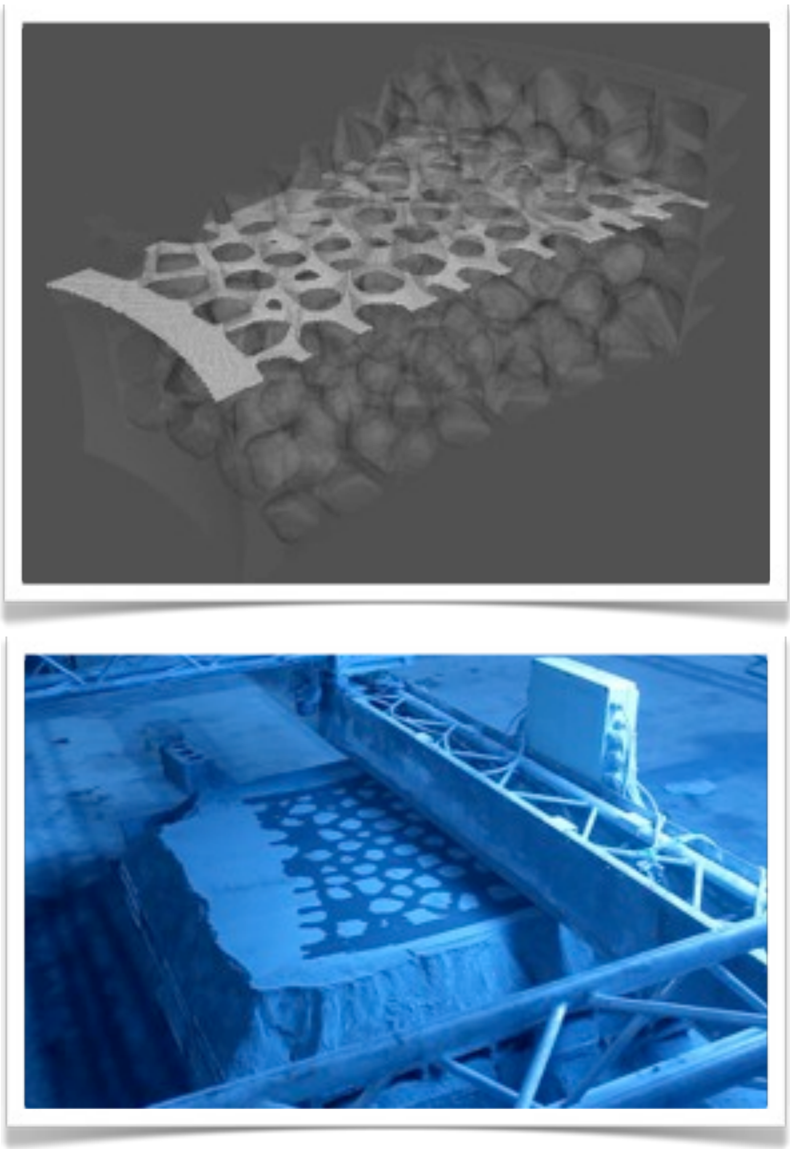

Fig. 4: Building block of the external shield of the lunar outpost and its printing process

The design of the lunar outpost's structure and of the building blocks have been developed by the famous Londoner design company Fosters+Partners, that was also a partner of the project. The lunar "houses" should be similar to "igloos", with an external thick shield made (or "printed") of regolith with an internal structure composed as a so-called "closed foam" (*i.e.*, with internal empty closed cavities) giving suitable thermal insulation and micrometeoroid shielding properties without requiring an excessive amount of binding material, while the innermost "core" will be constituted by an inflatable pressurized structure. The bottom layer diameter is about 10 m while the total height is around 5 m. Figure 3 depicts one of the prototypes of the building block (with an overall volume of about 1.5 m^3) with one layer which is put into evidence and the printing process of the same prototype, in order to understand how effective the D-Shape technology is in the realization of such structure.

Figure 5 depicts the prototype of the complete Lunar outpost.

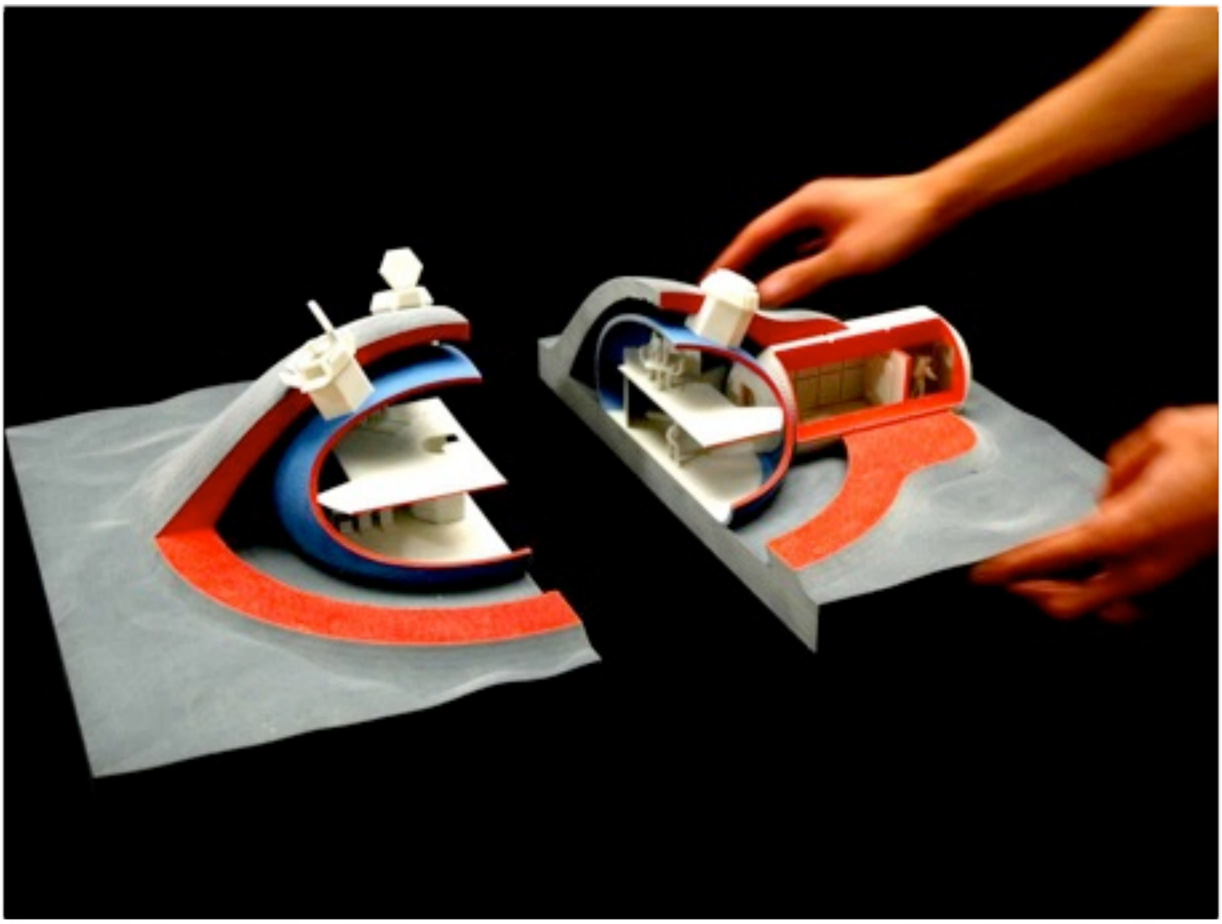

Fig. 5: Prototype of the lunar outpost. (Courtesy of Fosters+Partners, who participated to the project funded by ESA)

D-shape for the marine environment

The porous features of the artifacts that are printed through the D-Shape technology make them really suitable to be included in a natural environment. For instance the climbing vegetation can easily find foothold on these structures, by gradually covering them and giving birth to unique and unexpected shapes totally included into the natural scenario. According to the same principle, also submarine vegetation and small marine fauna can exploit these kind of structures (when suitably designed) as good habitat for life and reproduction. Therefore these artifact can also be successfully applied for the rapid restoration of seabed damaged by natural events or by the human intervention (such as, for instance, by accidents or as a consequence of non environmental-friendly constructions).

Conclusions

D-Shape is one of the largest scale 3D printing technologies exploiting sand material aggregated through a particular binder, which allows to print work pieces in a wide variety of shapes and for an incredible range of applications, from architecture to arts, suitable for really different environments, such as gardens, parks, buildings and deep sea. Future work will be devoted, on one hand, to further evolution of the printer, in order to make it faster and capable of self-diagnostic of failures; on the other hand, novel applications are currently under study and development, especially devoted to environmental-compatible architecture and structures for restoration of natural environments.

Acknowledgements

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Trabecular Bone Modeling with Support of 3D Printing of Physical Replicas

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Introduction

Osteoporosis is known as a silent disease that is characterized by bone mass loss and deterioration of the trabecular microarchitecture, causing bone fragility and increasing the fracture risk[1 2]. With current life span expansion, osteoporosis has now become a public health problem, with deep social and economical impacts[3]. Although bone mass is quite important in providing information about the mechanical resistance to load, nowadays it is known that other factors are also important to establish what is called bone quality, a predictor of the fracture risk. Bone mass loss is evaluated worldwide by measuring the bone mineral density (BMD), the gold standard for the diagnosis of osteoporosis. However, the BMD assesses the areal bone density and this is just one aspect of bone quality. Several other factors play also a significant role for the build up of bone quality, in particular the trabecular bone microarchitecture[4].

Bone is an organ that is primarily composed of osseous tissue, essentially formed by a composite of organic cells and a mineral matrix with around ⅔ of hydroxyapatite and ⅓ of collagen fibers and with cells accounting for 2-3% of the bone tissue. The bone is of two types, a compact dense one called cortical and a spongy one called cancellous or trabecular bone. The spongy aspect of the trabecular bone resembles a two phase porous medium, where the trabeculae correspond to the solid phase and the marrow cavities to the soft phase. Therefore, we can think of the trabeculae as grains and the marrow cavities as pores, following the porous media nomenclature.

The bone quality depends upon several biological, chemical, microstructural and mechanical processes, which finally will comprise the bone strength and fragility. As currently there is neither an invasive nor noninvasive validated tool to provide a fully reliable prediction of *in vivo* fracture risk, several approaches have been investigated largely based in *ex vivo* data. With the development of imaging techniques, like dual energy X-ray absorptiometry (DXA), computed tomography (CT), microCT (μCT), magnetic resonance imaging (MRI), high resolution peripheral quantitative computed tomography (HR-pQCT) and quantitative ultrasound (QUS), *in vivo* data are becoming more and more available as an instrument to support information building about the bone structure.

Several techniques have been developed in an attempt to better understand bone quality from micro up to macroscale[5]. At the microscale level, recent studies have shown that the osteocyte cells are quite important to orchestrate bone remodeling[6], regulating both osteoclast and osteoblast cell activities. At this level the remodeling process starts taking place and the microstructure understanding is fundamental to the bone tissue biology and engineering[7]. On the other hand, at the macroscale level several morphological and physical parameters seem to play an important role to establish the mechanical strength of the bone[8]. Mathematical and computational modeling of the trabecular structure as well as experimental mechanical stress-strain tests[9] have provided good results to scaffold biomechanics and development of bone prosthesis devices.

In both scale levels not just numerical and simulation models have been used to allow computer visualization, but in addition much attention has been given to the construction of actual 3D physical replicas molded to mimic the bone matrix[10 11 12], to realize mechanical experiments and properties[13 14 15 16], for tissue regeneration[17 18] and in reconstructive surgery planning and education [19 20 21 22 23].

The rapid development of medical imaging devices and image processing techniques have allowed 3D reconstruction and visualization. Nevertheless, in many senses we are still limited due to flat screens for visualization of 3D objects. The production of 3D replicas of bone and other tissues are turning into reality[24 25] with the fast development of additive manufacturing (AM) techniques for 3D printing[26].

This paper is not intended to be a review, rather its aim is to point out some aspects of bone research which has been making use and taking advantage of 3D printing of physical replicas. Of course the paper is not complete and many relevant and interesting studies were not included in the reference list, but the ones cited here are already a good starting point to observe the fast integration between bone tissue biomedical engineering and 3D printing technology.

Stereology

Stereology is a set of mathematical and statistical methods applied to describe geometrical characteristics and properties of 3D objects departing from measurements obtained on 2D sections of the object structure[27]. The name stereology has its root in the Greek word *stereos* meaning solid. One of the first applications of stereology were in geology during the first half of the 19th century, but only quite recently, in the early 1960's, it was firmly established as a new discipline.

Since then, stereology has been applied in many different fields, but in biomedical sciences it found a very fertile soil for applications. One way to investigate the bone microarchitecture is calculating some histomorphometric indices[28] by means of stereological methods. Several parameters are computed based on two-dimensional section measurements, such as trabecular thickness, trabecular density, trabecular separation and trabecular skeletal length. On the other hand, other quantities such as trabecular bone connectivity or tortuosity[29] require the analysis of two contiguous sections to be able to infer geometrical and topological changes that may occur in between. In stereology there are four basic types of probes that are used to sample structural features in sections, namely: points as zero-dimensional probes, lines as one-dimensional probes, areas as two-dimensional probes and the disector, a 3D probe constructed by using two thin contiguous sections with a small separation[30].

The disector

The current image-based data acquired, for instance from bone, produces a set of registered sequential images that are 2D parallel sections with a small separation between them, and each pair of contiguous images forms a disector probe. The volume of a disector is defined by the area of the sections times the distance between them.

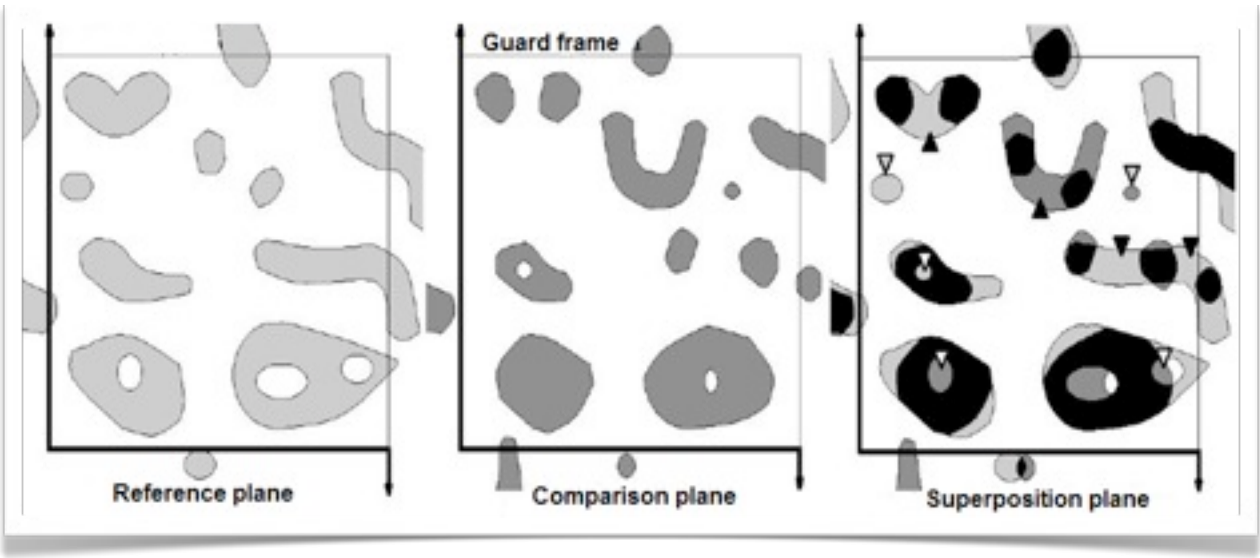


Fig. 1: Section profiles and observed features within a disector. Gray arrow indicates an island (I), white arrow a hole (H) and black arrow a branching (B)

The image disectors can be applied to observe the profiles of one slice and compare them with the profiles of the next slice. By these observations it is possible to count, for instance, curvature changes that occur in a trabecula within a disector. In Figure 1 it is illustrated how features such as islands (I), holes (H) and branching (B) may be counted in a disector. The gray arrows show that an object has either appeared or disappeared within the disector, they are counted as islands (I); the white arrows show that there is a hole (H) inside an object within the disector, and finally the black arrows indicate that a branching (B) of an object has occurred withing the disector.

Trabecular modeling

The gold standard for the diagnosis of osteoporosis is bone mineral density (BMD). This measure is able to indicate how much bone mass has been loss in comparison to a normal value (T-score). In simple terms, when it is observed a mass loss above 25% of a normal subject the patient is classified as osteoporotic. When this value is between 10-25%, the patient is said osteopenic. The BMD is a very important indicator of bone quality and is responsible for around 70% of the bone strength variation. However, recent studies have shown that BMD alone is not able to discriminate the risk of fracture between osteoporotic subjects. Research development have shown that the trabecular bone microstructure is also very important to establish its mechanical competence[31] and the quality of its microarchitecture can increase the perception of bone fragility and consequent fracture risk. Figure 2 shows three trabecular bone samples of distal radius where the trabecular structures are normal, osteopenic and osteoporotic, respectively.

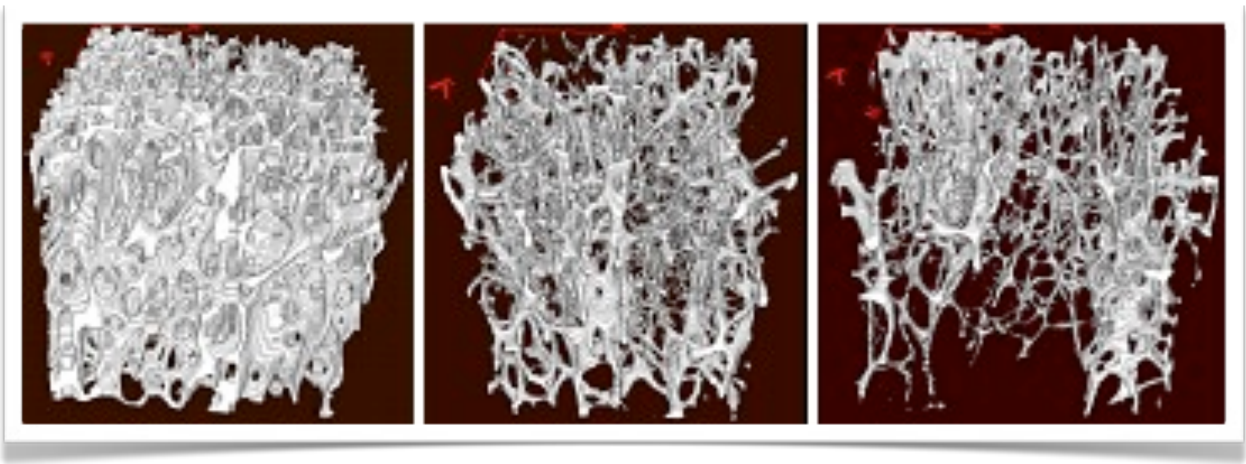


Fig. 2: Trabecular structure: normal (L), osteopenic (C) and osteoporotic (R)

In a recent paper[32] a mechanical competence parameter (MCP) to grade trabecular bone fragility has been proposed based on four quantities that can be estimated from a set of image disectors. These are basic quantities to describe the trabecular bone response to load, namely: the trabecular bone volume fraction, which gives the volume content of bone matrix in a sample; the connectivity of the structure; the tortuosity, that estimates the degree of sinuosity of the trabecular network and the Young modulus, that provides the linear elasticity behaviour of the structure when submitted to stress.

The trabecular volume fraction[33] is estimated by the ratio BV/TV, where BV is the trabecular bone volume estimated by counting the voxels corresponding to trabeculae and TV is the total tissue volume of the sample.

By means of a set of image disectors, the number of disconnected parts of a trabecula corresponds to the number of isolated objects #I (islands) and the connectivity is expressed in terms of the number of tunnels #B (branches) and the number of enclosed cavities #H (holes)[34]. The connectivity number corresponds to the maximal number of cuts through an object that does not produce two disconnected objects. The Euler-Poincaré Characteristic (EPC) is an integral geometrical measure that can provide an estimate of the connectivity of the trabecular structure[34 35]. An important aspect of the EPC is that it does not change under deformation or scaling of an object. In other words, it is a topological invariant. Essentially, the EPC for a 3D structure is defined as the number of isolated parts minus the connectivity. The EPC is a zero dimensional quantity and as such it has to be estimated using a 3D probe, by the equation $EPC=\frac{1}{2}(\#I+\#H-\#B)$. In Figure 2 it is clear the loss of connectivity in both, osteopenic and osteoporotic samples.

In simple mathematical terms, the tortuosity τ of a trabecula is defined as $\tau = LG/LE$, where LG is the geodesic length between two connected points in the trabecular network and LE is the Euclidean distance between these points. To estimate the tortuosity of the trabecular network, based on 3D binary images, a geodesic reconstruction algorithm has been applied[32]. Tortuosity analyses of trabecular bone samples have shown that the trabecular network tends to get aligned in the direction where the structure is more often compelled to stress[29], in agreement with observational results.

To obtain the Young modulus of elasticity for the sample the 3D trabecular bone structure was meshed using an optimized algorithm[36] implemented in Matlab R2011a (The MathWorks Inc., Natick, MA), which converts each voxel to an hexahedron element (brick element). Compression stress-strain test in each space direction was numerically simulated by a finite element (FE) linear-elastic-isotropic analysis performed in Ansys v11.0 (Ansys Inc., Southpointe, PA). The bulk material properties were set to E_{bulk}=10 GPa (compact bone)[37 38] and Poisson's coefficient ν=0.3. A deformation of 1% of the edge length was imposed in all the compression simulations. After application of the homogenization theory[39], apparent Young modulus (E_x,E_y,E_z) results were obtained in each space direction. Figure 3 illustrates the parametric reconstructions of the nodal stress distributions resulting from the z-axis direction compression test.

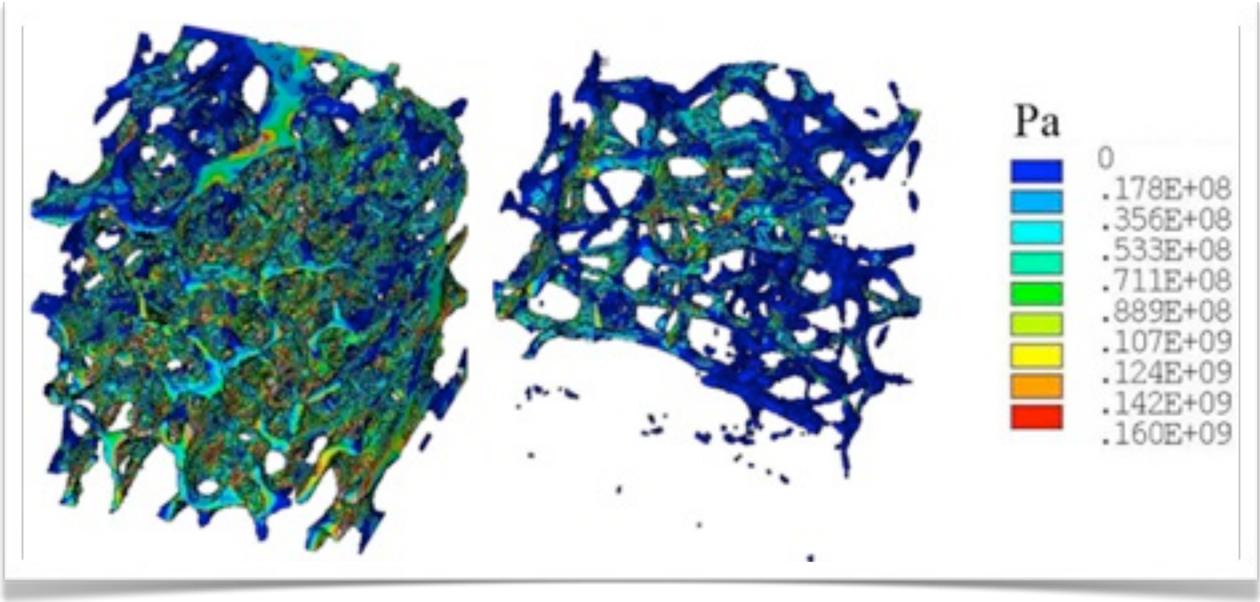


Fig. 3: Parametric stress maps of the simulated compression tests in the z-axis for the normal (L) and osteoporotic (R) samples

The results for a set of μCT image samples of distal radius trabecular bone have shown that a structure with low volume fraction, low connectivity, high tortuosity and low Young modulus has a normalized MCP very close to zero, in other words, the structure is fragile, while normalized MCP close to one correspond to structures with much better stiffness (see Figure 4). The results provided by the MCP were obtained simply by computational means, nevertheless to better understand how *de facto* the structure behaves under mechanical loading conditions, simulating possible falls, experimental tests would provide additional support[40]. Approximately 40% of the costs with physical therapy due to osteoporotic fractures are related to the treatment of distal forearm, thus it is quite important to produce better results improving the overall understanding.

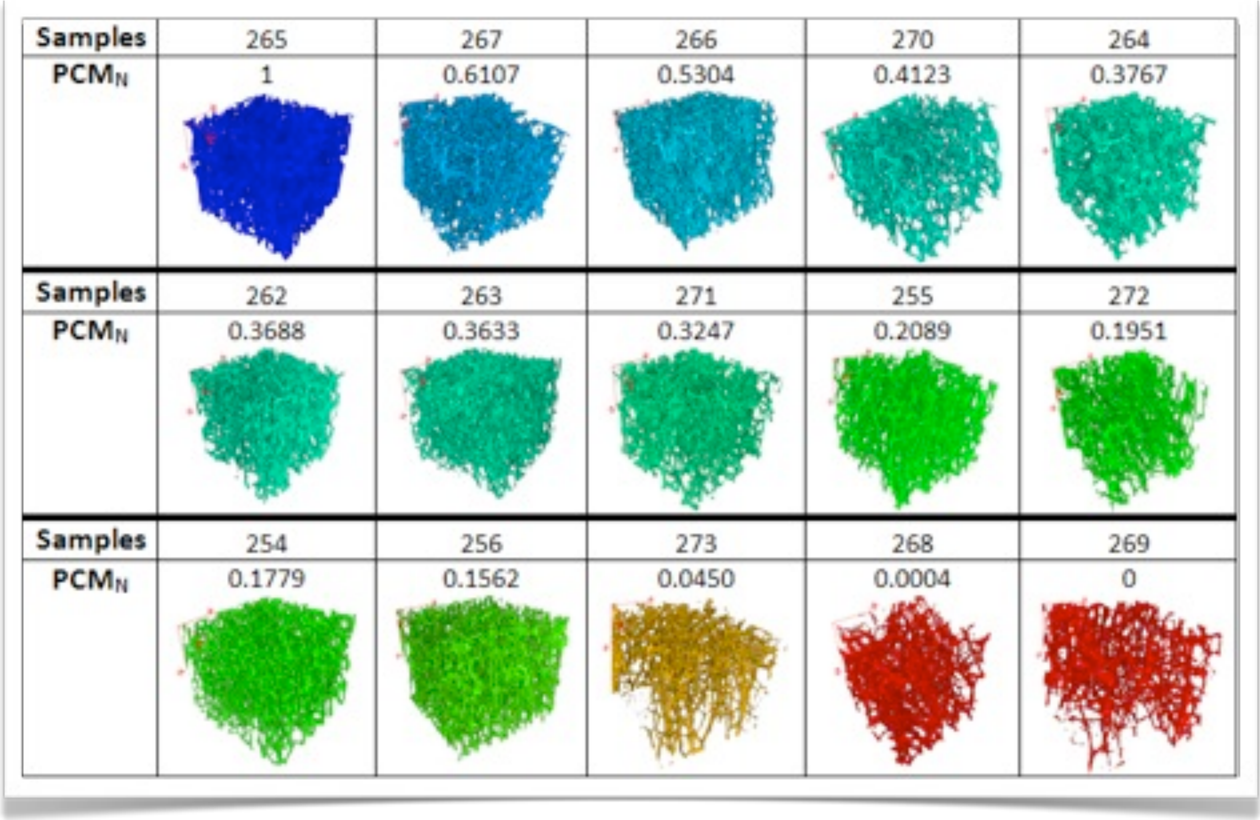


Fig. 4: Color spectrum of normalized MCP for 15 distal radius trabecular bone samples

Of course, to perform experimental tests with real bones is not a simple matter as the acquisition of bone specimens are either from cadavers or from patients that were submitted to bone biopsies. The former case is not very simple as there are several rules and ethical protocols to follow before getting permission to extract bone from cadaveric donors and the later is an invasive *in vivo* procedure that is uncomfortable and provides just a very small bone sample. To circumvent these difficulties, several approaches have been proposed to mimic the mechanical behavior, most of them using finite element analysis[9 41] simulations based on 3D image reconstructions.

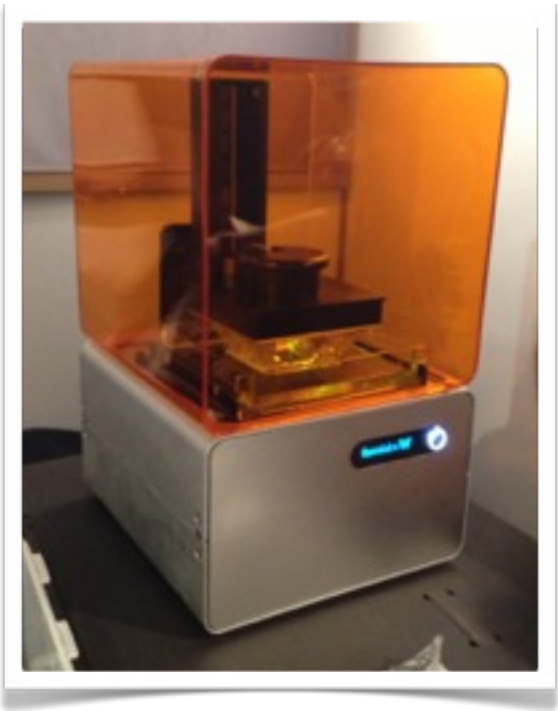
In tissue engineering, porous scaffolds must be developed with sufficient mechanical strength to preserve their initial structures after implantation, in particularly when dealing with the reconstruction of hard, load-bearing tissues, such as the femur bone, for instance. The mechanical and biological stability of implants depends on factors such as strength, elasticity, impact absorption at joints and biochemical degradation. In this regard, 3D printing of bone tissue is a very useful tool to produce high accuracy bone replicas from image samples and then these replicas can be submitted to mechanical stress tests and other studies[14 42 43].

Additive manufacturing

The construction of physical 3D objects from a set of 2D contiguous image sections of finite thickness is a new technology known as additive manufacturing (AM)[26]. In contrast to the subtractive methods, that construct a final 3D object by cutting away material from an initial block, the AM machines are fed by cross-sections in such way that they can be merged in a layer-by-layer sequence to form the physical object. Clearly the thinner the layer is the better will be the approximation to the actual object. The AM machines available nowadays make use of the layer-based approach, nevertheless they may differ according to the type of materials they can use, on how the layers are created and glued onto each other.

For the industry, the construction of prototypes is essential for the success of a product. Although computer systems like CAD/CAM are very useful for product model design and development, many aspects are not touchable as in a solid model of the object. On the other hand, with the current industrial competition for innovation, there is a high demand for rapid prototyping of product models. Therefore, rapid prototyping technologies have emerged to provide a much faster way to product development by integrating the four fundamental aspects: input, method, material and applications, as stated in the book [44].

Stereolitography and 3D printing



Stereolitography[45] is an AM technique that uses a laser beam to selective draw the corresponding 2D image on a photosensitive resin solidifying it. The result of stereolitography is a 3D physical replica of an object, in other words it is understood as the result of a 3D printing, similar as a 2D printing. In fact, stereolitography and 3D printing were originally the names given by the US company called 3D Systems and by MIT researchers that have invented the ink-jet printing technology, respectively. As the printing technology is everywhere familiar, the idea of printing a 3D physical object is becoming also a common place, and the AM technology is now getting very well known as 3D printing.

3D bioprinting

The 3D printing technology has called the interest of biologists and physicians as an alternative way to construct artificial tissues and living organs from someone's own cells to be genetically compatible for further transplantation. This very idea has already started on an experimental level with aid of computer bioadditive manufacturing[46], a process that deposits living cells in an appropriate scaffold to generate 3D tissues and organs. This cell printing technology has been referred as 3D bioprinting.

Bioprinting foresee many different applications, like for instance spraying cells in situ to regenerate tissues. This certainly will be very important in the treatment of skin burns. In [47] the reader can find a very nice up-to-date discussion of 3D bioprinting with current challenges and perspectives.

Conclusion

The development of new drugs associated with the improvement of life style have helped to raise the life expectancy worldwide. In contrast, the aging of the world population has brought the incidence of osteoporosis to a much higher figure, which due to its consequences lessen the quality of life of this population. One of the main outcomes of osteoporosis is bone fracture, therefore much research in this field is devoted to predict the fracture risk.

The bone quality is a result of a large number of biological and biomechanical processes and the understanding of these is fundamental to better diagnosis and early care to prevent fractures. On the other hand, once fractures have occurred it is necessary to have a rapid response to regenerate the bone tissue or to implant a prosthesis. In general fractures in elderly people brings a series of mobility problems, morbidity and in many cases is an indirect cause that leads to the patient death. The current advances in 3D printing, more precisely in 3D bioprinting, is opening up new perspectives in bone tissue engineering[48] and the possibility of constructing accurate physical trabecular bone replicas that can ease the study of mechanical properties with experimental tests. In addition, 3D bioprinting is already fostering the development of bioactive composites and nano-materials[49] [50].

The 3D printing has called the attention of the research and industrial communities, particularly due to the possibility of rapid prototyping of solid objects, but its cost is still high. However, the next generation of low-cost environmental friendly 3D printers will make them affordable to schools and hospitals, improving the teaching quality. Unfortunately, everything in life has pros and cons, and 3D printing has already been thought of as a technology to develop new weapons, but this is not a fault of the technology in itself, rather a human weakness. Instead it would be far better to apply the 3D printing technology to build prostheses to supply for free among physically impaired people in poor countries.

There are quite a number of websites devoted to 3D printing[51]. As said by Joseph Schumpeter, an Austrian economist, technology is a creative destruction, and 3D printing will certainly destroy some previous technologies, but its benefits seem very promising.

Acknowledgement

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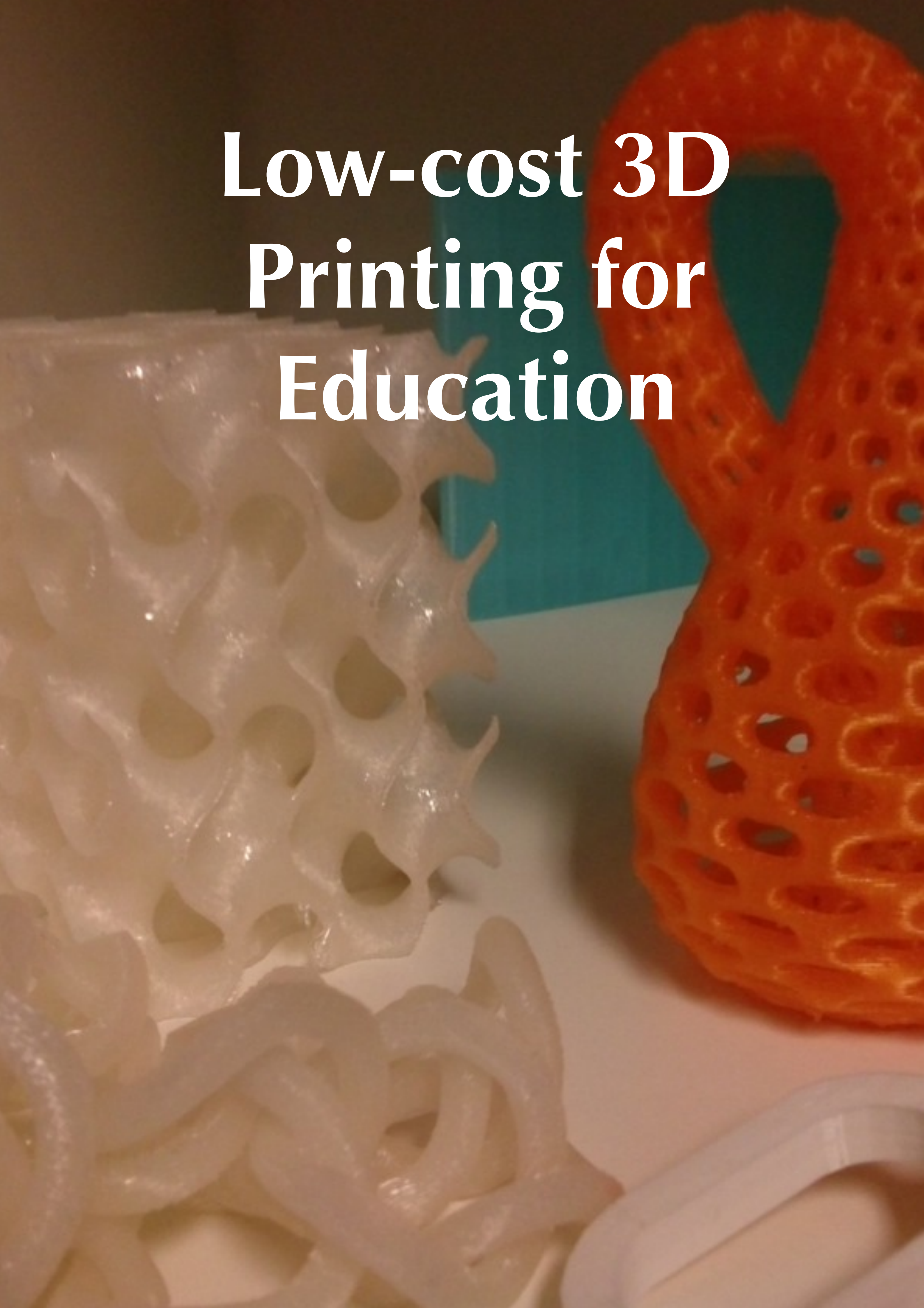
Low-cost 3D Printing for Education



Using 3D Printers at School: the Experience of 3drucken.ch

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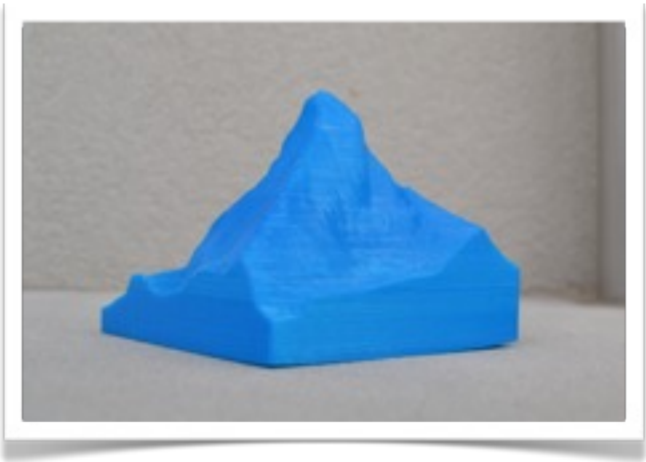
3D printing at school

Low-cost 3D printers are being introduced in the school environment resulting in novel education possibilities. Models designed on computers can be printed and thus prototyped in three dimensions (3D). Theory is quickly transferred into physical objects, which can be touched. Students are able to work with modern and trend setting tools.

Applications of 3D printing in various school subjects are for example:

- Mathematics: Designing, printing and calculating 3D objects.
- Geography: Reliefs.[1]
- Arts: Designing different objects and print them.
- Sciences: Printing models of molecules.
- Music: Printing simple instruments.



Relief of Matterhorn, generated from DEM data, 3D printed

Many additional options are possible, limited rather by imagination than technical limitations. A large number of 3D models can be found online on Thingiverse [2] or in the 3D Warehouse[3].

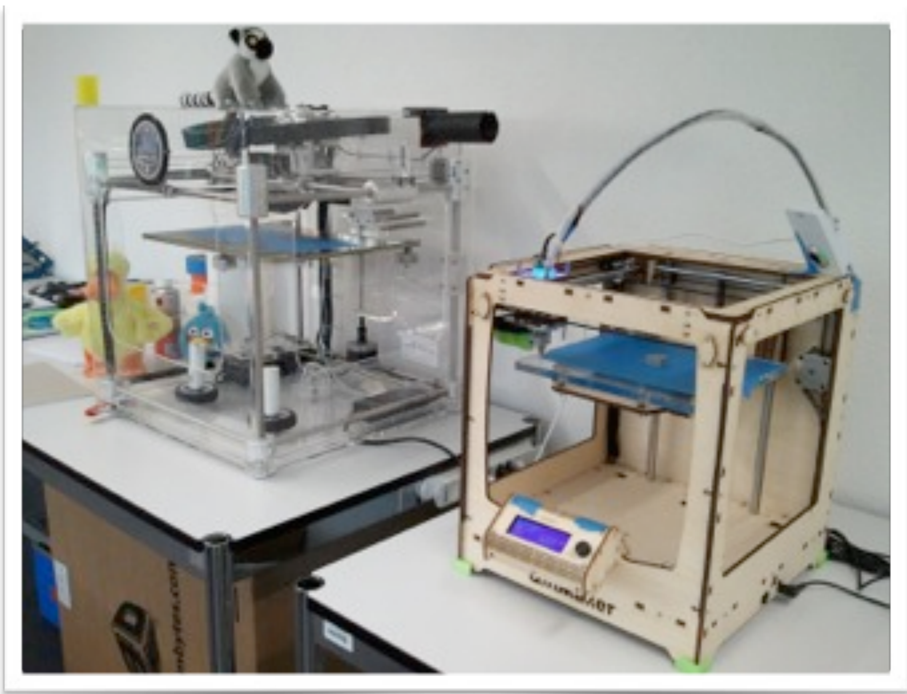
Project Description "Güggeltown: Students are printing their own City" [5]

Preparing the Project

The project was realized from August 2012 to January 2013 within a course of 16 lessons (each 90 minutes) in technical drawing[5] at a 8th and 9th degree class in Steffisburg with 14 to 15 year old students. Lead by Kurt Meister, school of Steffisburg, and Gregor Lütolf, University of Teacher Education Bern (PHBern).

Before starting the project, an evaluation of 3D printers had been made. The first choice printer BfB 3DTouch was limited by different factors. It was big, heavy, worked too slow, had a bad accuracy and was based on both closed hardware and software. Being active in social media communities as Google+ and blogging on http://3drucken.ch about our research, we decided to buy two assembly sets of Ultimaker[6]. This printer was awarded best product in the categories 'Most Accurate', 'Fastest' and 'Best Open Hardware' in the Make:magazine November 2012 edition[7].

For the 3D modelling, a CAD software was required. After an evaluation of several products, it was decided to use the cloud based software Tinkercad[8]. This was used in combination with the free tool Sketchup[9] with an additional plugin[10] to export the data to the 3D printer.



BfB 3DTouch on the left, Ultimaker on the right

Running the Project

Introducing Tinkercad

To introduce the students to the modelling process on a computer, they were given the task to sketch a ship. The only assistance they got was a tutorial document of Tinkercad. No further instructions were provided by the teacher.

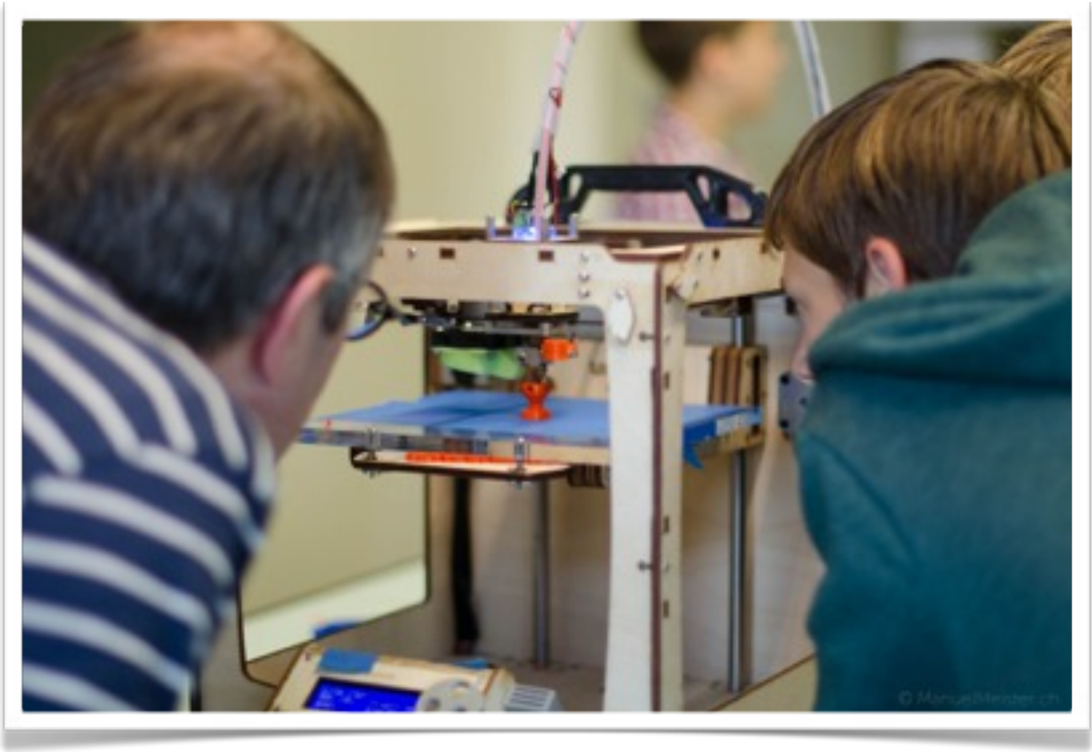
Ships sketched in Tinkercad by students

Introducing Sketchup

During the next lessons the students were introduced to Sketchup by tutorials too.[11]

First contact with the printer

The students were introduced to the steps involved in working with a 3D printer, such as modeling, slicing and printing in teams.



With interest first printed objects are expected

GüggelTown is growing

Inspired by a kide[12] project, every student sketched a building for their small city called GüggelTown. The lots on the city map had various sizes and were shaped differently.

Restrictions

The object's size was limited:

- The lots size must not be overlapped
- Each dimension has a maximum of 20 cm
- The three-dimensional-domain is not more than 600 cm3

Ideas

The students draw several sketches on paper.

First draft of a student's idea

Dimensions

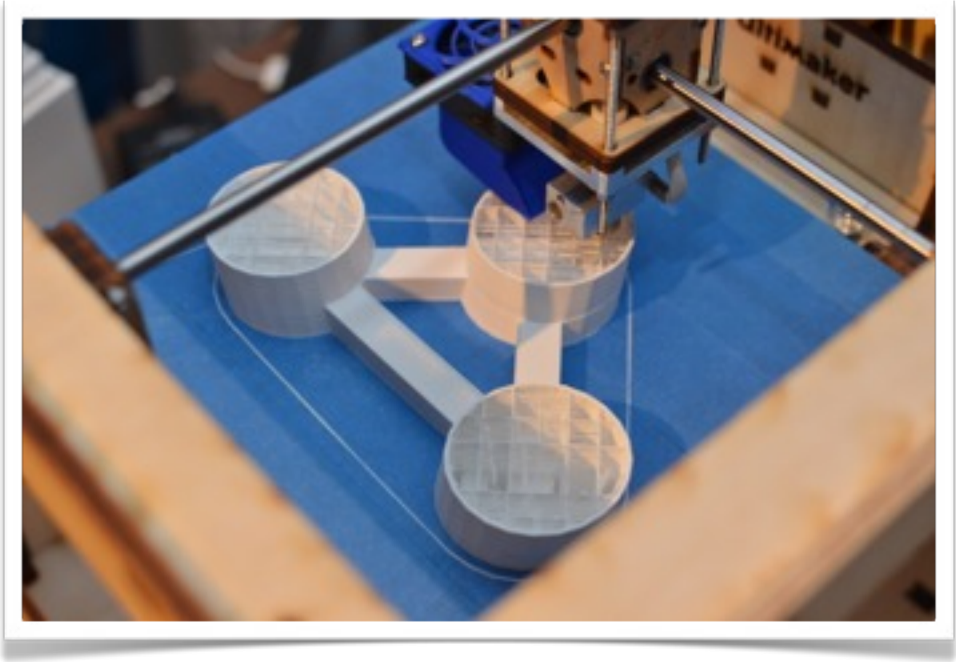
Each student chose one sketch and draw this one on a preprinted paper in common prospect. They defined the dimensions for the CAD drawing as well.

Modeling by CAD[13]

Using one of the former presented tools Tinkercad either Sketchup the students modelled their building step by step.

Printing

The objects were printed. Despite of optimized settings (filling only 5%) the Ultimaker took about 120 hours to print all the buildings. That's why most of the prints were accomplished over night.



One of the buildings is getting printed

Final Presentation

A presentation of GüggelTown for parents and other interested people was arranged during the final lesson. The students presented the workflow of the 3D printer live on the Ultimaker. The findings of the project GüggelTown and their formation were presented on several small information points.

GüggelTown, shown on the final presentation

The event was well attended and in addition the local press[14] was interested in the project GüggelTown.

Conclusion - What did we learn from this project?

We were surprised by the highly motivated students throughout the whole project. They hardly missed any lessons, even if they had other events to attend to. Based on our observations and the feedback given by the students, some of the motivation was due to presence of the 3D printer, which gave them the opportunity to get their ideas and models to real life objects. Other motivation came from the easy to use free software tools, the possibility to use a PC for the only two hours each week at school, or the fact that they were free to design a building of their dreams. Some of the students had more experience in using CAD software, others put more hours even at home to design the buildings. In the end, all of the students came up with a printable design of their own. We also encouraged the more experienced students to help their colleagues.

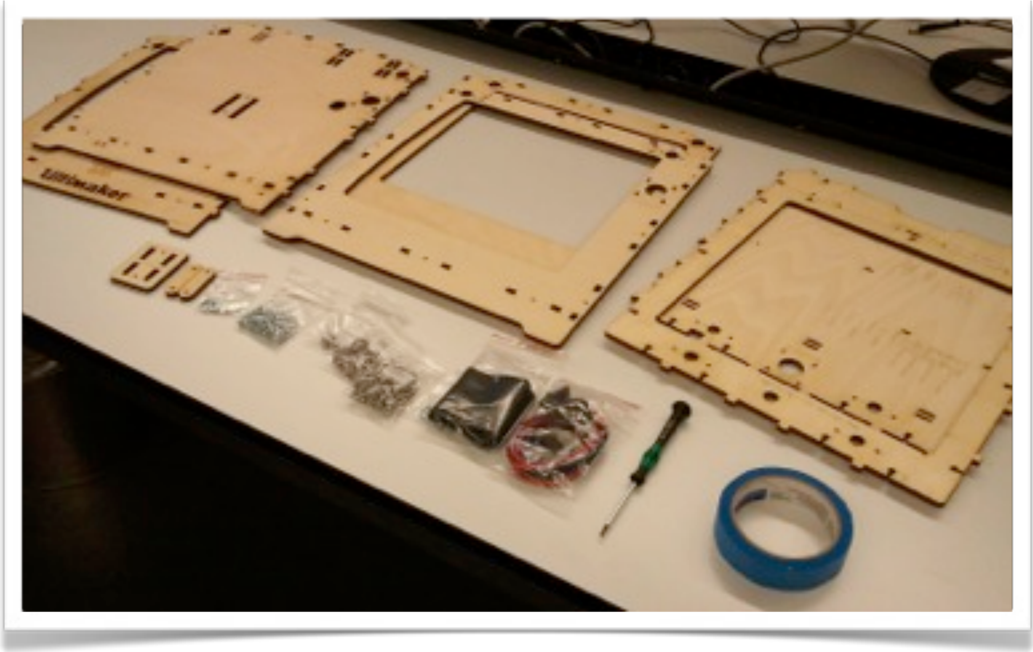
Expenses and expenditure of time

3D printing at school means a big time investment. The acquisition and assembling of the printer are time-consuming. In addition, one needs to get familiar with the controlling of the printer. It might be useful to establish cooperation between school and an advising- and education-center. In such a venture, the center may supply the technical support and the school may plan the educational setting.

The time and effort to built up the Ultimaker, about two days, was done during working hours at the University of Teacher Education Bern. This effort would be a lot of time for a teacher, but it turned out being a good investment since they gain understanding into the technics of the 3D printer, valuable in case of future trouble-shooting.

Overall we calculated expenses of 3500€. Most of the costs were paid by the University of Teacher Education Bern thus the hours of work of Gregor Lütolf were provided by the University of Teacher Education Bern. The expenses for each assembly set of the Ultimaker reached about 1500€. Further on we bought tools and printer filament (PLA) for another 200€. The printer filament costs about 30€/kg. The school of Steffisburg payed about 150€ to print the citymap, and financed the final presentation event.

In this calculation are not included the countless hours of work which were spent to assemble the Ultimaker, to get the know how to control the 3D printer and to learn the work flow from idea to finished print.



Some parts of the Ultimaker assembly set

Didactical concept

Independent learning is possible throughout the whole process. Starting with the idea and ending with the printed object. The 3D printer is a secure tool and absolutely risk-free when used by students. The iterative process is convenient for classes because sketches can be adapted and reprinted at any time. Consequently, a product can be developed step by step. In addition, it is a good alternative to classic „learning by reading and writing" education, since the work is rather *"learning by acting"*.

Printable 3D models

Digital 3D models can be realized in three different ways:

(ix) with a CAD software on a computer,

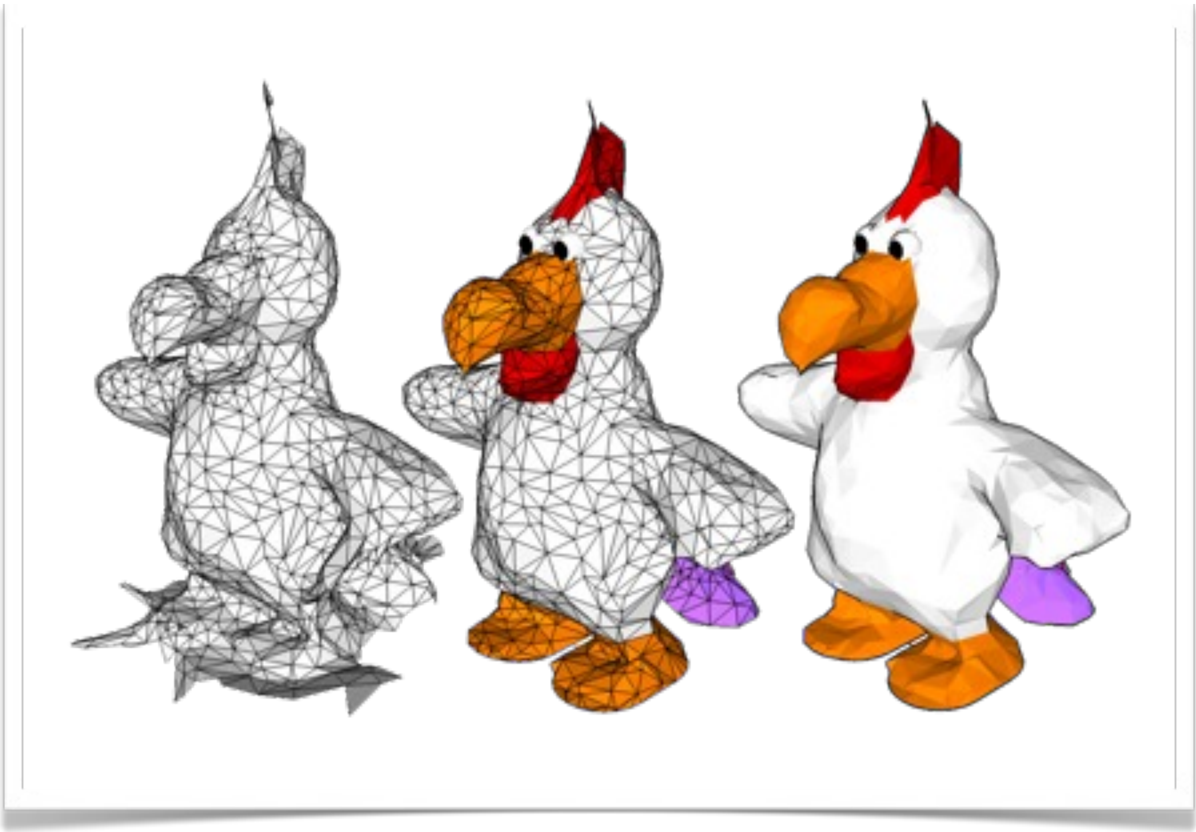
(x) taken from a scan of an existing 3D object, or

(xi) generated by codes.

To be printable, those digital models need to be further conformed to fulfill other criteria in comparison to only be displayed on screen. This is why one absolutely has to pay attention to avoid holes in the models and that the surfaces are well adjusted. Elements, which are to filigree can get lost in the slicing process. One must thus avoid strongly extended overhangs since they have to be completed by automatically generated supports.

Long-term objective: Fab Lab at school

A Fab Lab is a high-tech workshop where one can find equipment, such as 3D printers, laser-cutter and CNC-machines. The first Fab Lab has been initiated in the year 2002 by Neil Gershenfeld at the Massachusetts Institute of Technology (MIT). At this time a multitude of those Fab Labs exist worldwide[15]. A Fab Lab at school is providing access to this modern production processes to all interested students.



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Prehistoric Collections and 3D Printing for Education

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Background – Turkana Basin and the African Fossils project

The paleontological expeditions began in the Turkana Basin of Northern Kenya in 1968, and since then numerous important specimens of both hominids and other fauna have been recovered[1]. These are currently stored in the National Museums of Kenya or at the Turkana Basin Institute facilities at Lake Turkana. With new technology and software, especially in the area of photogrammetry, an opportunity presents itself to capture, in a digital format, many of these impressive collections. These digital models can then be accessed on-line and interacted with using an on-line viewer and provides a unique opportunity for teachers and students to explore our past.

Digital capture and software

Several methods of digital capture have been used in the African Fossils project, although photogrammetry has been the primary method of acquisition. In addition a FARO arm scanner and also more recently a 3D3solutions structured light scanner with a macro lens attachment, have been used to capture the largest and smallest specimens respectively and have produced some good results.

The models are captured using a digital Canon SLR camera with a zoom lens. The images have been shot in RAW and JPEG format. Some 90 images are taken of the stationary object from above and then a further 90 images of the underside. These images are then imported into Autodesk® ReCap Photo and a variety of other software including Autodesk® Maya, Geomagic Wrap, Meshmixer and Adobe Photoshop and are used to creating the interactive digital models. The texture files can also be combined with a laser scan point cloud if this has been captured for the same specimen.

In addition to the models of individual specimens, actual field sites have been digitally captured, using a combination of photogrammetry and a laser scanner such as the ZFS Scanner (Zoeller and Froelich) or the FARO Focus3D. The photographs were taken both from the ground and with a Sony Nex 7 camera triggered with an Infrared shutter attached to a rig on a kite. This method has proved effective in the reconstruction of field excavations. Scantime software was used to publish them for interactive web viewing.

Printing of the digital models for education

The resolution of the digital models that we have captured using photogrammetry are still not as high in resolution as those that would result from CT scans or from the traditional high quality casting methods. Therefore 3D printing of these models cannot yet be considered a replacement for these techniques which are so important for detailed scientific study. However in so far as accessibility and interaction with the specimens from an educational perspective, the digital models captured using photogrammetry are excellent.

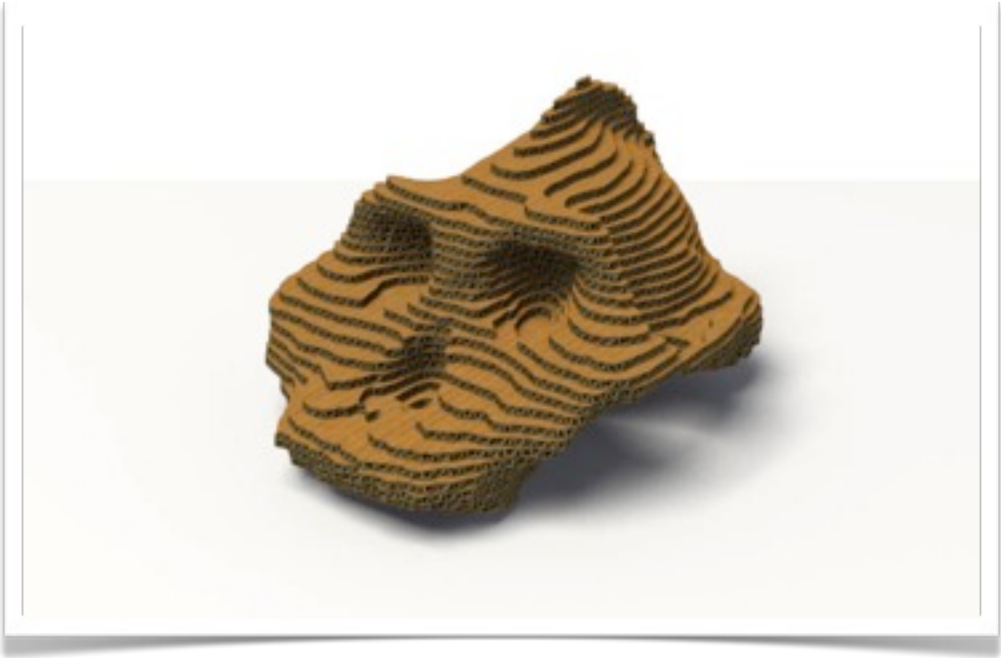
Other applications of the digital files for education

Web site design

To display the digital models and to provide a place to interact and explore them in more detail, a virtual lab was designed built on-line at **http://www.africanfossils.org**. This website will undergo some additional changes in the coming months to incorporate search, comparison, map and social media as well as the opportunity to download a low resolution file for home 3D printers. It provides a digital story and a window into the past.

Cardboard models for assembly

African Fossils used Autodesk® 123D® Make (free software) to cut out a series of templates from corrugated cardboard using a CNC laser cutter. This enables crude models of the skulls to be assembled by sticking one layer on top of another. These quick hands on projects are ideal for classrooms and for engaging children in building the cardboard reconstructions encouraging them to explore the diversity in the fossil record.



Copyright and Intellectual Property

In this digital age, copyright and intellectual property rights remain a concern to museums with large collections of artifacts. High quality files that are generated from CT data as well as high quality casts, in most cases remain the intellectual property of the academic and scientific institutions. These continue to be valuable and generate much needed revenue for institutions such as the National Museums of Kenya. Lower resolution files captured through photogrammetry and laser scans are arguably most valuable if they are made widely available and accessible so that they have maximum impact in education. This is an area where museums can have a major impact in terms of learning and engagement but is an issue that needs to be considered carefully.

Acknowledgements

We would like to acknowledge the contribution of Autodesk, the Koobi Fora Research Project, National Museums of Kenya, Turkana Basin Institute as well as all the individuals that have been a part of the African Fossils project through these organisations.

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3D Printing in Art Installations

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Alternate uses of technology have been rather common throughout history. Many of today's popular technologies of the entertainment industry have evolved from being plain and useful tools, to more playful and ludic devices. The realm of low cost 3D printing is no exception.

Low cost 3D printing is a relatively new technology, that started circa 2006 with the RepRap project. Back in the days, the traditional "first print" of a RepRap was a shot glass where you could pour your favorite drink and celebrate the completion of many hours of work resulting in your own hand built 3D printer.

Glass shot (source: http://www.thingiverse.com)

Do-It-Yourself (DIY) 3D printing was quickly adopted by tinkerers and electronic hackers alike, and many of the uses, then and now are simply ludic, playful, or fun. In fact, is not until recently that DIY 3D printers have become more of a tool and not just a very "nerdy" gadget. Printers have become faster, more stable, and prints have become larger, more consistent and of more quality thus making the home 3D printer a powerful and versatile tool.

As the learning curve to use this little machines lowers, more people have jumped into the 3D printing wagon. Users with little to none skills on electronics, programming or modeling have found in 3D printing a way to create and express themselves in a previously unknown very physical manner. Objects now jump from the screen to the desktop after a few clicks of the mouse. The immediateness of the process makes it highly rewarding, and people keep pushing the limits of their own creativity using this cheap, simple and at the same time very complex technology.

In the arts realm, creative minds have adopted this technology from the very beginning, and have given it uses that no one predicted before. From 3D printing a figurine of yourself or your unborn child, to scanning and printing ancient sculptures that otherwise could only be found in a museum.

3D printing and art installations

3D printing has also become a popular tool in ludic applications, some common examples of its use are:

Building of costume pieces for art installations

Art installations include a wide range of input devices such as cameras, sensors, switches, and also output devices like motors, actuators, or lights. This devices are usually out of sight for aesthetic or even safety reasons. To house this components, designers rely on existing commercially available products. With a 3D printer however, this housings can be customized to meet the exact requirements of the piece, making them a part of it.

One very common piece of electronic found in many of today's interactive art pieces is the Arduino board: Arduino boards can be connected to many I/O devices, but once we connect these devices we must house them all to avoid accidental disconnections. A quick search through Thingiverse[1], gives us over a hundred different housings for this board.

Arduino case (source: http://www.thingiverse.com/)

Building of large structures made up of smaller printed parts

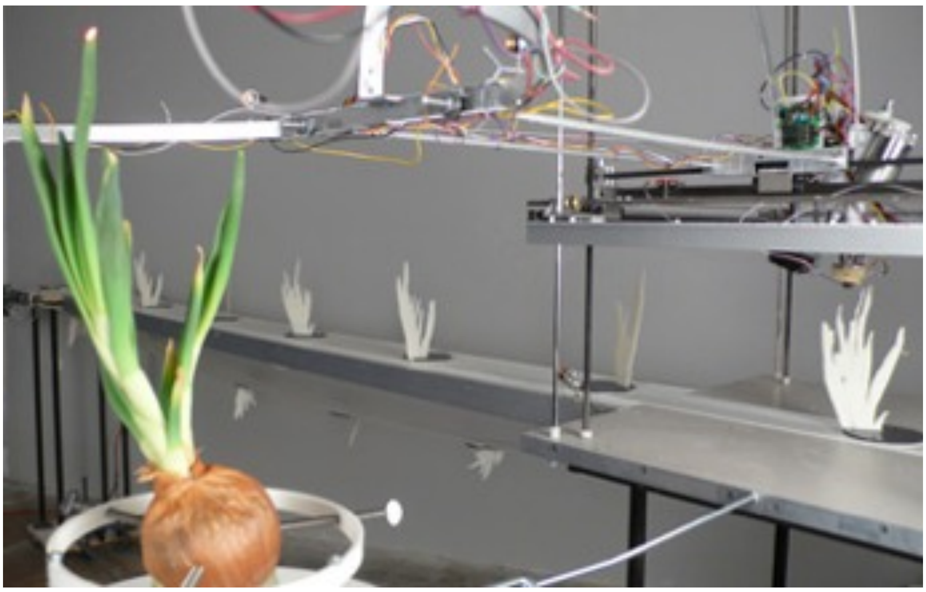
DIY 3D printers are not exactly fast. Printing a small 20mm cube can take a few minutes, and printing time grows exponentially with volume, so larger or more complex pieces can take hours to finish. For this reason, the printable area of this machines is usually confined to limit the time and amount of plastic used. Printing smaller parts that joined together will become a larger piece is a common workaround for this.

A beautiful example is a sculpture made by Cosmo Wenman[2]. Wenman uses a digital camera to make hundreds of photos from different angles of an existing sculpture, and then stitches them together using computer software. One of his most impressive works is the head of a horse belonging to an ancient marble sculpture found in Athens circa 438BC. After obtaining the model, it was split into smaller printable pieces, then it was put back together and given a paint job to resemble a bronze-like finish. This also brings up another use of 3D printing: the ability to reproduce museum pieces that can be shown anywhere.

Horse Head (source: http://www.cosmowenman.com/)

3D printing as the center of an art installation

While 3D printing is indeed a powerful tool of many uses, sometimes it becomes the core of an art installation. A piece called “Growth Modeling Device” by David Bowen uses real time laser scanning and a 3D printer to scan an onion plant and reproduce it in plastic over a period of time. The end result is a paradox, since the printer is producing a static piece of plastic of a living organism which is constantly changing[3].



Growth imaging system (source: http://www.dwbowen.com/)

Another example is the public installation "Be your own souvenir" by the blablablab collective, where 3 Kinect sensors were used to scan pedestrians of Barcelona's ramblas and then were printed on site. The result being a souvenir of your own self[4].

Be your own souvenir (source: http://www.medialab-prado.es/)

So, what can I print?

As personal 3D printing has gained wider acceptance, the need to provide suitable content for them has also increased. Common 3D modeling software such as Sketchup, Rhino or Autocad can be used to make printable models. However, 3D modeling software has been traditionally used to make very complex models intended for animations for video games, CGI for films, high quality renders for professional stereolithography machines, *etc*.

DIY 3D printing, on the other hand, is not meant to reproduce pieces with such a high level of detail, but rather to rapidly produce working prototypes.

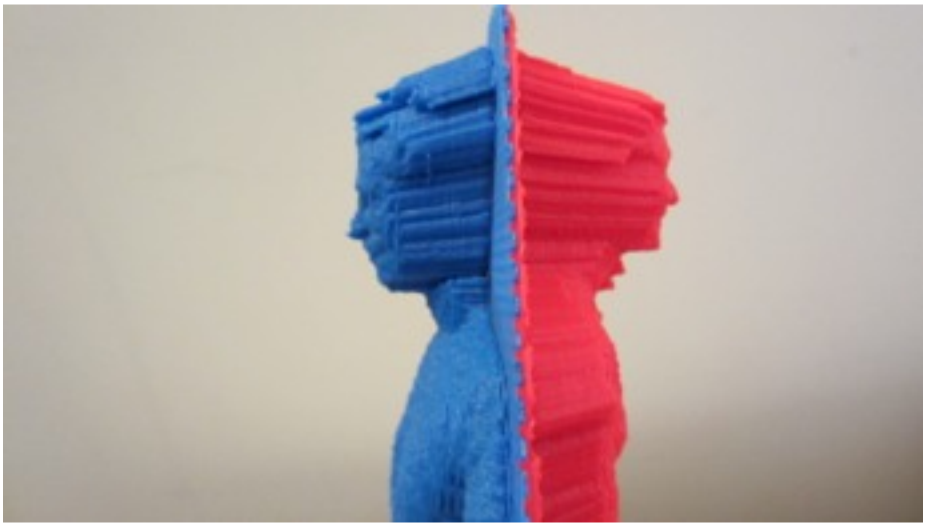
3D scanners and 3D printing

One of the means to produce printable models is to scan an already existing object that can later be reproduced. 3D scanners capture the geometry of a physical object by making hundreds of thousands of measurements. The result of a 3D scan is usually a point cloud or a polygon mesh.

High quality scanners using lasers for example are a great way to obtain models with a great deal of detail, but they are expensive, ranging from a couple of hundred Euros well into the thousands. Other 3D imaging technologies such as CAT scans, MRI's and ultrasound can be used to obtain printable models. But again, this are expensive machines that are well outside the range of the DIY community.

One common way to obtain a 3D scan is to hack common devices such as the Kinect controller from Microsoft®. The Kinect was meant to be an inexpensive input device to control games and other applications for the Xbox console using only the movements of the body, but it was quickly adapted and transformed into a simple low-cost 3D scanner. The way the Kinect works is by shooting an infrared point cloud over an area, and then using an infrared camera it "sees" how much this points have shifted in comparison to a unique calibration pattern.

The Kinect's rather low resolution is ideal for DIY 3D printing, and the models obtained with it can easily be printed with minor modifications.



3D scan using Kinect (source: http://www.ultra-lab.net/)

References

[1] http://www.thingiverse.com

[2] http://www.cosmowenman.com

[3] http://www.dwbowen.com/gmd.html

[4] http://byos.blablablab.org

From Math to Jewel: an Example

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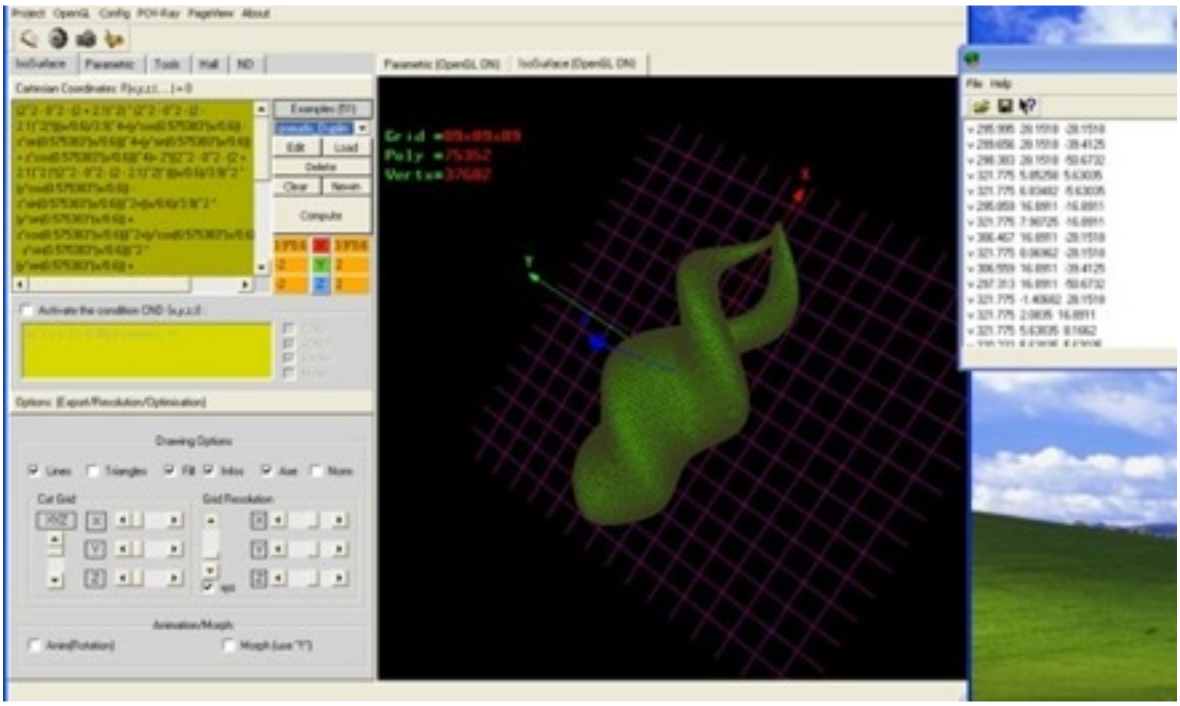
3D printing gives the possibility to transform what you can imagine into a tangible object that then can be also worn and showed off.

We will see how using just free tools available on the web we can transform a mathematical isosurface into an object that can be then used for instructional or decorative purposes.

The first step is to download a software that lets us visualize and manipulate mathematical surfaces in three dimensions. A good choice is K3DSurf[1], a free tool that works on multiple platforms and supports parametric equations and isosurfaces.

The software comes with more than 50 built-in examples, so you can start modifying the parameters in the provided equations to study the effects on the rendering result.



The K3DSurf interface

After playing around with the examples, you can start inserting your own equations in the text field, keeping in mind that the software requires the right-hand-side of the equation to be zero.

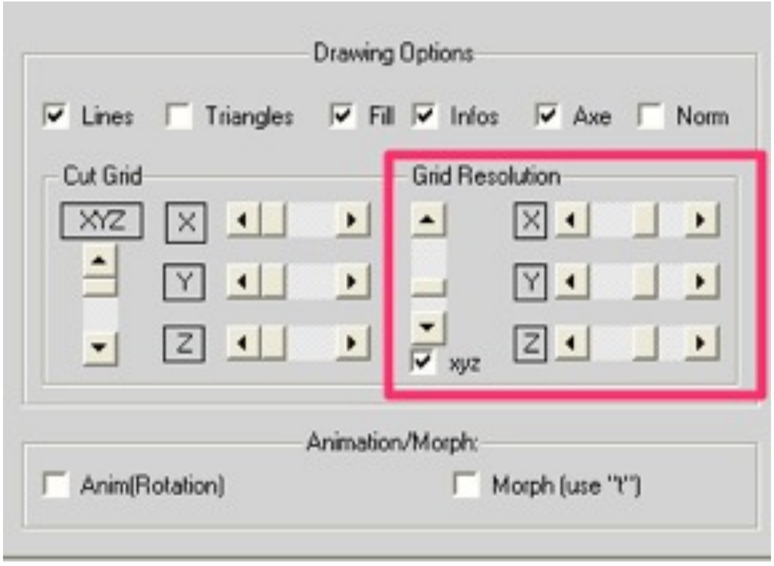
Some websites with interesting surface formulas are:

- Implicit Algebraic Surfaces
  http://www-sop.inria.fr/galaad/surface/
- University of Turin
  http://www.dm.unito.it/modelli/index.html
- Geometry, surfaces, curves and polyhedra by Paul Bourke
  http://paulbourke.net/geometry/
- Virtual mathematics museum
  http://virtualmathmuseum.org
- Java based tool that gives you the possibility to modify all parameters and visually see the result; you can then copy the corresponding equation on the formula tab
  http://www.javaview.de/demo/PaSurface.html
- Java based tool to calculate singular algebraic curves and surfaces
  http://www.singsurf.org/singsurf/SingSurf.html
- Isosurface Tutorial by Mike Williams
  http://www.econym.demon.co.uk/isotut/

For the following example we are going to use one of the build in examples provided with the software; an isosurface called pseudo-Duplin that was chosen because it looked interesting while still providing all the characteristics necessary for giving good printing results on a low-cost 3D printer.

```
(2^2 - 0^2 - (2 + 2.1)^2) * (2^2 - 0^2 - (2 - 2.1)^2)*(((x/0.6)/3.9)^4+(y*cos(0.575383*(x/0.6))
- z*sin(0.575383*(x/0.6)))^4+(y*sin(0.575383*(x/0.6)) + z*cos(0.575383*(x/0.6)))^4)+
2*((2^2 - 0^2 - (2 + 2.1)^2 )*(2^2 - 0^2 - (2 - 2.1)^2)* (((x/0.6)/3.9)^2 * (y*cos(0.575383*(x/
0.6)) - z*sin(0.575383*(x/0.6)))^2+((x/0.6)/3.9)^2 * (y*sin(0.575383*(x/0.6)) +
z*cos(0.575383*(x/0.6)))^2+(y*cos(0.575383*(x/0.6)) - z*sin(0.575383*(x/0.6)))^2 *
(y*sin(0.575383*(x/0.6)) + z*cos(0.575383*(x/0.6)))^2))+2* 2^2 *((-0^2-2^2+2^2+2.1^2)* (2
*((x/0.6)/3.9) *2+2* (y*cos(0.575383*(x/0.6)) - z*sin(0.575383*(x/0.6)))* 0-2^2)-4*0 *2.1^2
*(y*cos(0.575383*(x/0.6)) - z*sin(0.575383*(x/0.6))))*(((x/0.6)/3.9)^2+(y*cos(0.575383*(x/
0.6)) - z*sin(0.575383*(x/0.6)))^2+(y*sin(0.575383*(x/0.6)) + z*cos(0.575383*(x/0.6)))^2)+
4 * 2^4 * (2 *((x/0.6)/3.9)+0 *(y*cos(0.575383*(x/0.6)) - z*sin(0.575383*(x/0.6))))* (-2^2+0 *
(y*cos(0.575383*(x/0.6)) - z*sin(0.575383*(x/0.6)))+2 * ((x/0.6)/3.9))+4* 2^4 * 2.1^2 *
(y*cos(0.575383*(x/0.6)) - z*sin(0.575383*(x/0.6)))^2+2^8
```

After selecting the appropriate object you will want to check the grid resolution on the bottom of the window: choosing a very sparse grid will result in sharp edges and a "pixelated" appearance.

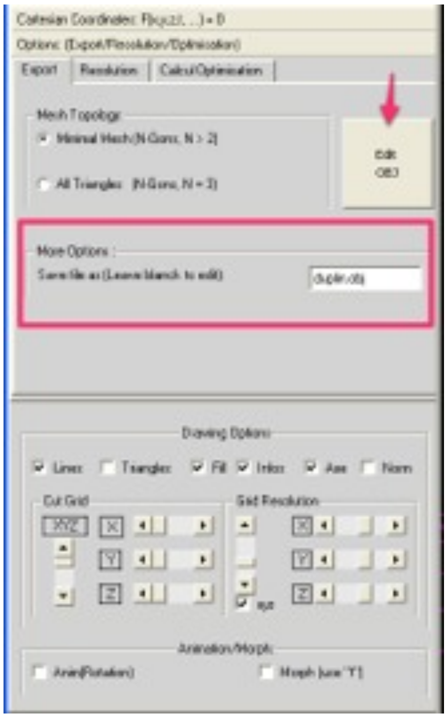


The K3DSurf drawing options tab

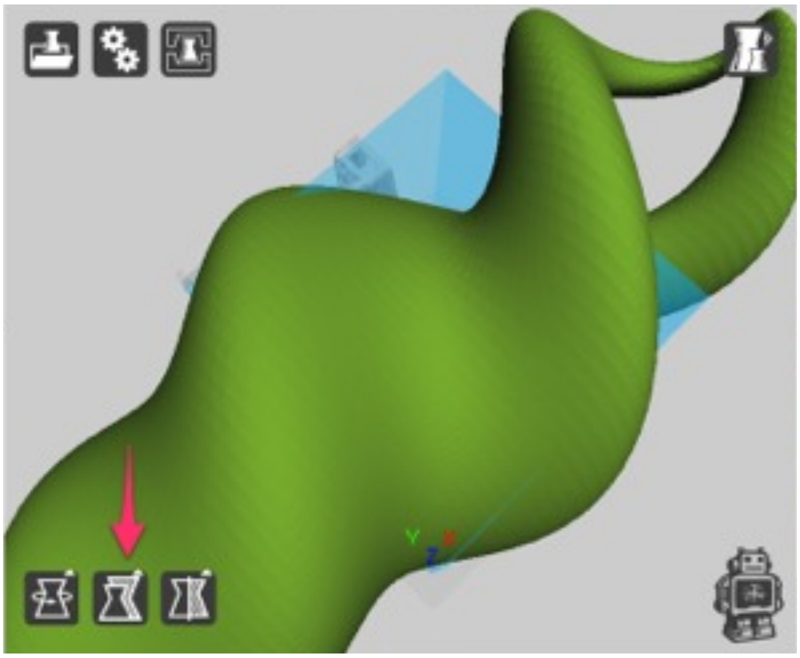
When you are satisfied with the result you can then export a OBJ file on the tab "Options: (Export/Resolution/Optimisation)".

Here you will insert the chosen name for your project (mind you have to add the *.obj* manually) and press "Edit OBJ".

The resulting file can then opened with Netfabb Basic[2] to detect and repair errors in the triangulated mesh, if needed, and convert it to STL, the file format most commonly used by the various 3D printing software. The following steps will be shown using Cura[3], a 3D printing software developed by Ultimaker[4] that avoids the need to convert the OBJ file as it accepts also this file format.



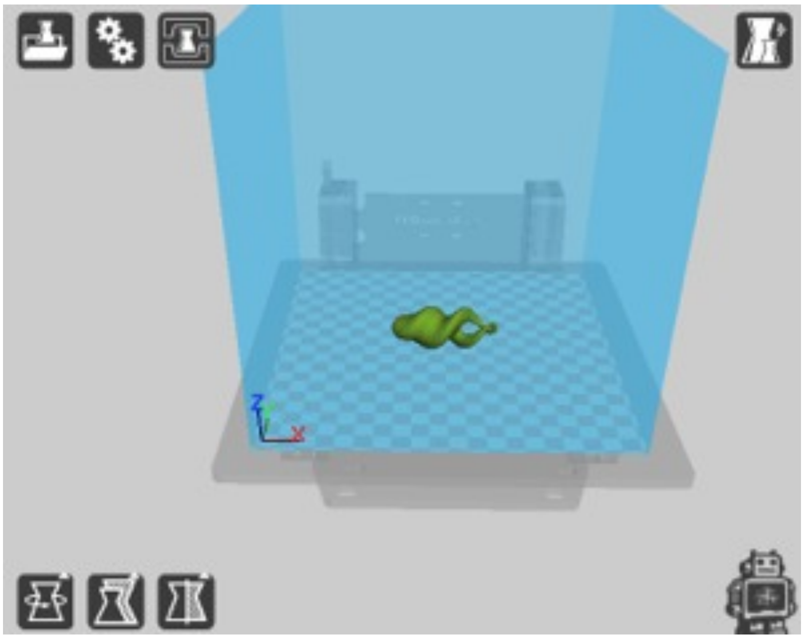
The K3DSurf Export tab



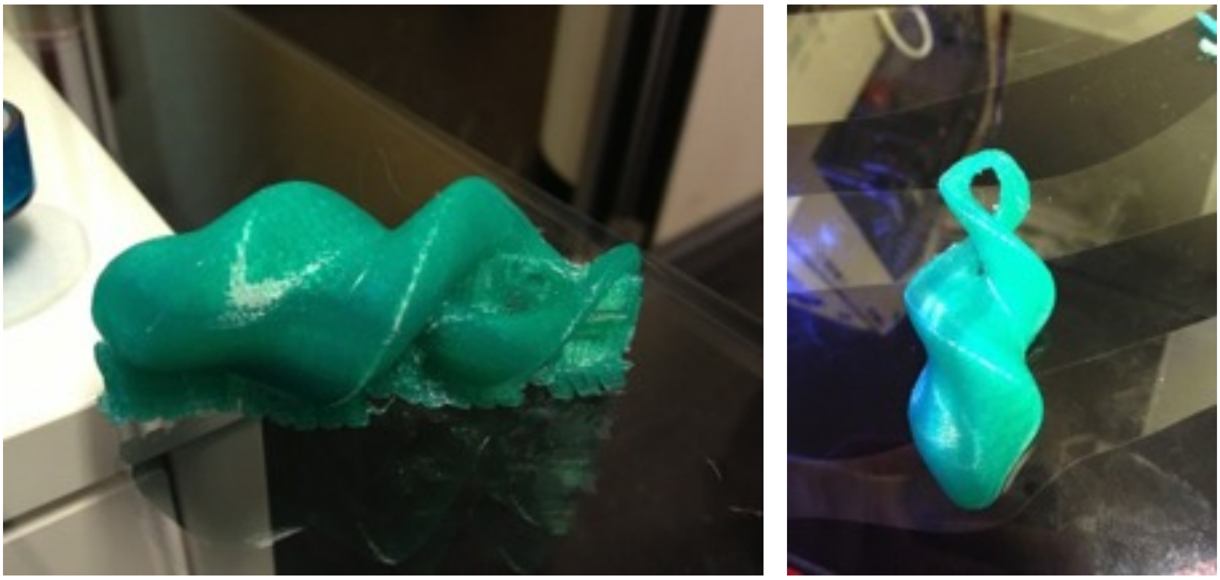
Cura's scaling option highlighted

With your slicing software you must first of all scale your object down to a reasonable size for printing, as K3DSurf will not give you the option of choosing the objects final dimensions.
Cura will let you do it easily with the "scale" button, while Netfabb Basic has a "scale parts" command with which you can obtain the same result.

The object can now be sliced, keeping in mind the adequate parameters for the chosen printer, and sent to your 3D printer. Bear in mind that most mathematical isosurfaces have a curved base and empty portions and will need a raft and/or a support structure to give printable results on a low-cost 3D printer.



pseudo-Duplin scaled for printing



The chosen object printed on the Ultimaker before and after separating the support structure

Some mathematical surfaces are particularly suited for jewelry for their shape and characteristics. For instance in this example there is no need to add any kind of ring to hang the object from a chain, while in other cases you might want to manipulate the .OBJ file in a 3D modeling software to manually add a mean of hanging it.

After the test with PLA on a standard 3D printer you can then decide to send the file to a print service to have it printed out in a different material like metal or ceramics.

This example was then printed in gold plated stainless steel by i.materialise[5].

Abderrahman Taha, the developer of K3DSurf, states on the website that *"Mathematics can be so fun!"* and *"an image is worth 1000 words"*.

While both these statements are certainly true I personally think that they can also be enforced stating that *"Mathematics can be so fashionable!"* and *"a 3D object is worth 1000 images"*. Math and art traveled side by side since the ancient Egyptians started incorporating the golden ratio in their monuments[6] and today we see mathematical principles applied to everything, including fashion. A low-cost 3D printer gives us the possibility to fill the gap between imagination and creation and have in our hands a mathematical structure to study, display or wear. This can then be used ad a prototype for the next step to a professional printing service or be appreciated by itself.

Acknowledgments

http://metamagics.wordpress.com

http://k3dsurf.s4.bizhat.com

Reference

[1] http://k3dsurf.sourceforge.net

[2] http://www.netfabb.com/basic.php

[3] http://daid.github.com/Cura/

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[5] http://i.materialise.com

[6] http://en.wikipedia.org/wiki/Mathematics_and_art

Low-cost 3D Printing for Sustainable Development

3D Printing in the Developing World: Learning from Techfortrade's 3D4D Challenge

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techfortrade is a UK based not for profit organization, founded in 2011, with a mission to ensure emerging technologies facilitate trade and alleviate poverty for farmers, workers and their communities. Increasing trade opportunities is critical for low income countries and the addressable market for the right products and services at the base of the pyramid is enormous. Whilst 2.6 billion people on the planet have an annual income of less than $3k p.a. and a further 1.4 billion have an income of between $3k and $20k p.a. this is still a market of more than $25 billion p.a.

However there are some significant barriers to trade at the base of the pyramid, not least of which is poor physical infrastructure which makes the movement of goods and services extremely difficult. The possibility that 3D printing might offer a solution that could address the challenge of poor infrastructure was a major driver for techfortrade's decision to mount an international challenge in 2012, in order to identify transformational uses for 3D printing technology that might change the lives of some of the world's poorest people.

The decision to launch the challenge was also influenced by the fact that the technology eco-system required for the implementation of 3D printing in developing markets is developing rapidly. This includes mobile penetration rates, access to the internet via a mobile feature or smart phone and the rapidly falling cost of open source 3D printing equipment and low cost mobile scanning equipment.

With a prize of $100k to be used to implement the winning idea, the 3D for development (3D4D) Challenge was launched on the 1st May 2012. The challenge process was as follows:

- Raise awareness of 3D printing opportunities in the developing world by staging a number of international workshops.
- Give entrants an easy mechanism to apply from anywhere in the world.
- Shortlist the best ideas and assign mentors to assist the finalists develop their proposals.
- Bring the finalists together in London to pitch their ideas to an independent panel of experts in order to select a winner.

By the 6th August 2012, the deadline date for entries, techfortrade had received more than 70 applications. Seven finalists were selected from the long list. They were:

- *Boris Kogan (Israel)* – small scale easy to manufacture 3D Printed robotic greenhouse to increase food production
- *Washington Open Object Fabricators - WOOF (USA)* – Enabling waste plastic to be reprocessed and manufactured on large scale 3DP machines into products required in day to day sanitation (composting latrines)
- *EN3D Project (Canada)* – 3D Printed solar tracker to increase efficiency of sustainable energy generation
- *Fripp Design & Research (UK)* – 3D Printing of soft tissue prosthesis (noses, ears) for congenital and trauma patients

- *Just 3D Print (India)* – Recycling of waste materials into economically and sustainable feedstock for 3D Printing community workers
- *Roy Ombatti (Kenya)* – 3D Printed patient specific footwear for sufferers of Jigger Fly infestation
- *Colalight (UK)* – Community assembled cola bottle based solar lamp with parts made using 3D Printing

The judges chose the WOOF project as the winner. WOOF's project will create new areas of employment by enabling waste plastic to be utilized as material for product creation.

The project team are working with Water for Humans (WFH) and their initial products will address local issues in water and sanitation in Oaxaca, Mexico.

Staging the 3D4D Challenge provided an opportunity to learn about the current landscape of people and organisations working on ideas related to the use of 3D Printing in developing markets. It is evident that there is a growing band of academics, entrepreneurs and 3D printing enthusiasts working on a range of ideas, from establishing libraries of useful 3D printable products that could be of use in developing countries to projects to develop solar charging carts for 3D printers. It is probably too early to describe this group as a community, although the Challenge has to a certain extent brought people together under the '3D for development (3D4D) banner'.

It was also evident at the workshops that some of the skills required to take advantage of the technology are in plentiful supply. There is a growing 'maker' community emerging in many developing countries and this community builds on a tradition of 'make do and mend' a skill set that has been lost in more developed countries. Also of relevance is the fact that more and more young designers and engineering students are competent in the use of CAD programmes and quickly grasp the concept of 3D manufacturing. In fact, a video[1] made at the House 4 Hack hackerspace near Johannesburg, where we held one of our workshops, shows that even school children quickly grasp the concept!

Finally, it's also clear that even in developing countries, young entrepreneurs have grasped the idea of using 3D printing as a low cost way of building prototype products and small product ranges. This is important because even with advances in injection molding technology, molds can still cost a minimum of $5k; a price that is unaffordable for small entrepreneurs in low income countries.

Since the Final, we have remained in touch with all of our finalists and most of them are making good progress with their projects despite not winning the prize. The Challenge provided a useful platform to showcase these projects and as a result many of the finalists have subsequently received offers of help.

Our winning project offers the opportunity to test a blueprint for a small scale community manufacturing business which involves plastic recycling and development of local 3D manufacturing skills to produce a range of needed parts and products for local markets. It also uses open source designs for large scale printing equipment and equipment for shredding and extruding waste plastic.

Whilst this blueprint might provide the basis for replication and scaling of initiatives such as WOOF's and indeed the Just 3D Printing project which has similar goals; there are a number of challenges to be addressed before this blueprint might have real commercial potential.

These challenges include:

- Developments in materials technology to broaden the range of plastics that can be properly recycled to make high quality filament in a simple low cost way.
- Developments in pigment technology to enable small batches of coloured filament to be made easily and at low cost. Addressing these first two challenges might allow developing countries to supply filament on a commercial basis as the market for 3D printing filament grows rapidly over the next few years
- Legal challenges associated with intellectual property that may prevent, for example, easy access to CAD files for spare parts.
- A better understanding of the economics of small scale 3D printing based manufacturing versus more traditional manufacturing & distribution in developing markets.

Commercial grade filament production from recycled plastic, collected and sorted at rubbish dumps in developing countries is of particular interest to us. We are not aware of any organization pursuing the concept of an 'ethical filament' proposition. In a recent blog entry for techfortrade, Joshua Pearce, Associate professor in the Department of Materials Science & Engineering, and in the Department of Electrical & Computer Engineering, at Michigan Technological University wrote[2]:

> *'One of our other major projects is building an open source RecycleBot, which can turn waste plastic into 3D filament ink. This has the potential to make it easier for waste pickers in developing nations to recycle plastic into high-value items for sale or simply to provide for their own needs. The use of a sustainable energy source and recycled filament not only holds the potential to help impoverished people but also improves the ecological performance of 3D printing.'*

At techfortrade we are planning new initiatives which we hope will encourage further developments to address some of these challenges and we are constantly on the lookout for collaborative partnerships that will help us to achieve our goals.

References

[1] http://www.house4hack.co.za/makerdroid

[2] http://www.3d4dchallenge.org/designing-the-future/

3D Printed Anatomic Replicas for Medical and Educational Purposes in Dental Surgery: Practical Projects from a Sustainable Development Point of View

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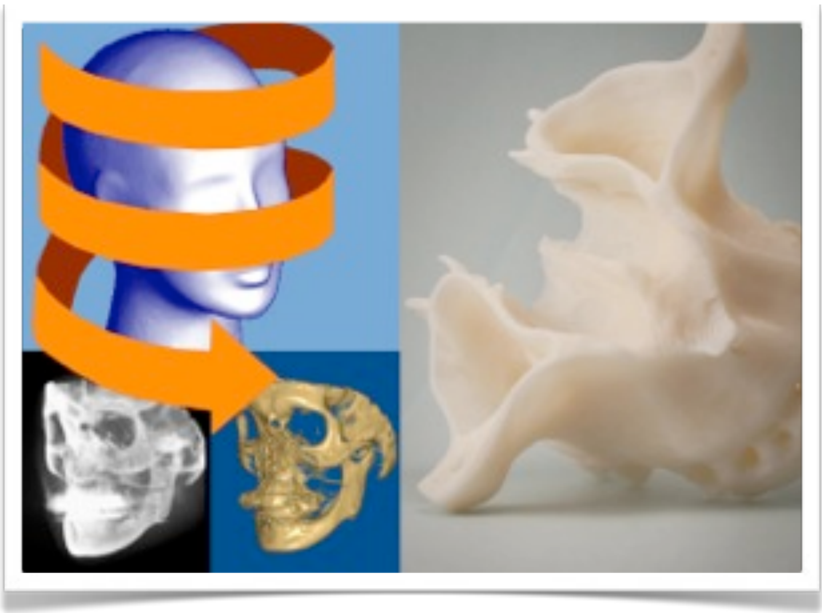
Introduction

Modern digital radiology departments analyze the bony structures of the human body by providing three-dimensional images suitable for morphological studies.



The use of a conical x-ray beam (Cone Beam Computed Tomography) allows in particular the acquisition of entire volumes of tissue. The absorbed doses of ionizing radiation is slightly higher than those of an old radiography and is reduced by 70% compared with a traditional CAT. The use of nuclear magnetic resonance allows to have details of soft and hard structures without the use of x-rays.

These images are very useful for the practical and correct design of surgical interventions in anatomically complex areas such as skull and maxillary bones, examining, for example, the structure of maxillary bones to locate a suitable surface for the bone removal, or for its insertion where needed.

The proposed technique is a system that allows the construction of anatomical replicas in the form of an anatomical medical model or professional stereolithography machines or through the use of 3D printers normally found on the market at a low-cost.

The aim is to ensure access to a technique already in use in oral surgery but, till now, reserved to an extremely limited number of clinical cases for its high cost, extending it to the largest possible number of users for didactic purposes, training and communication with the patient and among operators.

Two- and three-dimensional medical imaging in dental radiology: from Dicom files to the concept of thickness of the image

The close collaboration between radiologist and dentist develops through diagnostic questions related to complaints by the patient. Confronting the radiological investigation you can mainly follow two paths: first-level examinations, usually two-dimensional images carried out with direct scanning; and second-level investigations, that are grouped into those we can define "three-dimensional exams". The latter are of interest for the development of stereolithographical medical models.

The starting point is the "Dicom - Digital Imaging and Communications in Medicine" file, an interchange image format strictly for medical use, commonly used for both two- and three-dimensional images. A normal plate obtained through a digitalization process is composed of a raster image and a text file that may contain patient's data and the irradiation emitted during the execution of the examination; all of this makes up the Dicom files.

Two-dimensional Dicom medical imaging, normally used by dentists

In computer terms we analyze images composed of pixels, characterized by a value that in medical images corresponds to a "gray value" obtained from the impression of a digital sensor struck by an x-ray beam. All of these values, inserted into a defined size matrix, generate the radiographic image.

When we talk about three-dimensional imaging, we have to imagine that pixels, characterized by the "gray value", make up a volume and thereby the matrix has an additional feature, the "thickness". The complexity of the medical data obtained from three-dimensional surveys carried out with machines such as CT or MRI, is a small example of the decomposition of the volume into individual slices ("axial decomposition"). If you imagine the patient in an upright position, the axial slices are images oriented in the same plane of the ground.

Axial image from CBCT and three-dimesional acquired volume: the thickness concept

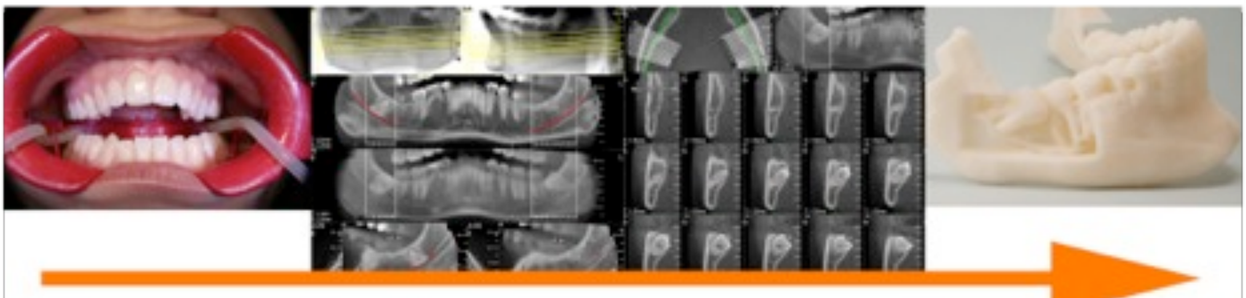
On the computer, we no longer get a single Dicom file, but a sequence of Dicom files, each of which contains an axial image characterized by a thickness, so the Dicom file describes all "gray values" composing a defined thickness of the volume under examination. The thickness and axial sequence concepts are the starting point for the construction of replicas with anatomical 3D printers. Actually, working on the value of the thickness, when generating the Dicom sequence, acquired by a CT scan, we can decide the amount of data to be analyzed to produce the 3D model and we can define their quality. For example, a low thickness generates many "slices" of the volume, giving the possibility to increase the definition of the model, but this also increases the errors that might characterize the anatomic model. On the other hand, a high value of thickness could generate a loss of anatomy details that could be relevant.

Picture of a model made with high thickness value: there aren't dental details, is impossible to recognize anatomical elements

Picture of a model made with the correct thickness value: anatomical elements are recognizable

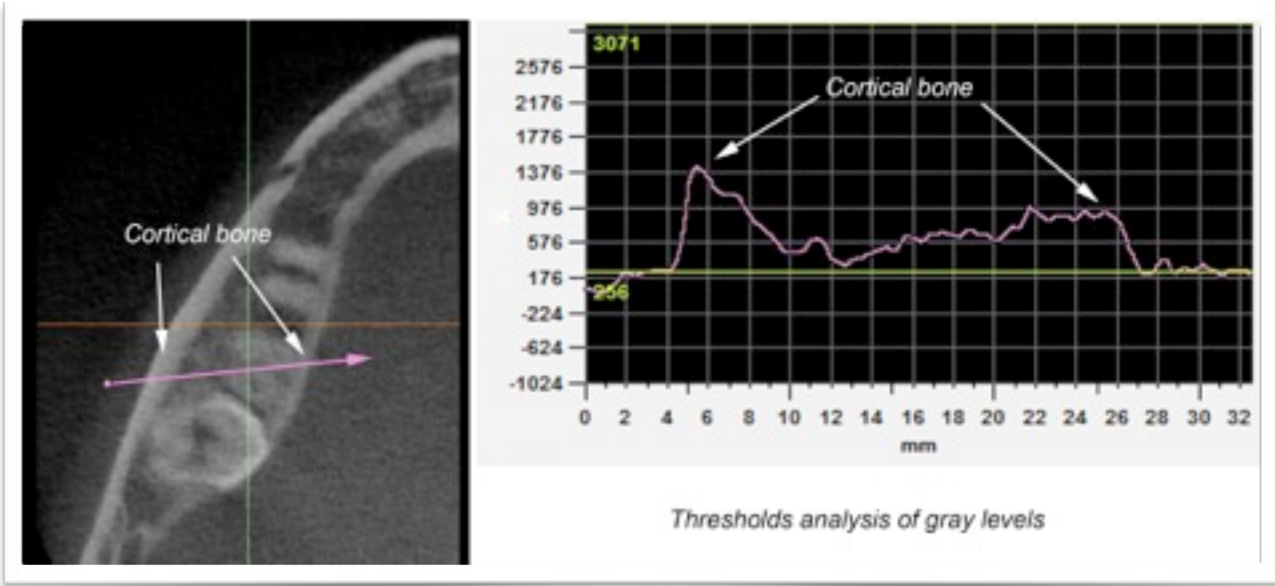
The reverse engineering and the implementation of the STL file: The three-dimensional printable model

The anatomic stereolithographical model is a representation in 1:1 scale of a real model: the patient. All post-processing passages leading from the acquisition-scan of the anatomical portion of the real printed three-dimensional anatomical replication follow a process of "reverse engineering".



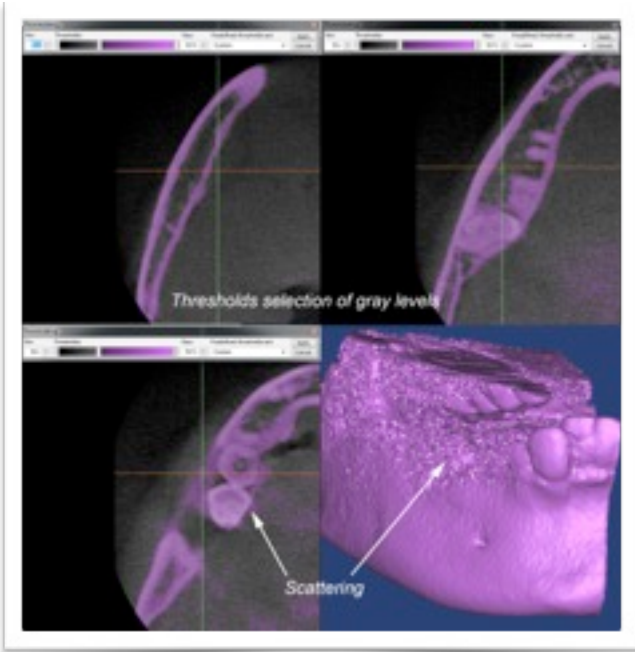
Reverse Engineering: from a real model to the 3d replay

The CT cone beam, used in dental radiology, is characterized by a very good diagnostic risk/benefit ratio for patients, but by using a low power radiating source it is not able to generate a precise correspondence between the "gray values" and the anatomical tissues of the patient. Until now, there is no scale (as, for example, the Hounsfield scale for multislice CT total body scan) that describes a clear relationship between real tissues and radio diagnostic images.

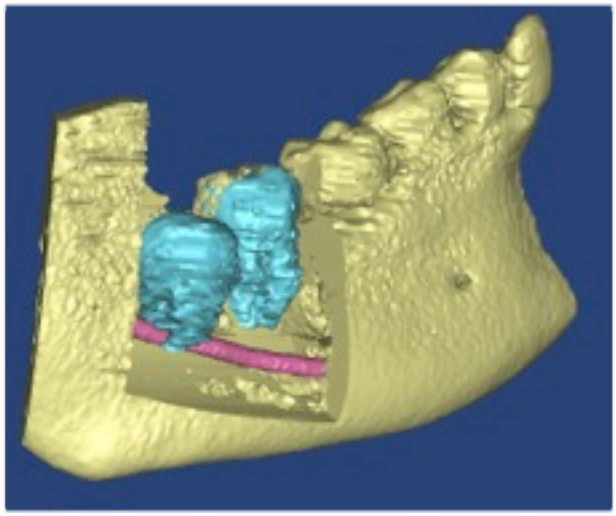


Thresholds analysis of gray levels

The first step in the realization of the stereolithography file "SLT" in the medical field is thresholding, a phase in which, after an analysis of the gray ranges making up the medical images, the axial ones are "processed", segmented into regions characterized with intervals of gray levels. All anatomical regions chosen at this stage will compose the three-dimensional model.

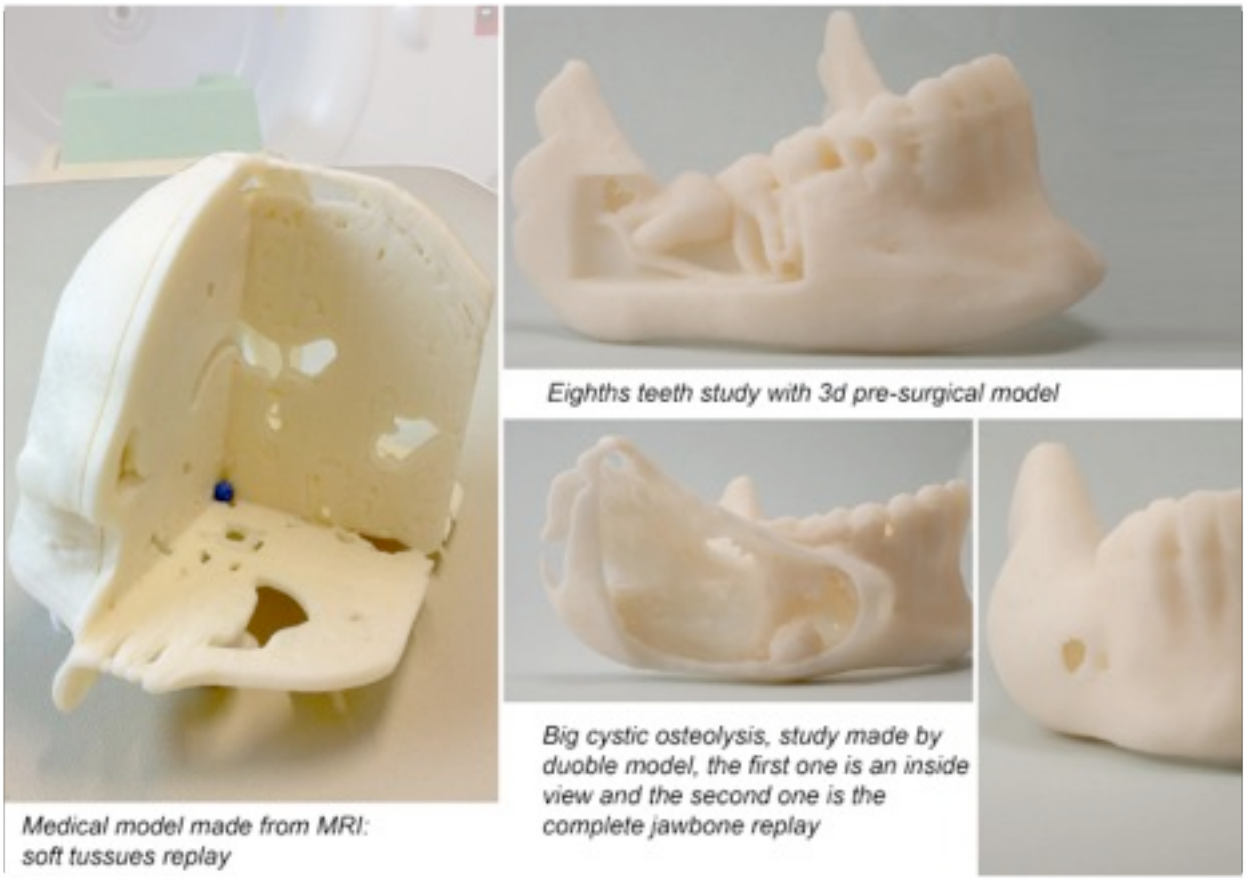


At this point, the three-dimensional model contains much "noise" and, especially at the level of extruded areas of the mouth, at the teeth reconstruction level it is ill-defined and loosely realistic. The reason for this is consequent to the scattering phenomenon of medical images in the dental field due to the presence of metals or materials for dental care. These materials, when hit by x-ray beams, impress gray values that display random ranges and nuances surrounding the place where the metal or the material from dental care is located.



To achieve a greater definition of the areas where scattering exists, we proceed to a "clean up" on each axial image where we start to eliminate from the segmented regions whatever makes up the "noise" of the 3D model.

At this point, the file is ready to be converted into an stl file and, after having verified the absence of any "holes" that could affect the 3D printing, we pass to the launch of the stereolithography printing processes.



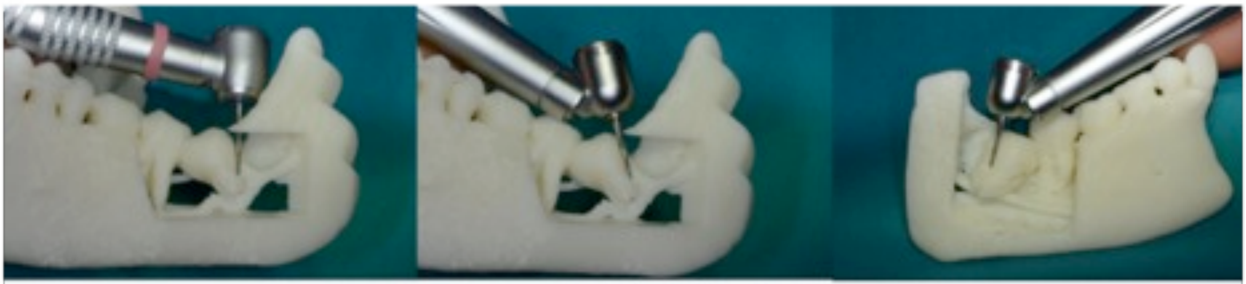
Eighths teeth study with 3d pre-surgical model

Big cystic osteolysis, study made by duoble model, the first one is an inside view and the second one is the complete jawbone replay

Medical model made from MRI: soft tussues replay

Using the 3D replicas for the didactic program of the intervention

In dentistry, oral and maxillofacial surgery processes and teeth are now normally reproduced in 3D, the upper jaw with highlighting of the maxillary sinuses, of the pterygoid processes and of the cheekbones or the entire mandible, with the lower alveolar channel highlighting starting from the data acquired with digital radiology (CT dental scan, coil, cone beam, *etc.*).

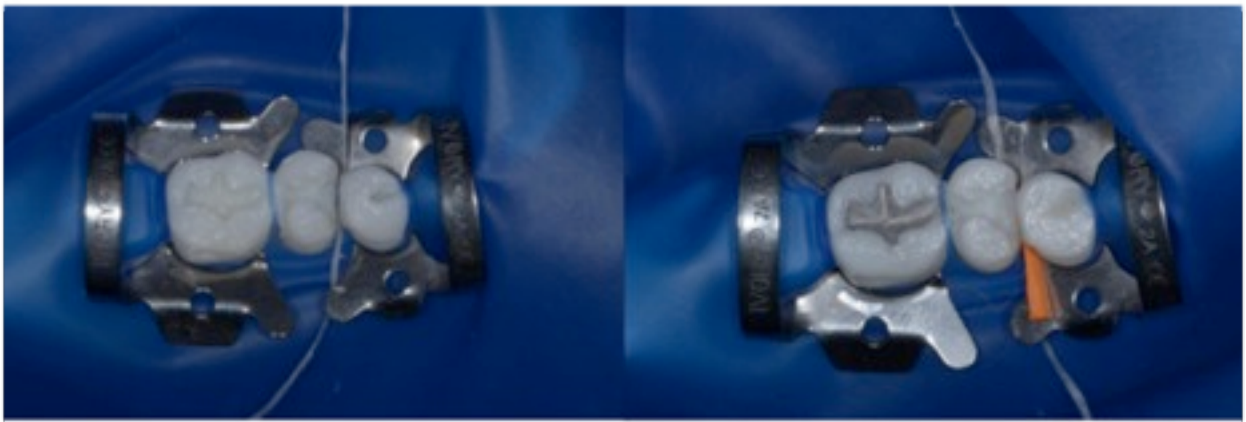


Teaching plan of eighths teeth extraction

Pre-implants teaching plan

The anatomical replication allows the surgeon not only to study and design the operation to perform, but also to simulate all surgery phases. For example, starting from the model, we can simplify the reconstruction of the atrophies by modeling, already in the extraoral environment, pieces of heterologous bone with the utmost precision, or simulate the placement of dental implants, evaluating a priori the bone volume and density, the morphology of maxillary sinuses or even design a surgical stent that, using the same 3D printer, or through our trusted laboratory, can be accomplished with extreme simplicity. To produce anatomical replicas we only need to use Dicom data of a patient's CT. However, dedicated software can allow the "cleanliness" of any scattering, by changing the images according to the needs and converting them, as needed, to a specific file format. The files processed in this way are sent to a 3D printer, producing anatomical replicas.

The materials used for the making of the anatomical replicas are of different kinds depending upon their usage, but essentially they are special thermoplastic ABS resins or sterilizable polyamides that are certified in the clinical setting. Then, once we design and simulate the intervention on the replication, all the materials can be sterilized and used on the patient, significantly reducing the surgery time, the discomfort to the patient and the risk of complications.



Example of using of the 3D model for training in conservative therapy

In summary, the extraoral design and simulation environment allows you to avoid any surgical surprise, sometimes making it unnecessary to resort to the uncovering of a mucogengival edge, defining an exact check-list of the necessary materials, size and type of implants, amount of biomaterial, size of osteosynthetic screws or pins, *etc*. It has proven to be very useful for the teaching of complex cases and for operators basic training of conservative and extractive therapy.

Perpetual Plastic Project

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From junk to jewelry

In a few simple steps we turn valueless plastic waste into a valuable and customized product using 3D printers. **Perpetual Plastic Project** currently uses old plastic cups, littering away on festivals, as material input. The machine cleans, shreds and extrudes the old waste into a 3D printing filament, which in its turn is used by a filament 3D printer to create a near endless variety of end products.

The Perpetual Plastic Project is all about the local recycling of plastics. Last summer the project was successfully launched at the Lowlands festival 2012, the Netherlands. Our mini-factory was installed and visitors could recycle their used drinking cups into new products operating the machine themselves.

The goal of the project is twofold:

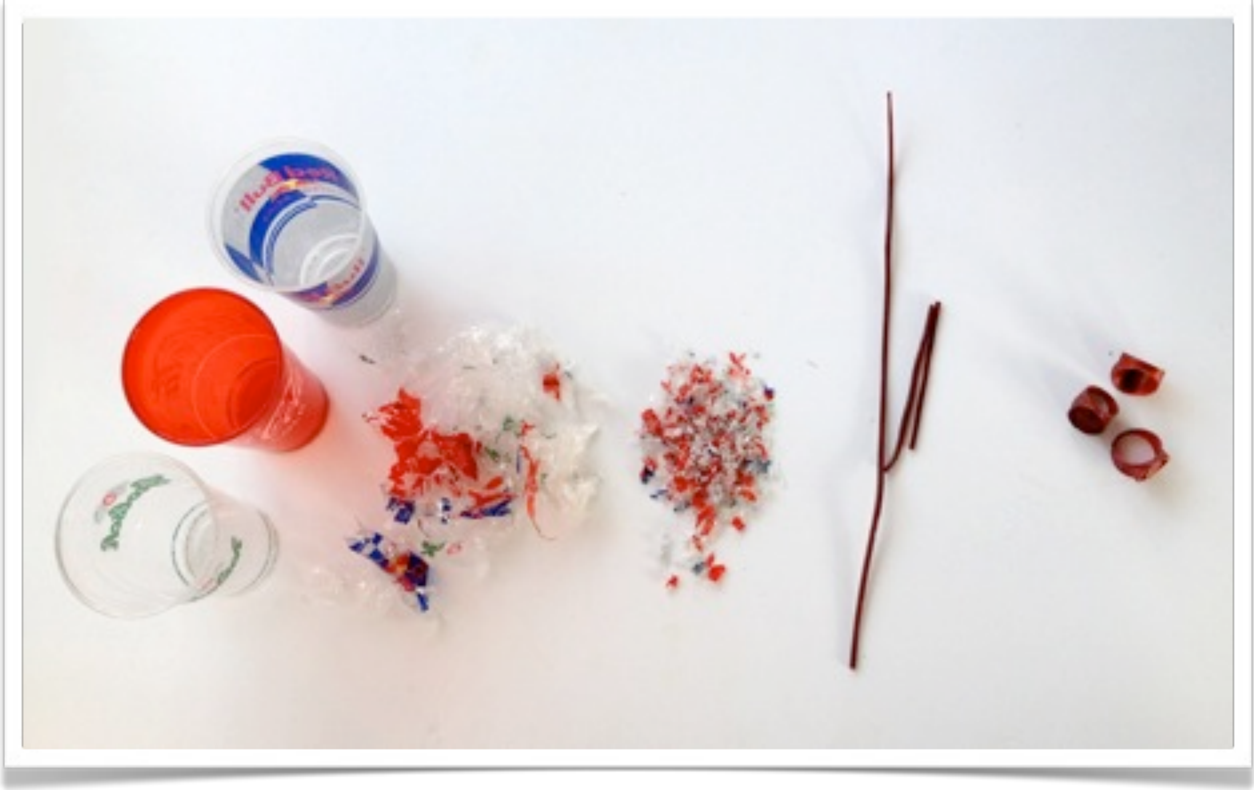
- Recycling plastics on a local level by exciting and involving people.
- Creating awareness amongst consumers by teaching them new ways of recycling.

For this reason, the mini-factory is as accessible and transparent as possible. You can drive the machinery by hand and learn by doing how the cups are transformed into building material and then again into a new product.

The Perpetual Plastic Project mini-factory

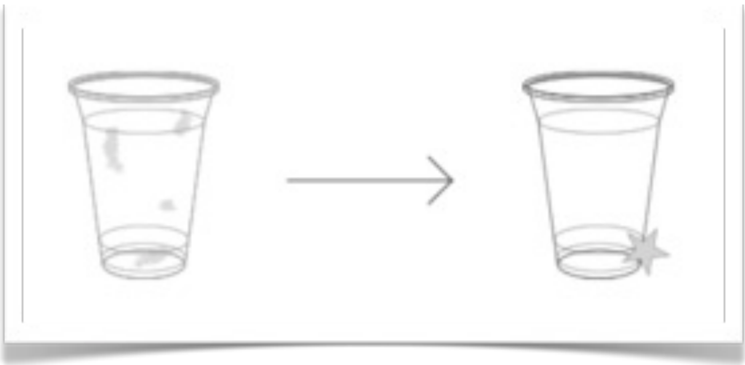
In order to create a new product people go through the steps of washing, drying, shredding, extruding and 3D printing with their used drinking cups. With a 3D printer, customized and personalized items are made for them to wear and take home. The items become a visible souvenir that stimulates discussion and spreads the word about its origins and the new recycling concept. Of course, a multitude of functional, durable and desirable products can be made with a 3D printer. It is up to designers to explore the possibilities of these evolving technologies and how to purpose them to serve people's needs.

The steps



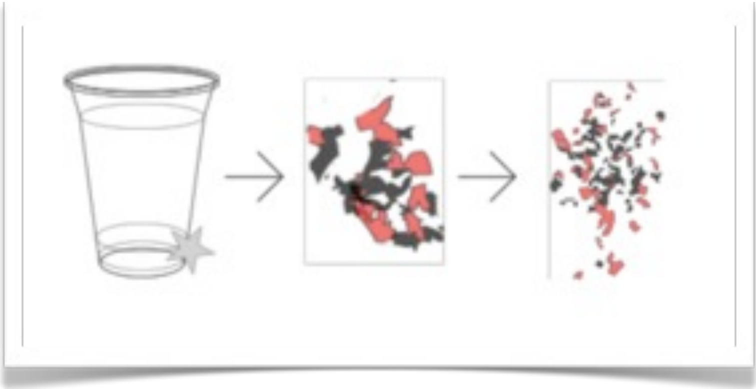
Step 1 - *Cleaning & Drying*

Wash your used drinking cups in the sink with water to get rid off any pollution. Then put them in the blower to make sure they will be completely dry. Any pollution or water will give problems later on in the process when the (bio-)plastic will be heated.



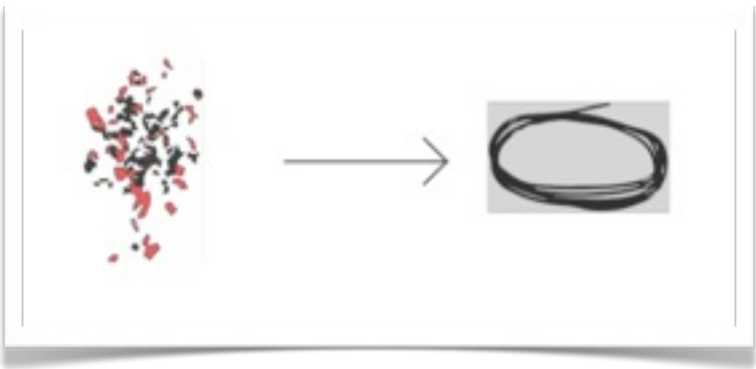
Step 2 – *Shredding*

Here you can shred your cup in small pieces with the shredders to get the right size of input material for the extruder. The cups are torn apart by sharp knives.



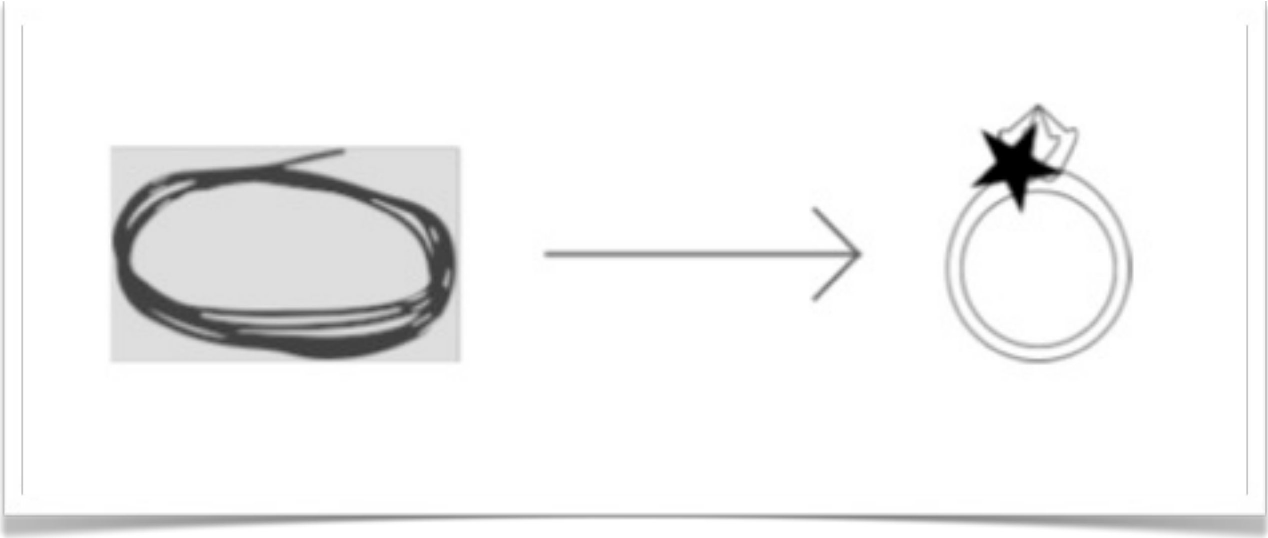
Step 3 – *Extrusion*

The small bio-plastic parts that used to be your cup are heated to around 190 degrees and pushed through a small hole in the extruder to get a thin wire of recycled plastic. Turn slowly!



Step 4 – *3D Printing*

This is where the magic happens, the 3D printer transforms the recycled bio-plastic wire into new products. 3D CAD files are basis to build up a product in small layers from molten plastic.



Why are we doing this?

At present, the better part of all plastic waste is valueless –and only if properly collected– most of it ends up in landfills or in an incinerator at its end of life. Landfills and incinerators have a huge environmental impact. However, plastic waste that is not properly collected ends up in the sea, rivers, forests, and eventually even animals. Only about 7-12% of plastic waste is recycled globally.

We think the real problem starts at the demand side, it starts at the consumer, where plastic waste is experienced as a valueless material. Unlike used wood, for instance, which currently enjoys an incredibly high increase of value if redesigned using simple tools like sanding paper, nails and polish. The fact of the matter is, there is no real tactile nor understandable solution for consumers to create something of value with the plastic waste they are mostly unintentionally making.

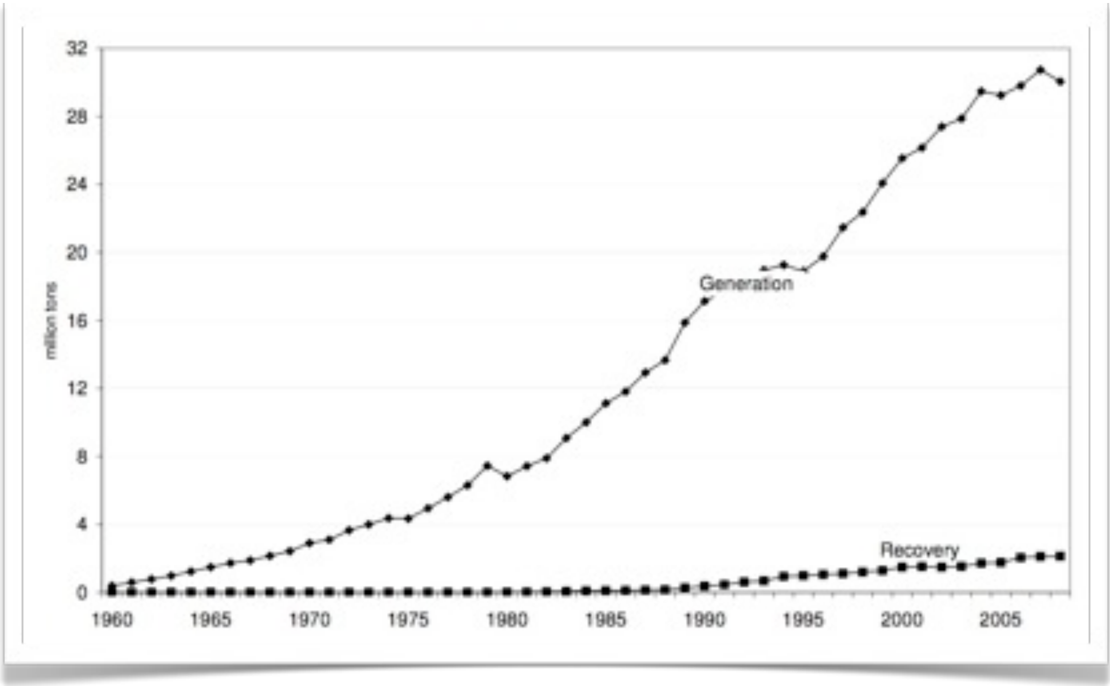


Image taken by the authors from EPA Plastic generation and recovery
http://www.epa.gov/osw/nonhaz/municipal/pubs/msw2008data.pdf

Although, as a material itself, plastic has many advantages over others. Using different materials for packaging would increase weight by 3.6 times, doubles the energy needed to make it, and emit nearly 3 times as much greenhouse gases. This means the problem is not with the material itself, but the true issue lies in the absence of recycling.

First Steps

First step: we want to show people that their plastic trash is valuable and how they can re-purpose it. We do this with our mobile mini-factory to let people transform used drinking cups into any kind of 3D printed products. Our machines are fun to use and inform people about the process in a tangible way: learning by doing. Exciting the consumer (people) about the project and involving them is the key to success and is our greatest asset as designers.

The second step: is to bring together the companies that affect the plastic life cycle. With their combined strengths we can close plastic material loops in a more direct way. We have already made contact with producers of bio-plastics and users of the plastic disposables. The open source community (RepRap) and 3D printer companies also play a big part in the development of technical solutions and production on a more human scale. We are connecting the dots in between technique, material, user experience, festival organizations and scientific research.

Our current partners include:

Ultimaker

purac pure by nature

TU Delft

Past events we have collaborated with (mid 2012 - early 2013):

End game

Our end goal is to develop the concept into a product with which people and communities all over the world can serve themselves. The trash that would otherwise pollute their living areas or be transported away can immediately be used to create something that they need. As a design collective, we want to tackle the world's bigger problems; we want to prove that a circular economy is not only necessary, but possible at this very moment. In this way we contribute to what we believe will be a better future.

Better Future Factory is 21st century craftsmanship:

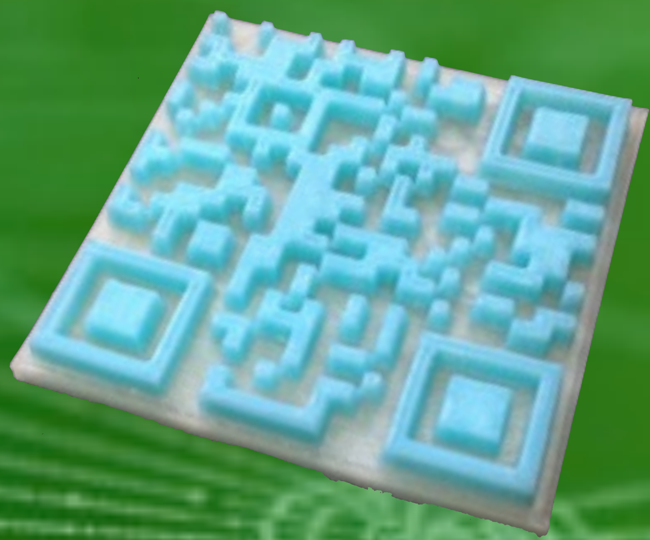
contact us at *love@betterfuturefactory.com*

The Abdus Salam International Centre for Theoretical Physics

Low-cost 3D Printing for Science, Education & Sustainable Development

Low-cost, three-dimensional (3D) desktop printing, although still in its infancy, is rapidly maturing, with seemingly unlimited potential. The hope is that this cutting-edge 3D technology will open new dimensions to science and education, and will make a marked impact in developing countries.

This book gives a reasonable, first overview of current research on 3D printing. It aims to inspire curiosity and understanding in young scholars and new generations of scientists to motivate them to start building up their own 3D printing experiences and to explore the huge potential this technology provides *–with the final goal of putting learning literally in their hands*.



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