Username: Stephanie Owens **Book:** Fabricated: The New World of 3D Printing. No part of any chapter or book may be reproduced or transmitted in any form by any means without the prior written permission for reprints and excerpts from the publisher of the book or chapter. Redistribution or other use that violates the fair use privilege under U.S. copyright laws (see 17 USC107) or that otherwise violates these Terms of Service is strictly prohibited. Violators will be prosecuted to the full extent of U.S. Federal and Massachusetts laws.

The printer of youth

William Shakespeare called old age a “hideous winter.” Many cultures tell stories of a mythical Fountain of Youth which gives people the gift of eternal youth. A medieval novel described the Fountain’s therapeutic power to turn old warriors into young ones.

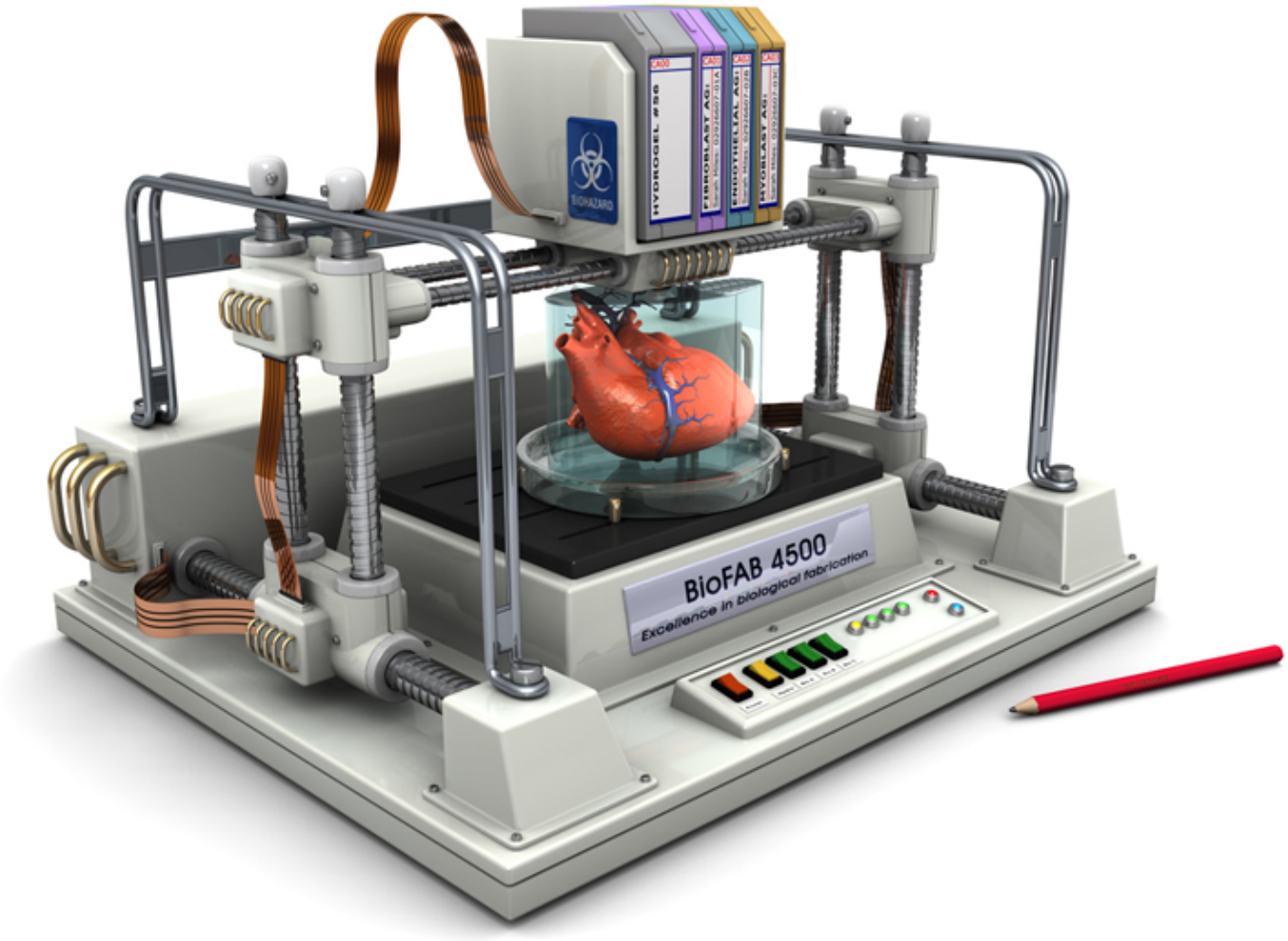
The old warriors; more than forty-six bathed in it and when they came out they were age thirty and like the best knights. Then the other old men . . . said see how old and bent we are? We have lived more than a hundred years and now you will see us in another guise. They entered the fountain and bathed four times as prescribed. They left the fountain rejoicing, and when they returned to Alexander he could hardly recognize them, so young they were.[2]

Despite centuries of searching, no one has yet found the Fountain of Youth. In modern times, people continue the quest with plastic surgery, replacement joints, new heart valves, miraculous vitamin supplements and skin creams. Maybe 3D printing technologies will finally end the search. Printed on-demand body parts will help people who need an organ transplant, or have failing joints. People with disposable income will order custom printed body parts optimized for a beloved recreational activity. The Olympic Committee in the year 2072 will struggle to to decide whether athletes with bioprinted organs should be banned from the Games.

3D printed body parts are still the stuff of fiction. Today the science of printing living tissue is just beginning its long ascent up a hypothetical “3D printed Ladder of Life.”

The holy grail of bioprinting is to 3D-print a functional organ from cell mixture and biomaterials.

Illustration courtesy of Christopher Barnatt, ExplainingTheFuture.comBioprinter concept created by and copyright © Christopher Barnatt, ExplainingTheFuture.com



Imagine a tall ladder of body parts arranged in order according to their complexity. Inanimate prosthetic parts would sit on the lower rungs. On the middle rungs would be simple living tissue such as cartilage and bone. Above simple tissue would sit veins and skin. Just below the top of the ladder would reside complex, critical organs such as the heart and liver, and the brain. Finally, perched atop the Ladder of Life would be complete living creatures, or perhaps someday, fully functioning synthetic life forms. Today, 3D printing technology has already placed its feet on the lower rungs of this imaginary ladder, aspires to the middle rungs and dreams of someday attaining the top rung.

3D printing the ladder of life

In a commencement speech at a Delaware High School, Joe Biden described a glowing future, when “using 3D printers, we’re going to be able to restore tissue after traumatic injury or a burn, restore it back to its original state. It’s literally around the corner.”[3] Biden’s bold claims are just that: bold claims. However, he’s not entirely off the mark.

Let’s start with the lowest rungs on the ladder—inanimate replacement “body parts” such as dental crowns or artificial limbs. The first wave of commercially available 3D

printed body parts are already out there walking around inside the bodies or regular people, perhaps even in yours. Non-living prosthetics such as 3D printed bone implants, dental crowns, contact lenses, and hearing aids reside in thousands of humans worldwide.

Phil Reeves, the managing director of Econolyst, a consulting company dedicated to the 3D printing industry, estimates that today there are “ten million 3D printed hearing aids in circulation worldwide.”[4] Invisalign braces—3D printed, custom-made, clear disposable plastic braces that hide over a patient’s teeth to pull them into alignment—have been a tremendous commercial success. There are an estimated half to three-quarters of a million 3D printed dental implants travelling around in people’s mouths right now.[5]

Like high-end 3D printed titanium airplane parts, 3D printed human body parts represent the ultimate in small batch, direct to digital custom manufacturing. The process for teeth, hearing aids, and braces is similar: the body part in question is scanned. The scan data is sent to a special lab where it’s adjusted into a viable design file. The design file is 3D printed into soft rubber, hard and shiny ceramic, or soft flexible transparent plastic.

Approximately 50,000 custom Invisalign braces are 3D printed every day.

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Today’s first wave of 3D printed body parts are made of a single material such as metals, ceramic or plastic. They make sense commercially since their market value rests on the fact they fit closely into a uniquely shaped body. Their custom shape, small batch production, and the fact they offer their manufacturer no economy of scale makes them perfect (and profitable) candidates for 3D printing. Getting past regulatory barriers is relatively simple. Unlike living tissue or medications, inert bodily “bolt-ons” involve fewer urgent health risks and their side effects are more predictable.

How about an artificial limb that has sex appeal? Today, about two million people in the United States have artificial limbs according to a national advocacy group, the Amputee Coalition. Most modern artificial limbs are still essentially unchanged from those fitted onto soldiers returning from the devastating battlefields of World War II. An artificial hand is made of metal, and its ability to grip small things is provided by a pincer-like set of hooks.

Bespoke Innovations, a small San Francisco-based company recently acquired by 3D Systems, designs and 3D prints custom prosthetic limbs. “The way most artificial limbs are made hasn't changed much over the years—you take a piece of foam, shave it into a rough approximate of a person’s leg, then make a mold and stamp it out,” said Scott Summit, a co-founder of the company.[6]

The science of artificial limbs is making a big leap forward thanks to improved medical imaging technology, better design software, and improved materials. 3D printing offers amputees and doctors a previously unheard-of level of customization. Bespoke’s 3D printed limbs are designed to fit exactly the shape of the wearers’ bodies and lifestyles and to appeal to their sense of style.

Bespoke’s process begins with scanning both a patient’s “sound side” leg and their current prosthetic leg. The data is modeled into a computer design file and their “sound” leg is superimposed onto the digital image of the artificial leg to make sure their new custom limb gives them their body symmetry back. After customers have selected their own unique design, or fairing, Bespoke 3D prints it out.

A stylish artificial limb

Image courtesy of 3D Systems

Bespoke's online tool called the "Configurator" allows customers to explore a range of design styles, including leg patterns, materials plating, and finishes that give its wearer the same social cachet offered by a racy designer motorcycle or unique tattoo. The company named its artificial limbs "fairings" after the specialized coverings used in sleek, high-end motorcycles.

Bespoke's website describes its offerings as follows. "Bespoke Fairings . . . not only return the lost contour, they invite an expression of personality and individuality that has never before been possible." Pictures of people wearing Bespoke's custom-made artificial limbs demonstrate the shift in mentality from the days that people used to hide their artificial limbs. Bespoke's customers wear their artificial limbs proudly.

If we return to the 3D printed Ladder of Life and ascend another rung, we leave behind prosthetics and reach the next rung, 3D printed bone implants. 3D printed bone implants and artificial joints are still considered exploratory medicine. At the time of this writing, 3D printed, custom-made artificial joints made of titanium are available to patients fortunate (or courageous enough) to receive advanced and/or experimental medical care.

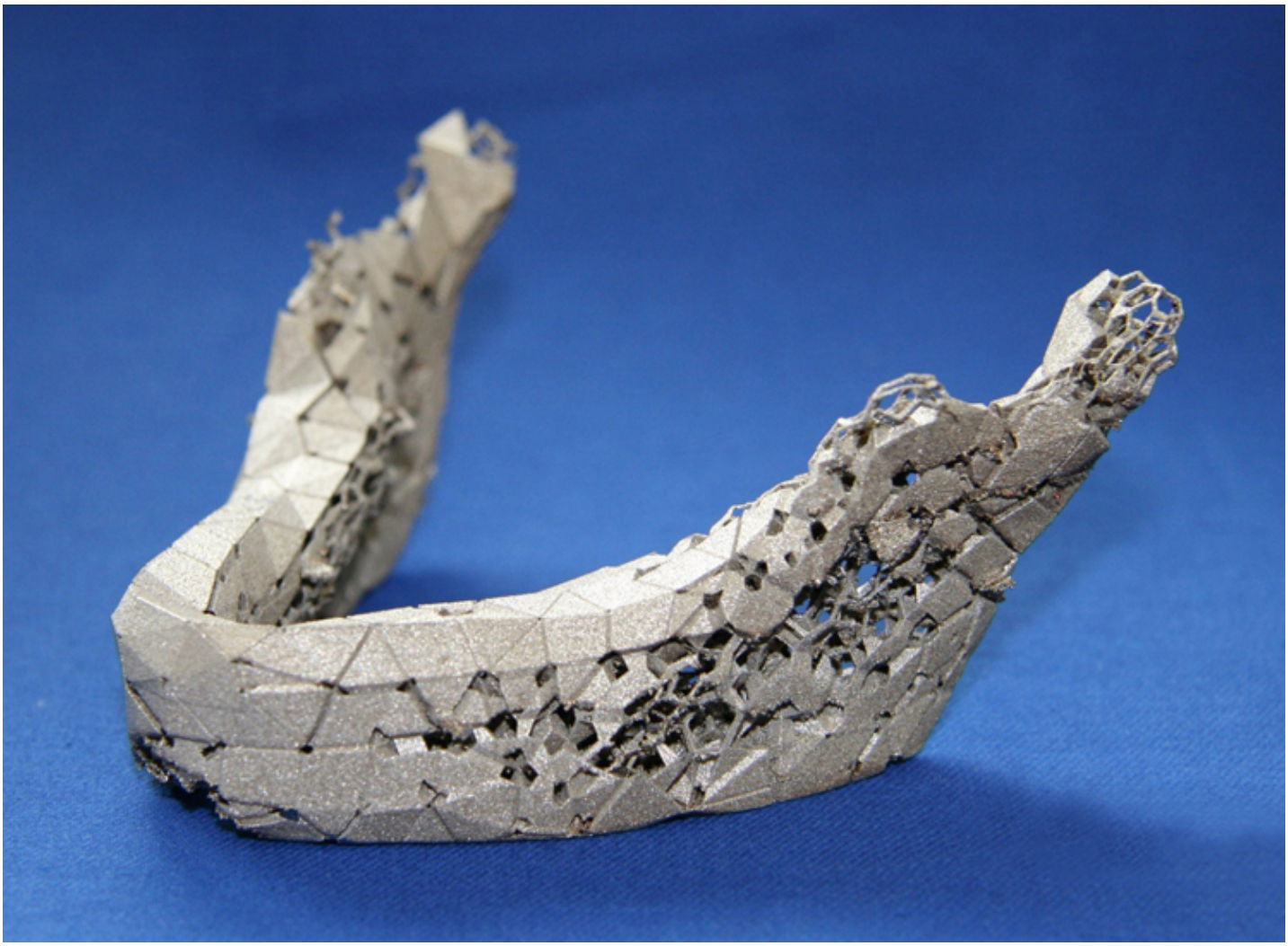
Most standard bone replacements are injection molded if they're polymer or cast in metal if they're made of titanium. The same limitations that apply to making any plastic or metal machine part also apply to making bones. For example, separate bone parts must be molded separately and then assembled later. Freshly molded bones demand precision cooling conditions so they won't shrink or distort and will remain clean. Overcooling can make a new polymer bone brittle; undercooling will result in a bone that's too soft and will smear while handled.

3D printed titanium bone implants have received regulatory approval, but printed polymer bone implants have not. When polymer printed bones receive regulatory approval, they offer new possibilities since polymer has special properties that titanium and ceramic lack. For example, a 3D printed polymer bone could be infused with bioactive bone growth additives and active pharmaceutical ingredients such as antibiotics or anti-inflammatory drugs. A 3D print head could spray droplets of these bioactive chemicals with unmatched precision.

One dramatic surgery made the worldwide news in 2012 when a team of surgeons inserted a titanium, 3D printed bone into the jaw of an 83-year old Belgian woman with oral cancer. The process began when the medical team took a CT scan of the woman's jaw. A medical design company, Xilloc Medical, adjusted the CT scan data into a printable design file and used computer algorithms to add thousands of irregular grooves and hollows into the jawbone. This way, the woman's veins, muscles and nerves could knit themselves more quickly into the new jawbone to fully integrate it into her body.

An individual jawbone implant "baked" from powdered metal

Image courtesy of Fraunhofer IFAMHuman lower jaw with biomimetically graduated cellular structure, made by SLM (metallic bone foam) (c) Fraunhofer IFAM.



In the final step in the process, the titanium jawbone was printed by a Belgian company called LayerWise that specializes in high-end, medical-grade 3D printing technology. The smooth, gleaming new titanium jaw was printed by shining a laser into titanium powder, fusing 3,000 meticulously laid layers. Finally, the printed bone was coated with ceramic. Hours after the surgery, the woman spoke and sipped soup.