Anne E. McMills

3D PRINTING BASICS FOR ENTERTAINMENT DESIGN

A **Focal Press** Book

ROUTLEDGE

3D Printing Basics for Entertainment Design

Affordable 3D printers are rapidly becoming everyday additions to the desktops and worktables of entertainment design practitioners – whether working in theatre, theme parks, television and film, museum design, window displays, animatronics, or… you name it! We are beginning to ask important questions about these emerging practices:

- How can we use 3D fabrication to make the design and production process more efficient?
- How can it be used to create useful and creative items?
- Can it save us from digging endlessly through thrift store shelves or from yet another late-night build?
- And when budgets are tight, will it save us money?

This quick start guide will help you navigate the alphabet soup that is 3D printing and begin to answer these questions for yourself. It outlines the basics of the technology, and its many uses in entertainment design. With straightforward and easy-to-follow information, you will learn ways to acquire printable 3D models, basic methods of creating your own, and tips along the way to produce successful prints.

Over 70 professionals contributed images, guidance, and never-before-seen case studies filled with insider secrets to this book, including tutorials by designer and pioneer, Owen M. Collins.

Anne E. McMills has been teaching 3D printing since 2011. Her passion is for expanding 3D technology's home in theatrical design. Furthermore, Anne is involved in advisory panels and focus groups for 3D technology companies where she has the opportunity to be a voice for the entertainment industry.

In addition to her passion for 3D printing, Anne is a lighting designer, professor, and also the author of *The Assistant Lighting Designer's Toolkit*. She has worked in theatre (from Broadway to the West End) as well as in dance, opera, theme parks, concerts, award shows, industrials, architectural lighting, and television. Anne is the Head of Lighting Design at San Diego State University (where she also teaches 3D fabrication) and a proud member of United Scenic Artists, Local 829.

3D Printing Basics for Entertainment Design

Anne E. McMills

Routledge
Taylor & Francis Group
NEW YORK AND LONDON

First published 2018
by Routledge
711 Third Avenue, New York, NY 10017

and by Routledge
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

Routledge is an imprint of the Taylor & Francis Group, an informa business

Notices
Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, and medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

Library of Congress Cataloging-in-Publication Data
A catalog record for this book has been requested

ISBN 978-1-138-21134-6 (hbk)
ISBN 978-1-138-21135-3 (pbk)
ISBN 978-1-315-10869-8 (ebk)

Typeset in Times New Roman by
Servis Filmsetting Ltd, Stockport, Cheshire

To Jonathan,

whose endless shared passion for emerging technology inspires me every day.

Contents

Appendices

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

Acknowledgments

The creation of this book has been such a long journey for me. It would not have been possible without the love and support of so many people.

First and foremost, thank you to my partner Jonathan Mulvaney for always putting up with the hours and hours I spend in front of my computer. You are always there to listen and support me. I couldn't have done this without your enthusiasm, patience, and love.

Thank you, as always, to my mom Rose C. McMills, who is my guiding light, my role model, and my inspiration. A big thank you to all my family and friends. And to Sienna who may be the most passionate 3D printing enthusiast I know. Endless love to our new arrival, Toffee, and to the ones we lost along the way – Cosette and Sneakers. It's hard to think about Cosette being here through so much of this book and not being here now. I miss you every day. You are my heart. Forever.

A huge thank you to friend and colleague John M. Kennedy for pushing to get our first MakerBot at Cal State L.A. Without you and your support this book would not exist.

Thank you to my editor Stacey Walker at Focal Press (as I will consider it always). You are always so wonderful and supportive. I appreciate your patience and guidance as a partner in crime and friend. And thank you to Routledge for inviting us into the family.

I am overwhelmingly grateful to all the artists, practitioners, pioneers, and tinkerers that not only brought this technology to the masses, but also shared their thoughts and images with me for this book. You have blazoned a great path, and I am honored to share your passions in this text.

There are so many contributors to this book I cannot even begin to list you all by name. Please know that I am beyond humbled by the access you gave me into your worlds and the fantastic images you gave permissions to use. A significant shout-out to Alex Tollington from AVID Labs® who let me borrow the groundbreaking, first-ever commercially 3D printed lighting fixture to share with my students.

A special thanks to Kacie Hultgren, my technical editor and vast contributor. Without you I may never have discovered this fabulous art form. And to Owen M. Collins who is an inspiration and a great collaborator; thank you for the amazing tutorials.

To John Lee Beatty – it means a lot that you agreed to write the foreword for this book. Your insight is invaluable to its contextualization. What an honor to have you be a part!

I am forever grateful to my test readers – Conor Mulligan, Caroline JL Andrew, Tim McCalister, and Owen M. Collins. Thank you for helping me out of the kindness of your hearts. You helped make this book what it is today.

And, finally, thank you to all of my extremely patient students at both Cal State L.A. and San Diego State University who have learned along the way with me. It is for you that I learned this artform-technology, and it is for you that I write this book.

Foreword

John Lee Beatty

As I sit here writing at a borrowed desk, three little Chippendale chairs are scattered under the screen. They seem to be in 1/4" scale, but I know enough to know they might be in most any scale. The fact that they are absolutely identical is no longer noteworthy to me, nor is their existence – casually discarded as they are – especially remarkable. All of which goes to show just how remarkable 3D printing is.

As supposedly "mainstream" or "old school" a designer I might be labeled, I was astonished to find upon examining the production of *The Nance*, which I designed for Broadway at the Lyceum Theater, that whatever looked the most hand-painted was actually computer-painted and that which might have looked mechanically crafted was actually handmade; the computerized cutting table and the Vacuform machine worked in tandem with computer-executed material inspired by my handwork to create what looked like "handwork." Oddly, these modern tools made the scenery and props more honestly a reflection of my personal hand, revealing more of me and less of the shadows of multiple and inconsistent human interpretations. Accustomed as we are to calling crafted theater objects the last of the truly "handmade" items, it seems to be time to redefine the term "handmade."

3D printing has allowed one to "build" from a drawing, not allowing the difficulty of miniaturization (or in some cases, full-size creation) of hand designing to interfere with the original style impulse. A Chippendale chair emerges intact with little glue-and-cardboard interference – and, in fact, can emerge identically and in profusion as long as required. So, too, can full stage model pieces be repeated identically without frustration, huge effort, or late-night panic. 3D printing allows one to finish a designer's work more clearly and removes one layer between "large" and "small" design inspiration and its accurate structural realization. And not just from large design to small and then onstage to large again; in reality, soon the 3D printer will be producing larger and larger components of scenic expression. And some pretty nifty props too.

This new tool, much like the computerized painting machines and the computerized cutting table, may lay more – not less – responsibility on the designer's own hand. The realization of a painting, a furniture design, a model of a piece of scenery, or even an actual piece of scenery has less "interference." One is returned to the original charge of design: What does it look like? How big is it? What details of style does it possess? Is it a feasible construction? And, as a three-dimensional object, is it coherent from all viewing angles?

Some 3D printing can be a diagnostic of design – for instance: "Print it out and see what it looks like," or "Do the corners actually meet?" One of my favorite moments working with Kacie Hultgren, who had set up printed versions of one of my designs, was when she said, "Let me print your forced perspective farmhouse, and you can actually see what you drew." You can actually see what you drew! No wishful thinking or bending of Bristol board … "You can actually see what you drew." Remarkable.

And getting back to those Chippendale chairs.… On a personal note, I must say my greatest thrill from the 3D printer is that I can ask for 73 Chippendale chairs and no assistant will groan; the chairs will all look exactly the same, the director and I can see what a pile of 73 Chippendale chairs would look like, and we can decide to go another way with no blood, sweat, or tears. And those same Chippendale chairs might be lying in wait on someone else's desk someday – scattered underneath the screen – quietly existing in their remarkable, unremarkable existence.

John Lee Beatty
Broadway scenic designer

Introduction

"What is it you print?" I'm often asked when I tell others about this book. They look at me confused, heads cocked. Yes – you caught me. I'm a lighting designer. Although lighting design may not be among the primary uses of 3D printing at this point, questions like, "what is it you print?" shows just how little understanding still surrounds this versatile art form. There's so much out there for this technology! Those who are uninitiated just don't realize it … yet.

> *"As lighting designers and projection designers we are frequently the gateway drugs to technology in the theatre; we're early adopters of technology. Even though a lighting designer probably isn't doing a lot of 3D printing, I would bet the percentage of lighting designers who have printed or own a 3D printer might be higher than that of others."*
>
> **Ben Pearcy**, creative director for 59 Productions

Ironically, I discovered 3D printing while researching textbooks years ago for the one scenic design class I was asked to teach – we needed a professor to fill the slot, and I felt comfortable teaching the basics. One weekend, as I was casually flipping through *The Handbook of Set Design* by Colin Winslow, I felt my heart jump to my throat! I had turned to the page on 3D printing … something I had never heard of at that time. It seemed so mystical and mysterious! How the heck does a *printer* create something in *3D*?! Looking back now it's funny how simple the technology actually is, but, as with most people when they first learn of it, it sounded like magic at the time.

I spent the next week running around with Winslow's book dog-eared to that page, telling anyone who would listen about my discovery. It wasn't long after when I stumbled upon a video of scenic designer Kacie Hultgren discussing 3D printed model furniture for her work on Broadway with John Lee Beatty; and the best part: she was using a desktop 3D printer – something we might be able to afford! It was then that my real mission began.

As the Head of Design at my university at the time, I was always looking for ways to introduce cutting-edge design practices into our curriculum, and, as the "for now" scenic design professor, 3D printing was a perfect match; add to the mix a new then-Chair who was interested in infusing more technology into the program, and it was a perfect recipe for change.

After a long and drawn out battle with administration, we were able to secure the funds to get one printer, a modest amount of filament, a hand-me-down computer, and a closet-like room above the scene shop for a "lab." I spent hours upon hours with the machine as one part after the other broke or needed calibrating. On weekends, I camped out at school fixing things and scouring user groups to try to learn its idiosyncrasies – all with the goal of getting it working enough to use in class. Needless to say, my partnership with our first printer was like being in an abusive relationship – when things were good, they were great; and when things were not working I obsessed for hours over how to make it better.

Although that was years ago now, it was then that the seed of this book began to sprout. As fascinating as it was to be a part of the "Macintosh moment" of an emerging technology, it was equally frustrating not having one go-to resource. I felt like I was learning this technology in the dark and needed some guidance that didn't take hours of surfing the web to find. Second, it seemed like there was very little information about 3D printing for entertainment design out there at that time. If it weren't for Kacie's videos, there may not have been any.

As the years passed, while teaching 3D printing for theatrical design and simultaneously developing this book, I have seen the 3D printing industry move through many phases. I watched the overly hyped Prosumer Revolution fade away into the just-as-hyped No-sumer What?-alution. The fascinating thing was that all along those of us who work in the shadows have spent our time embracing the technology – not caring if there was a printer in every household as long as there was one in every shop and design studio.

The more I researched this book, the more I realized just how everyday 3D technologies have become in the entertainment arts. As I interviewed every designer, technician, artisan, and company that would speak to me, it became clear just how many problems 3D fabrication solves. It has made many processes quicker, less expensive, and more convenient; not to mention enabling the production of items created in ways never before possible.

This book explores how professionals are using this technology as well as the "how-to" for the beginning plug-and-play user. My hope is that it takes the guesswork out of the process and allows the reader to enjoy the experience, while finding inspiration in the work of others.

Other notes: One of the biggest challenges to writing a book like this is that the software used to create 3D models and printed objects is vast and varied – so is the hardware. On the other hand, staying completely software-agnostic seemed a bit unrealistic in a "how-to" book. Therefore, I have chosen to focus mainly on my personal favorites, Vectorworks and Meshmixer, for creation; Vectorworks is among the standard programs used by arts professionals, and Meshmixer is a powerful (and free) program that can be very helpful for 3D printing. However, the reader is encouraged to use whichever 3D modeling software with which he or she is most comfortable. As for hardware – printers and scanners – I have tried to cover the range of technologies for which the reader may feel an affinity, with a strong focus on FDM machines which are typically the easiest for beginners to learn. This book attempts to work as a general guide no matter the reader's preferences.

Also, note that images listed with a "thing" number associated in the caption are found on Thingiverse.com by entering *www.thingiverse.com/thing:*## in the address bar of any search engine. Write the thing number where "##" is listed in this address. Do not enter a space between the colon and the thing number.

Most importantly, every user is responsible for their own personal safety and the safety of those around them. The author does not assume to be an expert on the safety of the equipment discussed in this text and takes no responsibility for the use, misuse, and/or consequences of these machines and the materials used in the creation of objects. Every measure of safety (whether described in this book or not) is strongly encouraged. New technology and emerging materials are often not studied to the fullest when first arriving on the fabrication scene. It is up to each user to do his or her own research on the equipment and materials of choice and make his or her own decisions requiring the proper safety methods required.

PART I

The Basics

Photo courtesy of: Anshuman Bhatia, www.shapeways.com/shops/ab

SO, WHAT EXACTLY *IS* 3D PRINTING?

3D printing (often abbreviated as "3DP") is a rather ambiguous term. In recent years, it has become a popular buzzword encompassing a mixed cocktail of manufacturing techniques and technologies. To make things even more complex, many 3D printing techniques have acquired multiple, interchangeable names.

TERMINOLOGY USED INTERCHANGEABLY WITH THE GENERAL TERM "3D PRINTING"

- Rapid Prototyping (RP)
- Rapid Manufacture (RM)
- Rapid Tooling (RT)
- Additive Manufacturing (AM)
- Additive Layer Manufacture (ALM)
- 3D or Desktop Fabbing
- Direct Digital Fabrication
- Personal Manufacturing
- Desktop Manufacturing
- Digital Manufacturing

Formally, 3D printing is defined as the process by which a virtual 3D model is translated into a physical three-dimensional object, usually by means of computer control and instruction. Most often the object is manufactured by the build-up of multiple small layers of material.

3D printing is considered additive manufacturing – meaning that the printer adds material together to create the object. It essentially creates something from nothing – a green technology nearly devoid of waste. This method is the opposite of subtractive manufacturing (used by CNC machines and other traditional sculpting methods) which carves (or "subtracts") an object out of an existing block of material, thereby producing excess waste.

On a very basic level, the concept of 3D printing is not so different from our decades-old 2D printer technology. A 2D printer takes a virtual item (like a text document in the computer) and outputs a physical object – an exact replica of the virtual document in the physical form of a piece of paper. A 3D printer does the same thing only the resulting object is three-dimensional. The object may even have moving and functional parts.

CHAPTER 1

Methods of 3D Printing

There are four basic types of 3D printing methods at this time: Fused Deposition Modeling (FDM), Stereolithography (SLA), Granular Materials Binding (GMB), and Selective Deposition Lamination (SDL). All of these processes take a virtual model and build it – bit by bit – into a physical object. The *way* this happens is what determines the name of the method. Which one you choose largely depends on personal preference, your access to the technology, and the needs of the object you intend to create.

PRINTING TECHNIQUES

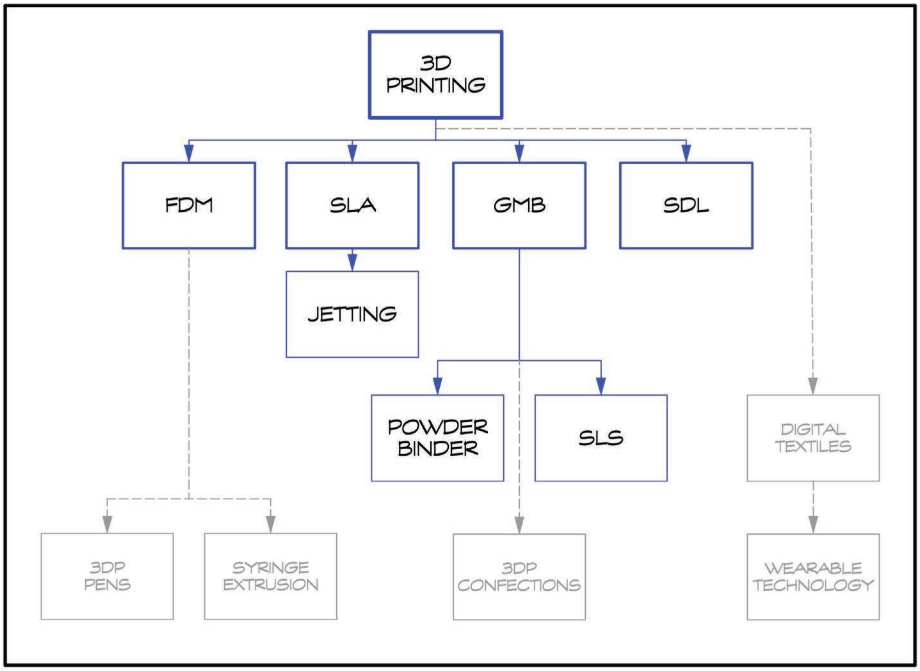

Figure 1.1 Flowchart showing the relationship between popular forms of 3D printing.

FUSED DEPOSITION MODELING (FDM)

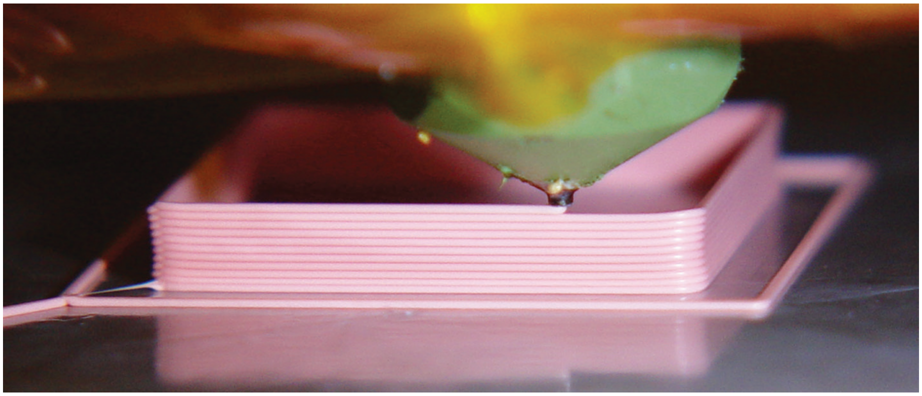

Figure 1.2 Fused Deposition Modeling (FDM).
Photo courtesy of: Softsolder.com

Fused Deposition Modeling (FDM) is a 3D printing process by which thermoplastic filament (or plastic that is malleable when heated) is extruded through a small nozzle into fine layers that stack upon each other to create an object (see Figure 1.2). FDM is the most common type of consumer-level 3D printer at this time and can use a variety of types of thermoplastic filament (consider this the "ink" for FDM printers); the most popular being ABS and PLA. (More on filament in Chapter 2.)

OTHER NAMES USED FOR FUSED DEPOSITION MODELING (FDM)

- Fused Filament Fabrication (FFF)
- Molten Polymer Deposition (MPD)
- Thermoplastic Extrusion
- Fused Filament Method (FFM)
- Plastic Jet Printing (PJP)

Think of FDM like a really smart hot-glue gun. In the same way a glue stick is inserted into the back of a glue gun, thermoplastic filament is fed into the 3D printer. The printer heats up the plastic to a molten state and extrudes (or squeezes) it through a small nozzle – much like a hot-glue gun oozes molten glue when the trigger is pulled. A computer controls the 3D printer's movement (based on your 3D model) and tells it to selectively deposit the molten plastic in the shape of the first layer of your object, which solidifies almost immediately as it cools. Then the next layer is extruded on top of the first layer, and so on (see Figure 1.3). As the layers build on top of themselves – tiny layer by tiny layer – the physical object begins to take shape.

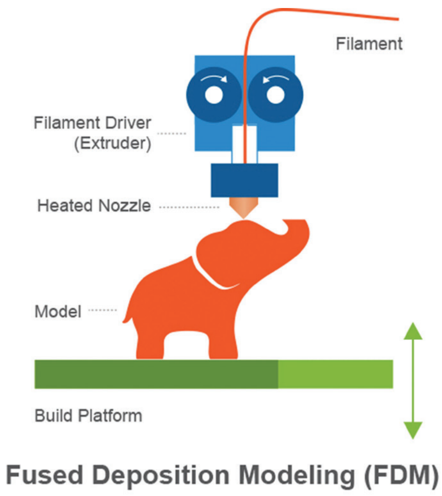

Figure 1.3 Fused Deposition Modeling (FDM) process.
Image courtesy of: Mark Jaster, www.printspace3d.com

The FDM process was trademarked in 1988 by S. Scott Crump (co-founder of Stratasys). Crump filed for a patent in 1989 which was issued to Stratasys in 1992. He also patented and trademarked the term “fused deposition modeling.”

For more than a decade, this technology was only available at an industrial level – out of reach for the standard consumer. All that changed when Dr. Adrian Bowyer at Bath University invented a desktop 3D printer he named the RepRap (short for Replicating Rapid Prototyper), which was relatively inexpensive and capable of replicating most of its own parts. In 2005, he released the RepRap as an open-source printer and began the RepRap Project – encouraging others to create their own. The RepRap Project spawned a massive outcropping of innovative FDM printers on the market, including the first-ever commercially available 3D printer – the BfB RepMan (January 2009) and the extremely popular MakerBot Cupcake CNC (March 2009).

STEREOLITHOGRAPHY (SLA)

Stereolithography (SLA) 3D printers, the second most common consumer-level 3D printer, use a process called photopolymerization. This process uses a high-intensity energy or light source to cure a liquid photopolymeric resin into solid layers (see Figure 1.4); a photopolymer is any material that can transform from a liquid to a solid almost instantaneously when stimulated by light. Depending on the energy source (a UV laser or a projector), SLA printers are divided into two categories: Spectrum Laser (SL) or Digital Light Processing (DLP), respectively.

Figure 1.4 Stereolithography (SLA).
Photo courtesy of: Formlabs

As each layer is "drawn" in the pool of resin by the light source, it solidifies. The object is shifted slightly from its surrounding resin bath and the process repeats (see Figure 1.5).

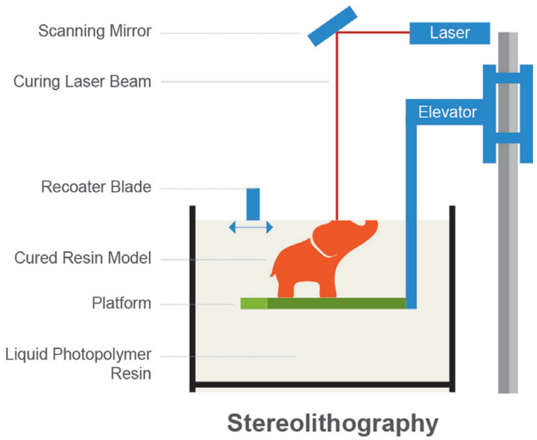

Figure 1.5 Stereolithography (SLA) process.
Image courtesy of: Mark Jaster, www.printspace3d.com

After the print is complete, the excess resin must be rinsed off with isopropyl alcohol (IPA). To completely dry, the object may also need to be post-cured in the sun or under a UV light source before safely handling. Resin comes in limited color choices.

OTHER NAMES USED FOR STEREOLITHOGRAPHY

- Optical Fabrication
- Photo-Solidification
- Solid Free-Form Fabrication
- Solid Imaging

In 1983, SLA ("Stereolithography Apparatus") was the first-ever method of 3D printing invented. It was invented (and later patented in 1986) by Charles "Chuck" Hull, who went on to found 3D Systems and is widely considered the father of 3D printing. He also coined the term "stereolithography," which is derived from the Greek words *stereo* (solid body), *litho* (stone), and *graphien* (to write). "Stereolithography" is still used today to refer to the file type read by most 3D printers and 3D modeling programs – abbreviated as an STL file. The first commercially available desktop SLA machines appeared on the market in 2012 – the B9Creator (DLP) and Formlab's Form 1 (SL).

SLA printers typically print more quickly than FDM printers, especially the DLP variety. DLP machines print in seconds per layer (instead of minutes) by printing a full layer at once (almost like stamping out each layer), instead of drawing it out line by line. SLA also produces higher-resolution objects with exceptionally smooth surfaces (see Figure 1.6). This level of detail can be ideal for scenic model pieces in 1/4" scale – a scale with which the average FDM printer can struggle. The surface of an SLA-printed object may be slightly slick, semi-gloss, or rubbery and can be fragile and brittle overall, but highly detailed.

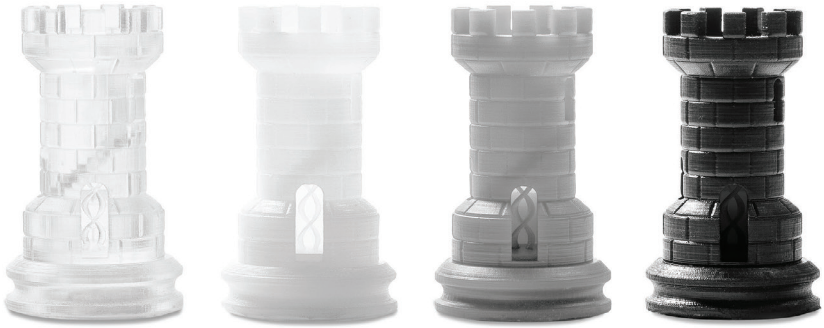

Figure 1.6 SLA printed chess pieces.
Photo courtesy of: Formlabs

When printing with SLA, avoid skin-contact – handling the resin material can be messy and unsafe. Check the material's Safety Data Sheets (SDS) to see which gloves are recommended for handling. Full ventilation or fume extraction is recommended at all times. Resin expires within a year from its production and can degrade in storage over time, which will cause final prints to be a bit sticky.

Photopolymer Jetting

Originally patented by Stratasys, Photopolymer Jetting, *also called PolyJet*, is an industrial-level derivative of SLA. It also uses the process of photopolymerization but there is one big difference – the resin is stored in cartridges, much like ink in traditional 2D printers.

OTHER NAMES USED FOR PHOTOPOLYMER JETTING

Poly-Jetting or PolyJet
Multi-Jet Modeling (MJM)
Jetting
Multi-Jet Printing (MJP)

Jetting printers selectively deposit tiny droplets of photopolymer material onto the build surface. Immediately following, a UV lamp moves over the print bed causing the droplets to instantly cure into a solid material. The printer repeats this process layer by layer until finished. The resulting objects are precise, smooth, intricately detailed, and printed in a very fine resolution with the possibility of full color. Unlike standard SLA, objects are ready for handling as soon as printing is complete.

Notably, jetting technology allows for a wide range of materials to be printed simultaneously within a single object. These can vary anywhere from rigid to flexible and from opaque to transparent. For example, a prosthetic leg can be printed as all one piece – combining both a rubbery, flexible joint with rigid frame and body components. Or an entire model ship can be built inside a transparent bottle within a single print. Manufacturers other than Stratasys have begun to produce similar technologies, such as 3D Systems' Multi-Jet Modeling (MJM).

Continuous Liquid Interface Production (CLIP)

Another close industrial-level relative to SLA, CLIP printing, created in 2015 by Carbon (then Carbon3D), prints in a fraction of the time without sacrificing the high-resolution surface finish. In fact, the finish is so smooth that resulting prints appear to have no distinguishable layers of any kind. Professor Joseph DeSimone (Chancellor's Eminent Professor of Chemistry at UNC), Professor Edward Samulski (Cary C. Boshamer Professor of Chemistry at UNC), and Dr. Alex Ermoshki (CTO and Co-founder) were key in its development.

During printing, CLIP projects light through a reservoir of UV-curable material, but it uses an oxygen-permeable window beneath it called "the dead zone," which allows for continuous printing – not single layers at a time (see Figure 1.7). Materials range from rigid to flexible, including silicone, rubber, polyester, and engineering-grade parts.

According to Carbon, the CLIP printing technique was inspired by the film *Terminator 2: Judgment Day* (1991). "They wanted to have the 3D-printed part rise out of a pool of liquid resin, just like the robot T-1000 rises out of pool of liquid metal, to assume the form of any person or object."[1] It is only fitting that practical effects giant Legacy Effects used the first CLIP machine for *Terminator Genisys* (2015).

Speed is an impressive distinction for the breakthrough CLIP printing – "printing 25 to 100 times faster"[2] than other types of printing. Jason Lopes, Lead Systems Engineer of 3D Print & Scan Technologies for Legacy Effects, conducted a shootout – printing identical objects simultaneously on both a Carbon M1 CLIP printer and an industrial SLA (DLP) competitor. The object took one hour and seventeen minutes to print on the CLIP machine and 28 hours on the SLA. "*And the level of detail is incredible*," he adds. When the experiment was repeated with a second object the results were similar: one hour and eleven minutes for a perfect print on the CLIP and 38 hours on the other (with flaws).

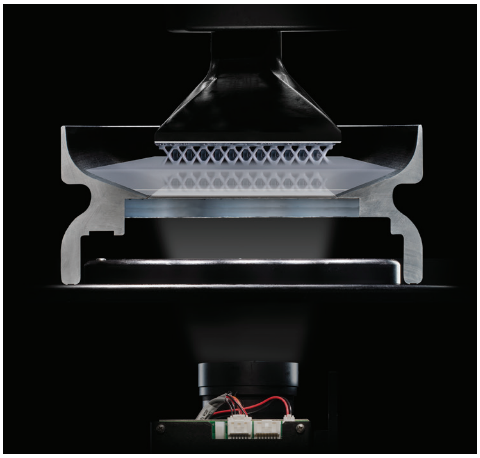

Figure 1.7 An object being printed using CLIP. Light from projector below passes through "the dead zone" to cure the resin above.
Photo courtesy of: Carbon

GRANULAR MATERIALS BINDING (GMB)

Granular Materials Binding (GMB) uses a binding material (like a glue, for example) or an energy source (such as a laser

Figure 1.8 Granular Materials Binding (GMB).
Photo courtesy of: LUMA-iD Ltd

or hot air) to selectively fuse layers of loose powder into a solid object (see Figure 1.8). The powder naturally acts as a support for the print, which is ideal for objects with complex geometries.

Many different materials can be used as the powder base for GMB printers: among them are nylon, plaster, gypsum, ceramic, porcelain, resin, plastic, glass (although it turns out opaque), silica, sand, sugar, cement, concrete, and metals, such as aluminum, titanium, tungsten, stainless steel, cobalt-chrome, nickel alloys, iron, copper, silver, and gold. Composite materials are also available, such as alumide – a mix of powdered nylon and aluminum. Almost any material that can be made into a fine powder or a granular state can be used.

INTERESTING FACT!

Renewable resources can also be printed with GMB. Oakland, California-based research and design firm Emerging Objects (spearheaded by professors Ronald Rael and Virginia San Fratello of U.C. Berkeley and San Jose State University) has been a leader in the development of 3D printing with sustainable resources. Materials such as naturally occurring sea salt, tea, sawdust waste from lumber yards, recycled newspaper, pulverized concrete, fly ash (a waste material that results from burning coal), bone, sand, and clay have all been fodder for experimentation. These materials have been used to print bricks, architectural components, and furniture (see Figures 1.9a–b).

Figure 1.9a "Saltygloo" by Emerging Objects – an igloo-like dome made from 336 individual, translucent, 3D printed bricks using salt from the San Francisco Bay, woven together with lightweight aluminum rods.
Photo courtesy of: Emerging Objects, www.emergingobjects.com

Renewable materials can cost up to 90 percent less than most traditional GMB printing materials. For example, resins and plasters can cost up to $3,000 USD for 100 pounds, while locally harvested sea salt costs an incomparably low $16 USD for the same weight. The San Francisco Bay Area produces over 500,000 tons of naturally occurring sea salt each year.

Figure 1.9b Saltygloo individually printed brick made from salt.
Photo courtesy of: Emerging Objects

The low cost and accessibility of these materials show promise for revolutionizing concepts like housing construction. In the future, 3D printing may enable abundant, low-cost housing structures for underdeveloped

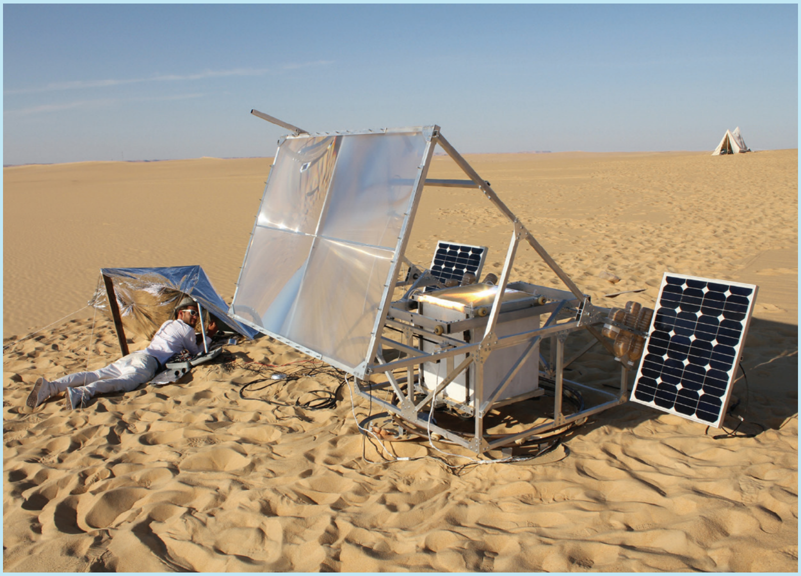

Figure 1.10 Solar Sintering printer. Photographer: Amos Field Reid.
Photo courtesy of: Markus Kayser

or impoverished areas – especially those with large stores of renewable resources. For example, Markus Kayser, a researcher at MIT, has developed a process he calls solar sintering. It uses the sand of the Sahara, a large fresnel lens with solar tracking, and the sun (instead of a laser) to 3D print structural objects directly from the land (see Figure 1.10). The focused sunlight reaches temperatures up to 2912°F (1600°C) to melt the sand into 3D printed objects.

Powder Binder 3D Printing

Powder Binder 3D Printing, sometimes called Binder Jetting, uses ink-jet style sprayers to selectively deposit a rapidly solidifying binder (glue-like material) onto a bed of powder. Each area that is sprayed with the binder forms into a solid. A new layer of loose powder is reset after each pass of the binder. This process repeats layer after layer until the object is formed.

After printing, excess powder still sticking to the print can be removed with pressurized air. The remaining loose powder in the print bed can be recycled for the next use. Initially the prints may be fragile, but with the addition of reinforced binders the resulting objects can be remarkably strong, lightweight, and even waterproof. Furthermore, dipping the finished object in cyanoacrylate resin (Super Glue) can also enhance the strength of the print.

Powder binder printers can also print in full color by incorporating standard 2D ink-jet color cartridges or dyed binders. Adding UV protectants to the finished print can also help to improve strength and reduce the risk of fading colors.

Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) is a technique developed and patented by Dr. Carl Deckard and Dr. Joseph Beaman at the University of Texas in 1987. Similar to the powder binder technique, it uses a high-powered laser – instead of a binder – to fuse each layer of powder into a solid (see Figure 1.11). Although made from granules, SLS produces surprisingly sturdy items. Once the layers are fused, they form a very strong bond. Even functional hand tools can be printed.

One SLS technique which uses fine metal and metal alloy powders is called Direct Metal Laser Sintering (DMLS). DMLS is popular among jewelry designers and can be a good choice for some costume accessories.

SLS is one of the most popular forms of GMB, so much so that the abbreviation SLS is sometimes used generically (and somewhat incorrectly) to represent the entire category of GMB.

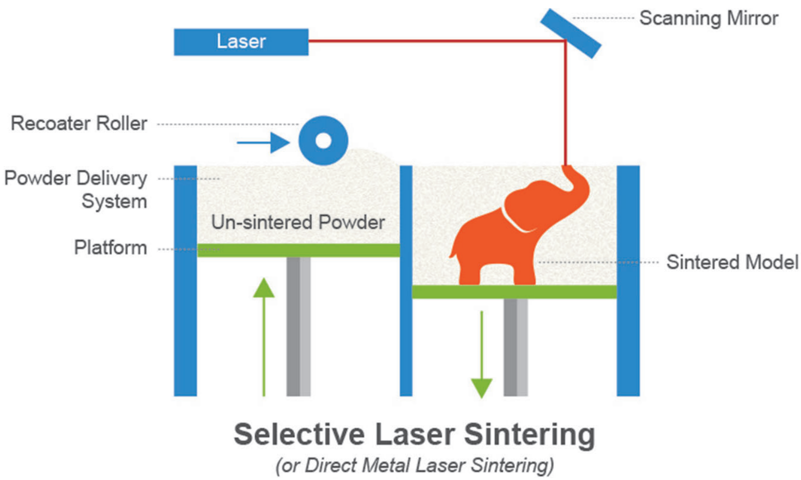

Figure 1.11 Selective Laser Sintering (SLS) Process.
Image courtesy of: Mark Jaster, www.printspace3d.com

SELECTIVE DEPOSITION LAMINATION (SDL)

In 2005, Mcor Technologies developed a method called Selective Deposition Lamination (SDL) which uses a computer-controlled tungsten carbide blade to cut out a three-dimensional object from a ream of standard office paper (see Figure 1.12). As each layer is cut, water-based adhesives are selectively deposited on the paper. Once the print is complete, the excess

Figure 1.12 Model printed with full-color SDL.
Photo courtesy of: Mcor

Figure 1.13 Weeding.
Photo courtesy of: Mcor

layers of paper can be pulled (or "weeded") away from the printed object by hand or by using tweezers (see Figure 1.13).

Surprisingly for being made out of paper, SDL prints are extremely strong and durable – especially after applying thin layers of Super Glue to the object. Functional tools can even be printed – such as a 3D printed hammer capable of driving an actual nail into real wood (see Figure 1.14).

Full-color, photorealistic models can also be created – great for props! (see Figure 1.15). And if the SDL print is being used near water or in areas of high-moisture, waterproof sealant can be used to coat and seal the print.

Figure 1.14 3D printed SDL hammer.
Photo courtesy of: Mcor

Figure 1.15 Fruit printed with SDL.
Photo courtesy of: Mcor

VARIATIONS ON 3D PRINTING

In addition to the main 3D printing techniques, many variations have also begun to surface that can be useful for entertainment design.

3D PRINTING PENS

Figure 1.16 3D printing pen.
Photo courtesy of: 3Doodler

3D printing pens, sometimes called manual 3D drawing tools, use FDM technology – pushing short sticks of filament through an internal extruder (see Figure 1.16). Instead of receiving instructions from a computer, the user simply "draws" with the printing pen as if using a standard pen or paint brush. Printing pens can be useful alone or for adding embellishments and decorations to existing props, set pieces, and costumes (see Figures 1.17–1.20).

Figure 1.17 Tiffany-style LED candleholders made with a 3D printing pen.[3]
Photo courtesy of: 3Doodler

Figure 1.18 Multi-media artwork using a 3D printing pen for texture enhancements, from the series *Willow Dream* by Barbara Taylor-Harris.
Photo courtesy of: Barbara Taylor-Harris

Furthermore, 3D printing pens can be used to repair 3D printed items. If an object warps or gaps form during the assembly of oversized objects, 3D printing pens can be used to fill in the gaps (see Figure 1.21).

Figure 1.19 Wearable sculpture created using a 3D printing pen.
Garment Credit: CRYSTAL MATRIX, Erica Gray, Australia.
Photo: © World of WearableArt Ltd

Figure 1.20 Augmented clothing using 3D printing pen.
Photo courtesy of: LIX PEN LTD

Figure 1.21 Close-up of gaps in 3D printed over-sized bust being filled by 3D printing pen.
Photo courtesy of: Michael J. Horejsi

SYRINGE-STYLE EXTRUSION

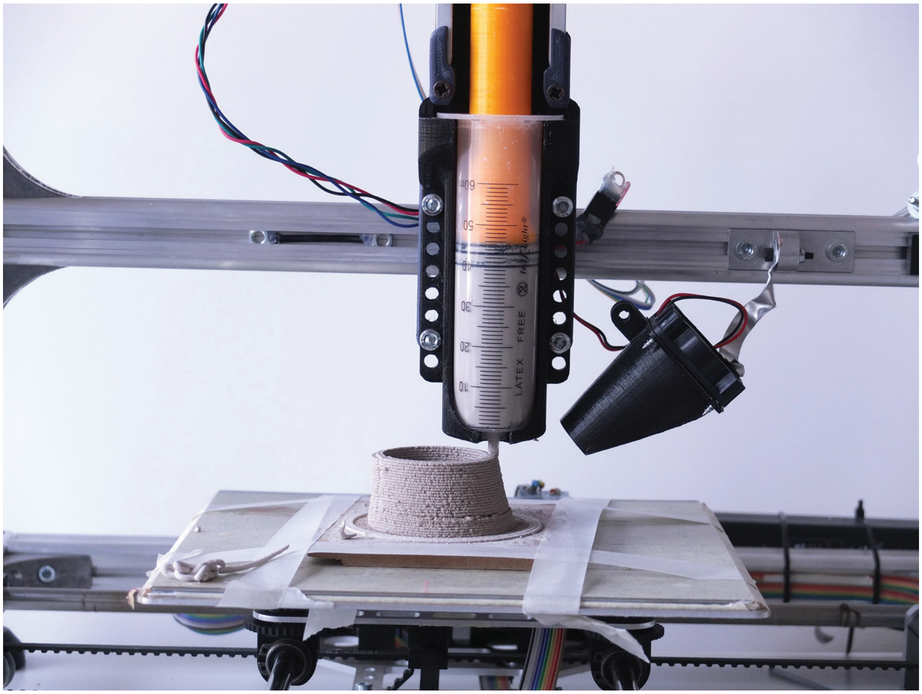

Figure 1.22 Syringe-style 3D printing.
Photo courtesy of: +Lab – POLITECNICO DI MILANO

Syringe-style extrusion is essentially FDM printing except that the traditional extruder has been replaced with a pressurized syringe (see Figure 1.22) which allows for the extrusion of pliable materials – anything from soft foods to clay. Due to this innovation, novelty items such as 3D printed pasta, breakfast cereal, candies, and chocolates have grown in popularity. And many of these items can even be printed made-to-order such as gluten-free pasta or vegan-friendly gummies! (see Figure 1.23).

Other popular adaptations include customizable printed pancakes (see Figure 1.24), burritos, and frosted cakes, as well as inedible materials like air-dry and Plasticine modeling clay, ceramics, Play-Doh!, and even tattoo ink (which uses a tattoo gun in place of the extruder).

3D PRINTING CONFECTIONS

In addition to syringe-style printing, edible products can also be printed with GMB technology. Ingredients such as sugar, salt, milk chocolate powder, and added flavorings can be used as a medium. This technique produces ornately architectural, edible shapes ranging from intricate cake toppers to customized sugar cubes for your coffee (see Figures 1.25–1.26).

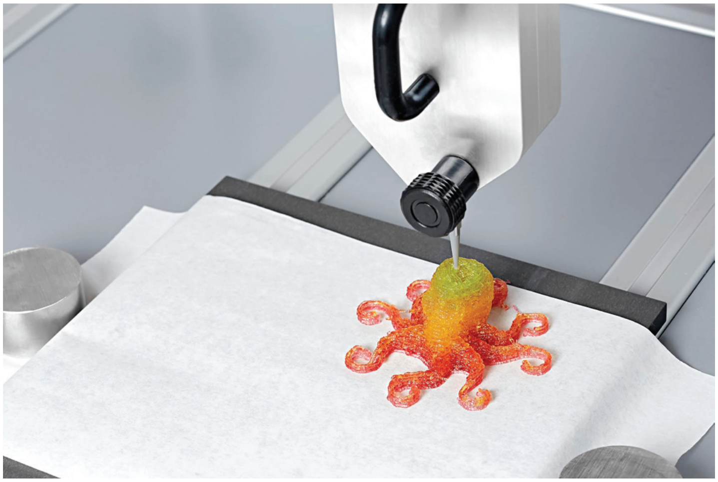

Figure 1.23 3D printed gummy octopus using syringe-style extrusion.
Photo courtesy of: Katjes Magic Candy Factory

Figure 1.24 PancakeBot, invented by Miguel Valenzuela, creating a pancake in the shape of the Eiffel Tower. It uses a proprietary system to dispense the batter onto a hot griddle.
Photo courtesy of: StoreBound, LLC

Full-color products with CMYK mixing abilities can even be created, or ones with moving parts and multiple flavors can be added into every bite for a truly Willy Wonka-like experience (see Figure 1.27).

Figure 1.25 3D printed edible full-color cake topper.
Photo courtesy of: 3D Systems Culinary Lab

Figure 1.26 3D printed sugar cubes.
Photo courtesy of: 3D Systems Culinary Lab

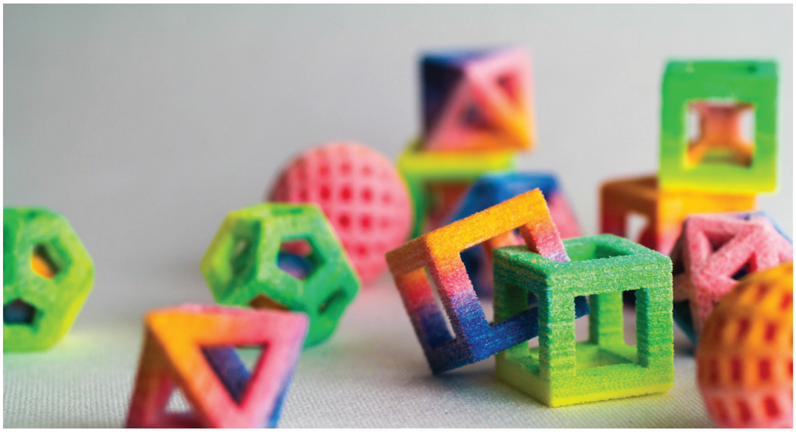

Figure 1.27 3D printed sugar cubes in full color.
Photo courtesy of: 3D Systems Culinary Lab

For food, the powder binder method with a water-based flavor binder (like sugar water) is used most often (instead of SLS). Although sintering sugar granules also works, the heat applied during this process caramelizes most sugars and may create an undesired color shift in the object.

These printing techniques are quickly changing the way professional bakers, pastry chefs, restaurateurs, mixologists, and event planners think about artful, sweet treats. And why not entertainment design? Edible, otherworldly props can help to complete a uniquely conceptual table setting.

DIGITAL TEXTILES

Digital textiles, also referred to as Digital Knitting or 3D Cloth Printing, is an experimental field still in its infancy at this time of print. Several methods are being developed as well as various styles of printers.

Some of the techniques employed by these machines echo traditional knitting; companies such as Ministry Apparel and OpenKnit use traditional yarn materials to produce seamless garments – fabric woven in the round to produce one finished piece rather than several flat pieces which need to be sewn together (see Figures 1.28–1.29). Others print fabric-like plastic structures that look like delicate interwoven lace or chainmail (see Figures 1.30a–b).

Even desktop printers are getting in the game. In 2013 at the Printshow in New York, XYZ Workshop debuted the longest 3D printed dress created at that time using a desktop printer. The *inBloom* dress was 100% 3D printed on a desktop Ultimaker 3D printer and was “made of 191 panels, took 450 hours to print, and used 1.7 kg of 2.85 mm Fexible PLA, the equivalent to approximately $103.50 USD worth of filament”[4] (see Figure 1.31).

Figure 1.28 3D knitted seamless blazer.
Photo courtesy of: Ministry Apparel

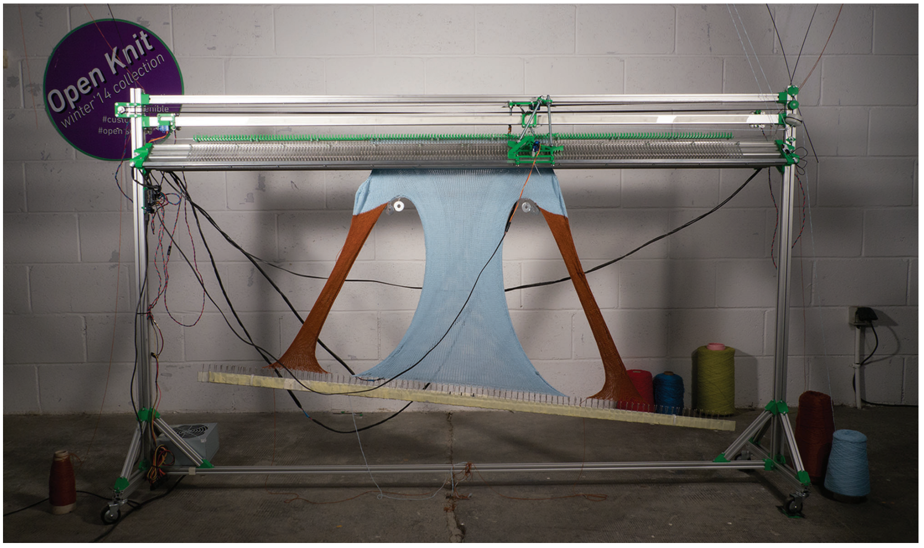

Figure 1.29 A 3D printer for clothes. Project: OpenKnit.
Photo courtesy of: Francesc Rubio

Figure 1.30a 3D printed chainmail-like dress, designed by Janne Kyttanen.
Photo by: Adrian Woods & Gidi van Maarseveen
Photo courtesy of: Janne Kyttanen

Figure 1.30b Close-up of 3D printed dress designed by Janne Kyttanen.
Photo courtesy of: Janne Kyttanen