Printing Architecture

Printing Architecture

Innovative Recipes for 3D Printing

Ronald Rael and Virginia San Fratello
of Emerging Objects

Princeton Architectural Press New York

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Mud. Or, more specifically, a few dozen PowerPoint slides of intriguing vernacular mud constructions. That's all that was needed for me to understand that the work of Emerging Objects was more deeply connected with our own discourse at Unfold than I had previously realized. While I was intimately familiar with the research of Ronald Rael and Virginia San Fratello on 3D printing architectural components with sustainable and locally sourced materials, I had somehow missed their shared, longtime fascination for earthen architecture. That is, until I sat down on the cozy chairs of the California College of the Arts auditorium in 2015 during the Data Clay Symposium, where Ronald and I each gave a presentation about our respective practices in architecture and design.

In recent years we've witnessed an unparalleled explosion of creative expression and experimentation with 3D printing—not only as a practical tool, but increasingly as a medium in its own right. A lot of media attention has gone to the wild and often baroque geometric-form languages that have been unlocked by the underpinning characteristics of 3D printing. Hod Lipson described in his book *Fabricated: The New World of 3D Printing* the ten fundamental principles of 3D printing: the first is "Manufacturing complexity is free." Unlike in traditional manufacturing processes, where extra complexity requires more expensive tooling, there is no such penalty with 3D printing. And hence we witness a flood of algorithmic designs straight from the future that exploit this freedom as if the objects were unbound by the laws of physics, the limits of real-world materials, or the age-old traditions and heritage of making things.

But what Ron presented onstage was not a story about elaborate computational design but a love story for the mundane material that mud is: how it is ingrained in the tradition of building worldwide, how "one half of the population lives, works, or worships in buildings constructed of earth." The story of architecture for thousands of years has been the story of mud. And where clay or earth has not been easily sourced, similar narratives can be told with wood, rocks, or ice playing the lead role. It was at that point that I understood that this love for the historic and contemporary use of earth in architecture is the root of Emerging Objects' quest to find a role for new technologies while respecting the codes of how we've been constructing our dwellings for ages—with locally sourced, renewable materials that possess intrinsic, enduring architectural qualities: humidity regulation, structural stability, natural cooling, and so on.

Only a handful of slides in that presentation were devoted to 3D printing, but for me they brought the story full circle, and the project shown—the Cool Brick masonry system—is probably my favorite among the projects you'll find in this book. The Cool Brick provides passive evaporative cooling similar to how buildings were cooled in ancient Oman before the advent of refrigeration, with a system called the Muscatese window, consisting of a porous ceramic jar sheltered from the sun by a wood *mashrabiya* latticework. The design of the Cool Brick combines these elements in a brick-size ceramic lattice that absorbs moisture and cools the air that flows through its open structure. In a clever way, the Cool Brick exploits the benefits of Lipson's first principle, "Manufacturing complexity is free," while handily cycling around the pitfall of craftsmanship mimicking excessive ornamentation that is so often associated with 3D printing. In a final act, the individual bricks have been assembled in an unapologetic way by setting them in mortar, alluding to the act of bricklaying as possibly one of the oldest additive manufacturing methods.

The work of Emerging Objects has, since its inception, been mostly focused on binder jetting 3D-printing processes that fuse a powdered dry material. The company has been internationally recognized for pushing the limits of this technique by introducing new materials into a normally closed-source machine. Since a 3D object printed with binder jetting is always supported by the powder with which it is constructed, this process offers some of the greatest freedom of form of all 3D-printing techniques. As such, it seems like a regression that Virginia and Ronald recently started venturing into extrusion-based wet clay printing, a process with much greater limitations in regard to obtainable form freedom. My studio, Unfold, developed this process in 2009 out of an interest in bridging digital manufacturing and the age-old clay-forming technique called coiling. But judging by the impressive and rapidly developing body of work that Emerging Objects has gathered under the moniker *GCODE.clay*, it certainly feels as though using wet clay, with its intrinsic limitations and quirky behavior, might be some sort of a homecoming—a return to the mud.

Dries Verbruggen

With his partner, Claire Warnier, Dries Verbruggen leads Antwerp-based design studio Unfold. Together they wrote *Printing Things: Visions and Essentials for 3D Printing*.

Emerging Objects and Unnatural Materials

At some point in their history, all building materials exist as particulate matter—dust, powder, or grains. Iron ore is crushed and ground into fine particles before it can be transformed into steel. The subtractive process of cutting and sanding wood reduces trees to sawdust. Grains of sand are melted to form crystal-clear glass. The provenance of particles—where they come from and how materials migrate—begins as geology or biology; becomes architecture via design; and, in the end, evolves into archeology or anthropology, as the specialists of those professions filter through the dust to uncover the fascinating history of material culture that traces a journey from mines, deserts, evaporation ponds, agricultural fields, forests, or factories.

Building from the ground-up, and understanding history, is central to our philosophy of conceiving of and making larger objects. The accretion of small particles or the assembly of small building components to create larger ones is not a new idea. While humankind has performed the tasks of adding water to dust to make clay, then shaping clay into bricks, bricks into buildings, and buildings into cities for more than ten thousand years, 3D printing has disrupted the idea of handcraft and introduced a deviation to the material lineage of transforming the small into the large.

Our interest in 3D printing is directly connected to traditional construction techniques. For many years we traveled the globe to study architecture constructed of friable soils (mud brick, rammed earth, cob), which took us to Peru, Yemen, China, Argentina, and closer to home in the American Southwest. Based on this research, Ronald completed his first book in 2008, *Earth Architecture* (Princeton Architectural Press), which presented the most widely used building material on the planet—earth (soil, clay, gravel, and sand)—as relevant to contemporary and modern architecture. In the book's afterword, a future scenario for the material was proposed—one that would use computer-aided design (CAD) and computer-aided manufacturing (CAM) processes. While it is commonly considered that digital manufacturing and earthen architecture exist at opposing ends of the technological spectrum, we embarked on research to bridge the wide gap that exists among nonindustrial, industrial, and digital modes of production, expanding the benefits of each.

In 2009 an article appeared in *Ceramics Monthly* on the possibility of 3D printing with

Haeckel Bowls 3D printed in cement, wood, and salt

clay, by Mark Ganter and his collaborators in the Department of Mechanical Engineering at the University of Washington.[1] Ganter had also begun to publish a series of open-source recipes for 3D-printable materials on the website Open 3DP.[2] Through collaborations with Ganter during this time, we experimented with several of these open-source recipes and began to build on them and on our own interests in certain materials, their sources, and their cultural significance.

It is through the lens of 3D-printing technology, coupled with an interest in craft traditions and place, that our explorations in developing materials for architectural production began.

The computer and the 3D printer have allowed us to use particles of light, jets of water, and bits of data to transform dust into customized objects and products that serve as new building blocks for the future, using materials that are locally available, inexpensive, and derived from sustainable sources or waste streams. These materials can be upcycled or transformed into durable and beautiful architectural components that possess the potential for weathering, tactility, and strength. The substances explored in this book—cement, sand, clay, salt, sawdust, coffee, tea, rubber, and others—all begin in powder form. Through 3D printing, they have formed the basis of unique explorations that envision a twenty-first-century architectural terroir that influences the crafting of objects and their meaning.

Our research challenges the limited sources available for rapid prototyping materials by introducing new possibilities for digital materiality. For us, it is not solely the computational aspects that have potential for material transformation but also the design of the material itself. The nature of these materials—that they can be sourced locally (salt, ceramic, sand); come from recycled sources (paper, sawdust, rubber); and are by-products of industrial manufacturing (nutshells, coffee grounds, grape skins)—might situate them in the realm of natural building materials. However, the expansive and nascent potential of these traditional materials, when coupled with additive manufacturing, offers unnatural possibilities, such as the ability to be formed with no formwork, to have translucency where there was none before, and to possess directed structural capabilities and the potential for water absorption and storage. The material condition often referred to as alternative or "natural" building materials now encompasses unnatural building materials.

Turning the small into the big

Considering the particle and the part and their inherent possibilities is not the only way we conceive of scaling up additive manufacturing. When we embarked on this research, 3D printers were expensive and small. The largest 3D printers within a reasonable price range were designed to fit through a door or sit on your desk. This limited the size of the object that the 3D printer could produce. Rather than see this as a limitation to producing architecturally scaled objects, we realized that there are several advantages to printing smaller parts to create larger objects. The first is that 3D printing, despite having existed for over three decades, is relatively new in the history of object making, and an imperfect technology. As most people who have worked with them know, 3D printers often do not complete their tasks—it is a trial-and-error process that typically requires multiple starts to finish a print job. If a large printer is used and a print job requires hundreds of hours, a failed print is a very time-consuming endeavor. Rather, we have employed the notion of a "print farm"—a battery of many 3D printers, each producing different parts. If one printer fails, other printers can continue the task. In our farm, we grow larger structures from smaller 3D-printed blocks, bricks, or tech-tiles. The beauty of a large, 3D-printed structure built of hundreds or thousands of smaller nonstandard or customized components is that each part can be individually fine-tuned to respond to the geomemetic particularities of a complex form. Each component can acknowledge its position in space relative to the whole—by encoding the instructions directly on the block—and to external forces such as climate, solar orientation, and adjacent programming requirements.

This process of working from the small to the large at times requires us to work backward—from the large to the small, subdividing large constructions into their constituent printable parts. Because smaller parts are at the scale of the hand, like the bricks humankind has used historically to construct buildings and cities, they are easily handled and assembled and do not require special skills or tools, no matter the ultimate complexity of an exuberant 3D-printed structure. By 3D printing small, fundamental architectural components, we aim to make 3D-printed architecture accessible, interactive, and related to the craft traditions of the past but with all the yet-to-be-explored potential that this emerging technology has to offer.

3D-printed parts being assembled

PrintFARM (print Facility for Architecture, Research, and Materials)

Additive manufacturing will transform the way buildings are made. Architects can use 3D printing to become material morphologists; it is a medium that ascribes value to design. Materials go in—and a product comes out. The driving factor in that process is design, which, as the research scientist Andreas Bastian points out, integrates both quantitative and qualitative information, turning raw material into a valuable and meaningful object.[3]

Traditional craft culture involved a direct relationship between the craftsperson, the material, and the product, but the Industrial Revolution fractured these relationships. Designers were no longer connected to the machine that made a product or the materials used in its manufacturing. However, 3D printing reconnects the designer to the material and the machine. In fact, the designer can design the materials, the machine, the software, and the product—expanding architects' capabilities to create more intimate relationships among the traditionally separate fields that define design, visualization, structural optimization, budgeting, and construction.

In addition, 3D printing is a potentially sustainable method of manufacturing. It can take advantage of local and ecological material resources and serve as a vehicle for upcycling, and it produces very little waste when compared with subtractive methods of production. Another advantage of 3D printing architectural products is that they can be made on demand, so there is no surplus, no storage, and no shipping products around the world—printed parts or digital files can be sent to job sites, where components can be fabricated in situ. In an era of disposable products, overconsumption, excessive energy use, and toxic materials, architects have a responsibility—to the public and the planet—to change our mind-set about what our buildings are made of and how they function, by engaging directly with the manufacturing processes used to construct architecture.

3D Printing Methods

ZPrinter 310 Plus powder printer jetting binder onto cement powder

There are many different methods of additive manufacturing, but the three types used most frequently by Emerging Objects are binder jetting, fused deposition modeling, and paste extrusion. We use these types of 3D-printing technologies because the machines themselves are not designed for a specific material, only a material dimension, and that allows for material exploration and innovation.

Binder Jetting, invented at MIT in 1993, consists of spraying, or jetting, liquid binder material on a thin layer of powder. The liquid binder solidifies the powder; then, another thin layer of powder is rolled out over the top of the previous layer. This operation is repeated hundreds, if not thousands, of times; after the process is complete, the three-dimensional object must be excavated from the loose powder surrounding it. This loose powder also serves as support material, which allows overhangs, undercuts, and complex forms to be created. The object is then cleaned with a brush to remove the loose powder, and the remaining powder is blown away or vacuumed off. The remaining powder can be recycled and reused in subsequent prints, which means that there is little to no waste. Printed parts can then be infused with a coating, or postprocessed, to provide additional strength. Wax, low-VOC epoxies, glues, and water can all serve as strengthening materials—the selection of which depends on the part's material and the application of the final product.

Fused deposition modeler 3D printing bioplastic

[Fused Deposition Modeling](), or FDM, was developed by S. Scott Crump in the late 1980s and was commercialized in 1990. One advantage of using an FDM printer is its relatively low cost; desktop FDM printers are inexpensive, as is the plastic filament used by the printers. In addition, the parts do not need any postprocessing.

Fused deposition modeling is commonly used for prototyping but rarely for making final products. FDM works on the additive principle by depositing plastic filament along a predetermined path. The filament is unwound from a coil and supplied to an extrusion nozzle. The metal nozzle is heated and melts the plastic, which is then extruded through the nozzle and deposited on a build platform. Printed objects using FDM methods are fabricated from the bottom up, one layer at a time. FDM is capable of dealing with overhangs that are supported by lower layers, but large overhangs and cantilevers require a printed scaffolding.

Paste Extrusion is rapidly becoming an accessible means of 3D printing very diverse materials. Quite simply, in this process, a paste, stored in a tube, is pushed through a nozzle and onto a build platform. The paste is pushed by either compressed air or a syringe or ram press. This is suitable for materials as varied as cement, clay, Play-Doh, silicone, resin, frosting, UV paste, mashed potatoes, chocolate, and many others. Extruding a line of paste onto a build bed is similar to traditional FDM methods of printing, except that the material is not heated in the nozzle. As in FDM, objects are built from the bottom up, one layer at a time. Currently, the diameter of paste extrusion can range anywhere from .0001 millimeters, for bio inks used in the production of cells for organs, to 25 centimeters wide, for mud and concrete used to make entire buildings.

Early users of computer numerically controlled (CNC) paste extrusion include Adrian Bowyer, who started the RepRap Project with a paste extruder in 2005, before filament extruders became commonplace; Behrokh Khoshnevis, who developed a contour crafting machine that extruded cement in the late 1990s; and Evan Malone and Hod Lipson, who released the Fab@Home multimaterial 3D printer in 2006. But it was not until 2009, when Dries Verbruggen, of Unfold Design Studio, rapidly advanced paste extrusion through the invention of the “claystruder” that the process became attainable and visible to a larger audience. Over the last ten years, clay extrusion has become very popular, because of the low cost of the machines, the low cost of the material itself, and the durability of the clay once it has been fired in a kiln; additionally, there is no waste, since all the leftover, dried clay can be reused. Many open-source kits for building clay 3D printers are now available online.

Potterbot paste extruder 3D printing clay

Salt

Buildings made of salt have existed since antiquity. Over two thousand years ago, when the Greek historian Herodotus (ca. 484–425 BCE) journeyed to North Africa, he saw “masses of great lumps of salt in hillocks” where men dwelled in houses built of salt blocks.[1] Herodotus was no doubt referring to the peculiar building technique in which blocks of salt were taken from the nearby saltwater lakes and adhered together with an abundant mud mortar, also very rich in salt, in what is today the Siwa Oasis. Siwa is the only city in the world that uses this technique of making blocks that are a combination of mud and up to 80 percent salt. Similarly, five hundred years later in Arabia Felix, Pliny the Elder wrote about his journey to “the city of Gerra, five miles in circumference, with towers built of square blocks of salt” that are “adhered together with copious amount of sea water.”[2] The city of Taghaza, in the African country of Mali, is also built of salt, but using a very different process. Workers in the enormous salt mines at Taghaza live in houses and pray in mosques constructed from slabs of solid salt that are roofed with camel skins. Extreme geologic and climatic conditions allowed for the construction of these saline cities. Because of a near-absence of precipitation, almost no vegetation grows in the desert regions of Africa and Arabia. The arid climate requires builders to look elsewhere for materials; the lack of rainfall in turn prevents the salt blocks from eroding.

Traditionally, salt was either harvested from solar evaporation ponds adjacent to bodies of water or mined from rock salt deposits deep below the surface of the earth. Therefore, salt has been used as a material for building both above and below the ground. One of the most interesting sites of salt harvesting in the world is the Wieliczka Salt Mine in Wieliczka, Poland. Extending 1,072 feet below the earth’s surface, the mine, in operation from the thirteenth century until 2007, is a World Heritage site and is often referred to as an underground salt cathedral. Throughout its history, miners carved grand interior spaces, salt crystal chandeliers, and intricate reliefs of biblical scenes throughout the underground building as they excavated for table salt. The salt mine contains enormous rooms where galas and banquets for hundreds of people can be accommodated, as well as private chambers where world leaders and scientists can conduct confidential meetings without the fear of being overheard.

Other mines are similarly intriguing for their sublime salinous spaces. In Grand Saline, Texas, Morton Salt mined a salt dome that is fifty-seven stories underground and has walls of white salt rock descending in silent splendor to a depth of eighty-five feet. In contrast to the towering underground palace, above ground, the town hosts a small, one-story Salt Palace Museum on Main Street. The palace is constructed of salt rock from the mine below and is the fourth and smallest of the salt palaces the town has erected—the first three melted! In its current iteration, the salt rock walls are made of salt rubble–style masonry and are protected by overhanging eaves. The building has been “re-salted” three times by a stonemason who replaces the salt rock veneer with new irregularly shaped salt rocks from the mine below.

More examples of salt-block buildings currently exist around the world. Constructed at the edges of the world’s largest salt flat in Salar de Uyuni, Bolivia, are three hotels and many houses and restaurants, all made of salt blocks. The *salar*, an expansive salt flat that covers over four thousand square miles, consists of a salt crust that varies in thickness from a fraction of an inch to thirty-two feet in some places. Because of the sheer abundance of salt (there are over eleven billion tons in the salar), most of the buildings in the area are constructed of salt bricks cut from the crust of the salt flat. The walls, domed ceilings, floors, and even the furniture of these buildings are often completely constructed of salt. The salt bricks are cut straight out of the ground in dimensions and proportions that vary; they can be lifted and placed by hand, reminiscent of the construction of an ashlar masonry wall. Colored layers present in the cut salt bricks indicate the vacillation between dry seasons and rainy seasons, when sediment is deposited—a natural process repeated annually. The strata of sediment and salt create a pattern of growth that can be seen on the surface of the building itself. The layers of salt and other sediments, coupled with the stacking of blocks, create buildings that appear in stark contrast to the vast, white planes of the expansive salt flat.

While salt has long been a traditional material, it can be found in contemporary architecture as well. One radical example of salt in architecture is its application as a chemochromic smart material in glass facades. The technology consists of a light-directing insulation glazing system that uses salt as a phase-change material. It is composed of four panes of glass, one behind the other, with external light-directing prismatic plastic panels and internal transparent plastic containers filled with a thin (⅝-inch) layer of calcium chloride hexahydrate. An excellent thermal mass, the translucent salt hydrate can absorb as much heat as a sixteen-inch-thick concrete wall. The salt makes it possible to replace thick, opaque walls with thin, transparent surfaces. The salt hydrate’s melting point is between seventy and eighty-six degrees, and during the summer months, when the building interior warms above this temperature, the salt melts and absorbs the thermal energy that would otherwise lead to overheating. However, because the salt remains translucent, light still penetrates the interior. When the outside temperature drops below the melting point, the molten salt begins to recrystallize, and heat is released, warming the building interiors during cooler evenings and nights. This use of salt as a facade element demonstrates how its performative properties can be exploited for their optical and thermal qualities to diffuse light and store heat, making salt a contemporary energy-efficient building material and technology.

Another example of contemporary salt architecture is in the city of Shiraz, Iran. An architect, Alireza Emtiaz, has transformed salt from Maharlu Lake, just outside Shiraz, into twisting sculptural forms that evoke a cave, to create the interior and facade of a restaurant called Namak, the Persian word for salt. The contrast between the soft undulations of the restaurant's facade and the city's hard edges makes the restaurant stand apart from the surrounding buildings. Loose salt crystals were mixed with a natural gum to make a thick coating that was sculpted into the novel, doubly curved surfaces of the restaurant's interior and its facade. The salty finish resembles stucco, and the architecture evokes an urban crystalline grotto emerging from the city.

The technique used to create the salt stucco of Namak is similar in some ways to the process used in 3D printing salt by Emerging Objects. In both cases, salt from a body of water is harvested and used in its granular form, which allows the salt to be shaped, and in both cases the salt is mixed with environmentally friendly resinous materials to become strong and waterproof.

Salt Hotel, Salar de “Uyuni, Bolivia

3D Printing with Salt

The Saltygloo is an experiment in 3D printing using locally harvested salt from the San Francisco Bay to produce a large-scale, lightweight, additively manufactured structure. In the landscape of the Bay Area, five hundred thousand tons of sea salt are produced each year, using only the sun and wind, making salt a locally available sustainable building material. The salt is harvested in Newark, California, where saltwater from the San Francisco Bay is brought into a series of large crystallization beds that are more than a hundred years old. Over three years, the brine evaporates, leaving five to six inches of solid crystallized salt, which is then harvested for food and industrial use. From this landscape, a new kind of salt-based architecture—created through 3D printing and computer-aided design—was realized. Inspired by traditional cultures that use the building material found

Salt crystallization beds in the San Francisco Bay

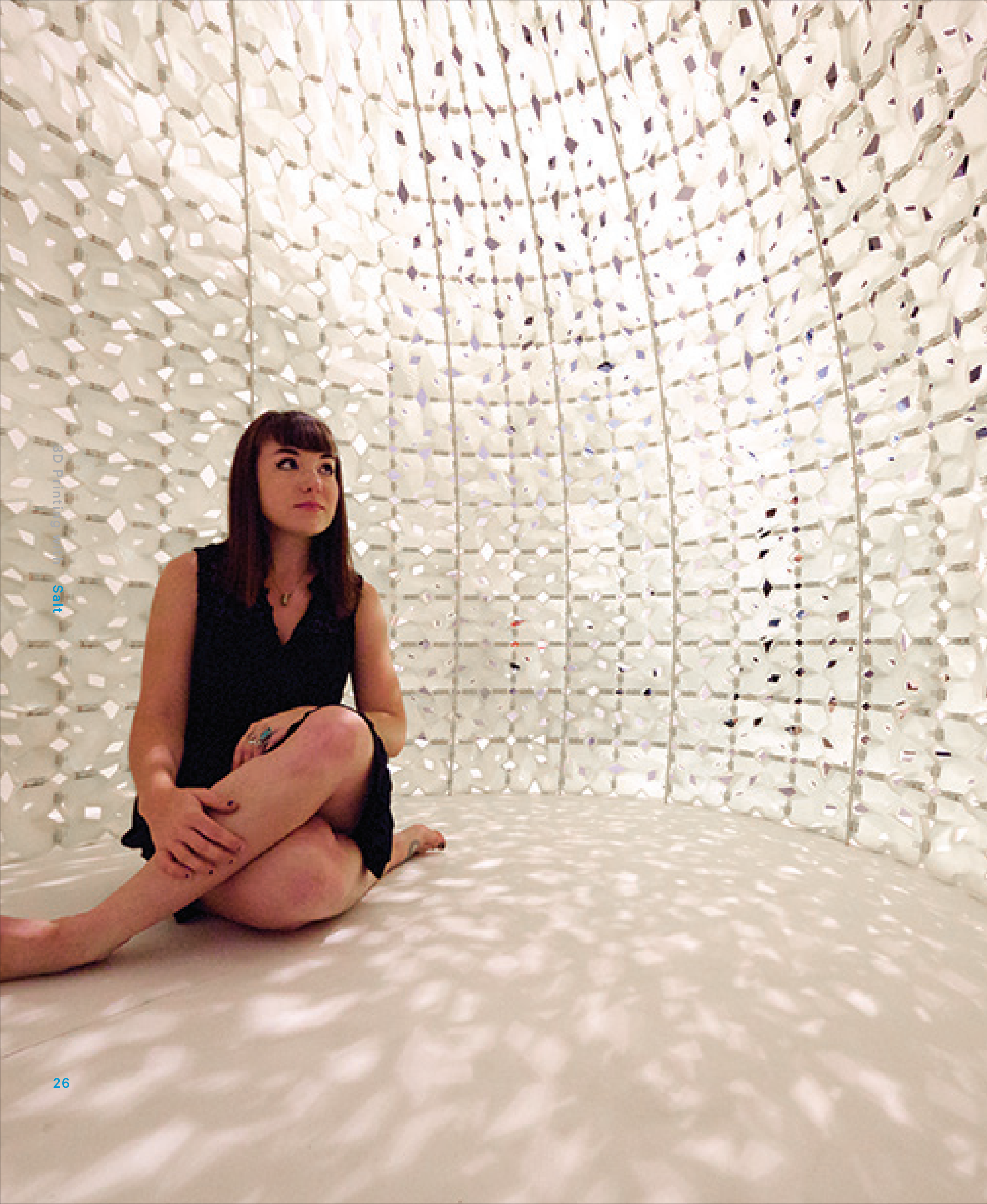
Ancient method of boiling brine to produce salt

directly beneath their feet, such as the Inuit with their igloos, Emerging Objects embarked on a similar process. It is named *Saltygloo* because it is made of salt *y* glue—a combination of salt harvested from the San Francisco Bay and glue derived from natural materials. This substance makes an ideal 3D-printing material that is strong, waterproof, lightweight, translucent, and inexpensive.

The form of the *Saltygloo* is drawn from the forms found in the Inuit igloos but also the shapes and forms of tools and equipment used in the ancient process of boiling brine. Additionally, the design of each tile is based on the microscopic forms of crystallized salt. The 3D-printed salt tiles that make up the

Saltygloo assembly

3D Printing with Salt



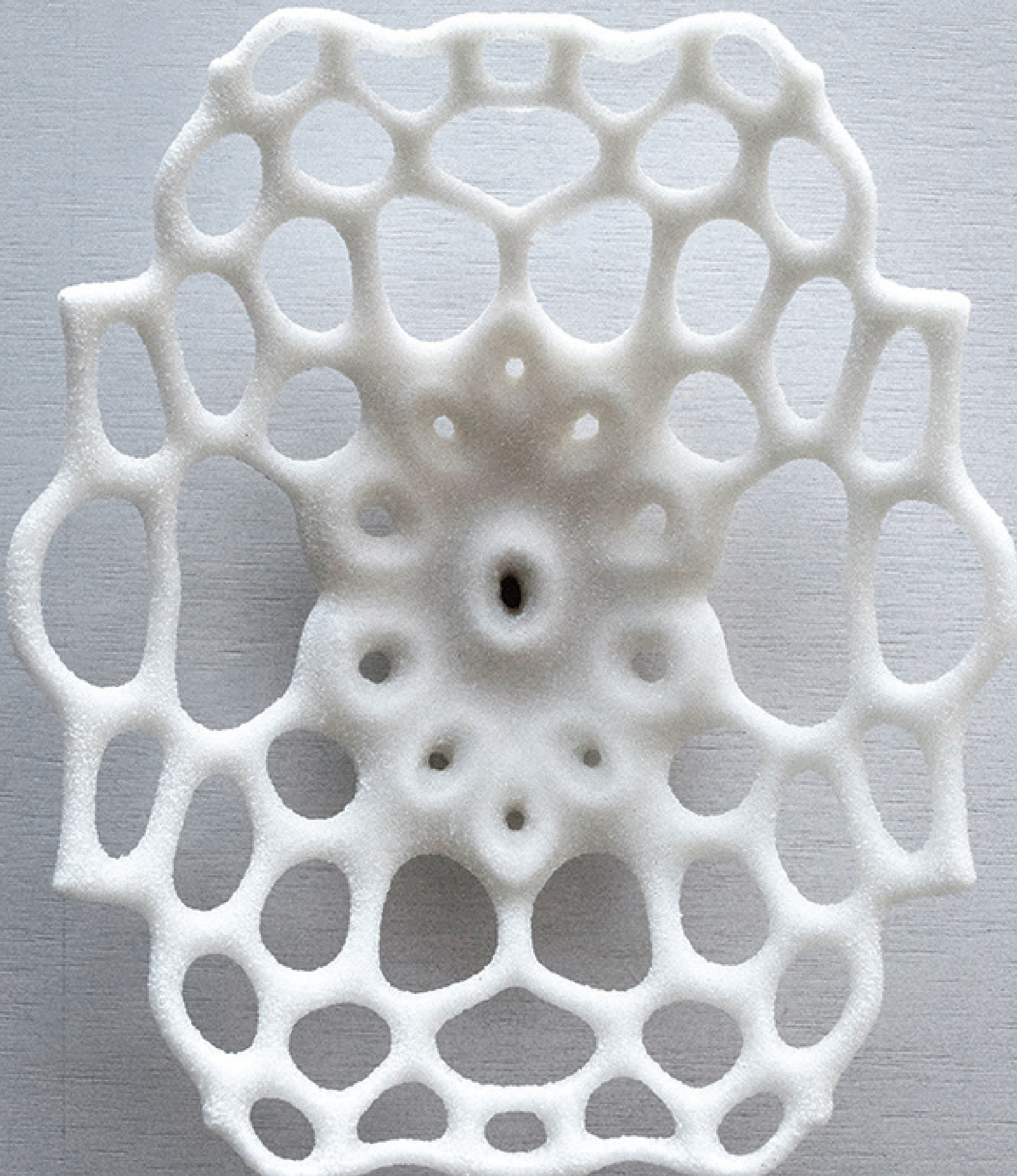
surface of the *Saltygloo*—330 in total—are connected to form a rigid shell that is further strengthened with lightweight aluminum rods flexed in tension, making the structure extremely lightweight, easily transported, and able to be assembled in only a few hours; it is in many ways a salt tent. The material's translucence, a product of the fabrication process and salt's natural properties, allows light to permeate the enclosure and highlights its assembly and structure, revealing the unique qualities of one of humankind's most essential minerals.

Salt Objects

Salt can be 3D printed and formed into familiar objects such as these functioning saltshakers. Each has a solid 3D-printed exterior, with holes printed into the top, allowing for the loose interior salt to be sprinkled on food. The binders and additives in the salt formulation are edible and nontoxic.

The GEOtube Tower is a scale model constructed as part of a proposal for a “vertical salt deposit growth system” for Dubai, designed by Faulders Studio. The model’s modular components and unique material formulation for 3D printing were developed and fabricated by Emerging Objects to be extremely translucent and consistent with the designer’s proposal for a building constructed of salt.

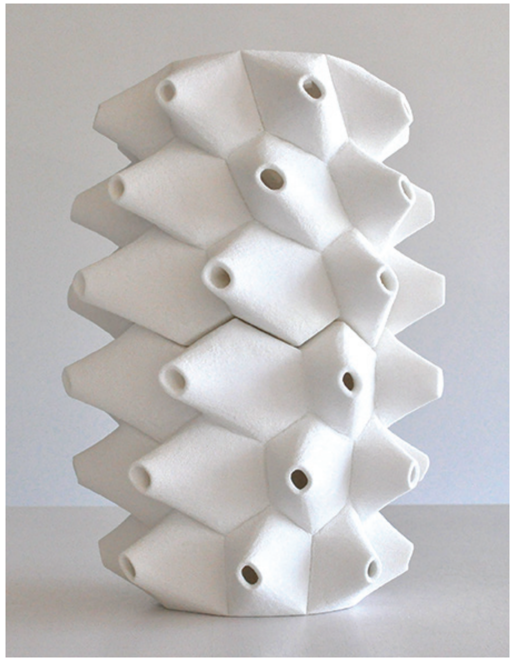
Faulders Studio’s idea for the *GEOtube Tower* was born from Dubai’s unique environmental conditions. The world’s highest salinity for oceanic water is found in the adjacent Persian Gulf (and the Red Sea). The result is a specialized habitat for the wildlife that thrives in this environment and an accessible surface for the harvesting of crystal salt. Gravity-sprayed with the waters of the Persian Gulf, the skin of this urban sculptural tower is designed to be entirely grown rather than constructed—in continual formation rather than fully completed—and to be created locally rather than imported.



The form of the Haeckel Bowl is inspired by the German biologist Ernst Haeckel's book *Die Radiolarien*, published in 1862. Radiolarians are tiny protozoa that produce intricate mineral skeletons made of silica. Because silica is impervious to many acids that often dissolve shells, these skeletons make up a huge proportion of the sludge found on deep-sea beds. The filiform skeletons typically have radial symmetry and are composed of ornate polyhedral lattices and substructures. The *Haeckel Bowl* is printed in every Emerging Object material as a test to study strength, because of the cantilever, wall thicknesses, and dimensional variability of the lattice-like structure, which becomes progressively thinner as it moves away from the center. The entire structure is very shallow—less than two inches deep—and can be printed quickly.

The salt version of the *Haeckel Bowl* is translucent and glows when light passes through it. This material attribute is remarkably similar to the glasslike qualities that the deep-sea radiolaria themselves possess, for when they are observed with an optical microscope, radiolaria are found to be low-contrast, light-scattering objects.

The Twisting Tower, 3D printed in salt, explores vertical aggregation along with techniques for stacking by interlocking. Its form is composed of undercuts, twists, and bends that make it extremely difficult to cast.



Sawdust

Sawdust is composed of tiny particles that come from sanding or cutting wood. It is largely an industrial by-product, generated by the wood industry in sawmills and furniture factories and on building construction sites.

Sawmills have historically been the largest producers of sawdust. They have been in operation since the Middle Ages and often were constructed near salt and iron works to produce fuel. In the early eighteenth century in North America, forests were so abundant that settlers moving across the country would construct sawmills in the wilderness as one of their first acts when establishing a town. The first frame house in a community, built with the lumber from the sawmill, would be notable, perhaps momentous. Frame construction in early America stood out as a revolutionary new paradigm in building.[1] Because they could be erected more quickly, houses using milled lumber and the balloon frame technique replaced the hand-hewn, heavy timber houses that previously had been commonplace. Balloon framing became the standard technique of mass housing construction in the nineteenth century. At that time, the United States was still a forest-rich region, and manufacturing boomed as new technology brought advances in the quick and cheap processing of wood in sawmills on a massive scale. This rapid industrialization created extremely high levels of waste. In fact, by the mid-twentieth century it was said that sawmills were in reality "sawdust factories, with a by-product of lumber."[2]

Eventually realizing that the forest was not, indeed, limitless, engineers and inventors began to speculate about how to be more efficient with its resources. Whereas previously, as much high-quality wood as possible was sent to the mill, new innovations exploited "wood waste" or sawdust. Eventually, sawdust became the driving force of the construction industry through engineered building products such as plywood, fiberboard, and chipboard. Nevertheless, the construction industry continues today to generate large quantities of sawdust during the manufacture of lumber and engineered building products, in addition to generating tons of wood waste during the construction and demolition of buildings. In 2013, in the United States alone, over forty-two million tons of wood waste were generated on construction sites.[3] If necessity is the mother of invention, then necessity demands that the world's continuing supply of wood waste be transformed yet again.

Sawdust waste

Wood waste is frequently incinerated as fuel at large factories, but it can also be ground into very fine wood flours. Wood flour has major industrial markets in the construction industry; for example, epoxy resins, felt roofing, floor tiles, wood fillers, caulks, putties, and a vast array of wood plastics are all made of wood flour. These products are frequently used in the construction of buildings, boats, and furniture. Additionally, wood scraps and shavings continue to be used to make building materials such as chipboard, fiberboard, and particleboard.

Pykrete is one of the most interesting and novel uses of sawdust as a building material. Freeze a combination of 14 percent sawdust with 86 percent water, and the cellulose fibers of the wood dramatically increase the strength and durability of ice. Upon freezing, pykrete is up to fourteen times stronger than regular ice, outperforming concrete in compression, and melts much more slowly. This novel process was invented during World War II by Max Perutz, who proposed using it to construct large, unsinkable ships and mobile offshore aircraft bases. A small-scale prototype of a pykrete ship was fabricated in Alberta, Canada, in 1943, but the idea was scrapped because of the invention of long-range fuel tanks for fighter and patrol airplanes. In 2014 students at the Eindhoven University of Technology built the largest ice dome in the world out of pykrete.

Sawdust can also be used to make wood pulp for paper manufacturing. In building construction, paper is used for sheathing and roofing; for insulation in laminated building products; and, of course, for wallpaper.

Repurposing wood-waste materials to make new wood products has contributed to a wood renaissance. One of the most visible current uses of recycled wood flour can be found in wood plastic composites used for decking materials. The wood flour found in these composites can be produced from locally sourced, reclaimed wood that would otherwise end up in a landfill. By incorporating reclaimed sawdust into products, manufacturers do not need to harvest additional trees. Wood plastic composites are very strong and easy to shape and mill. By adjusting the species, size, and concentration of wood particles in the formulation, variations in properties, such as color and strength, can be achieved.

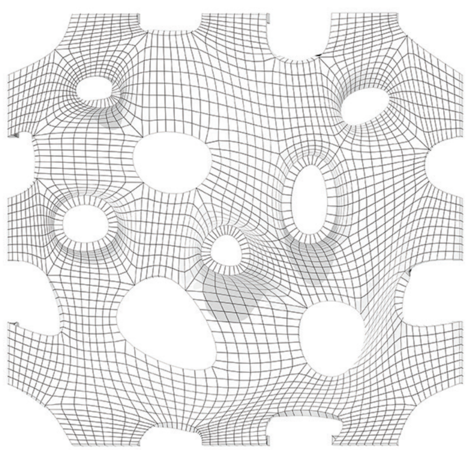
Building the Sagrada Familia in pykrete

3D Printing with Sawdust and Newsprint

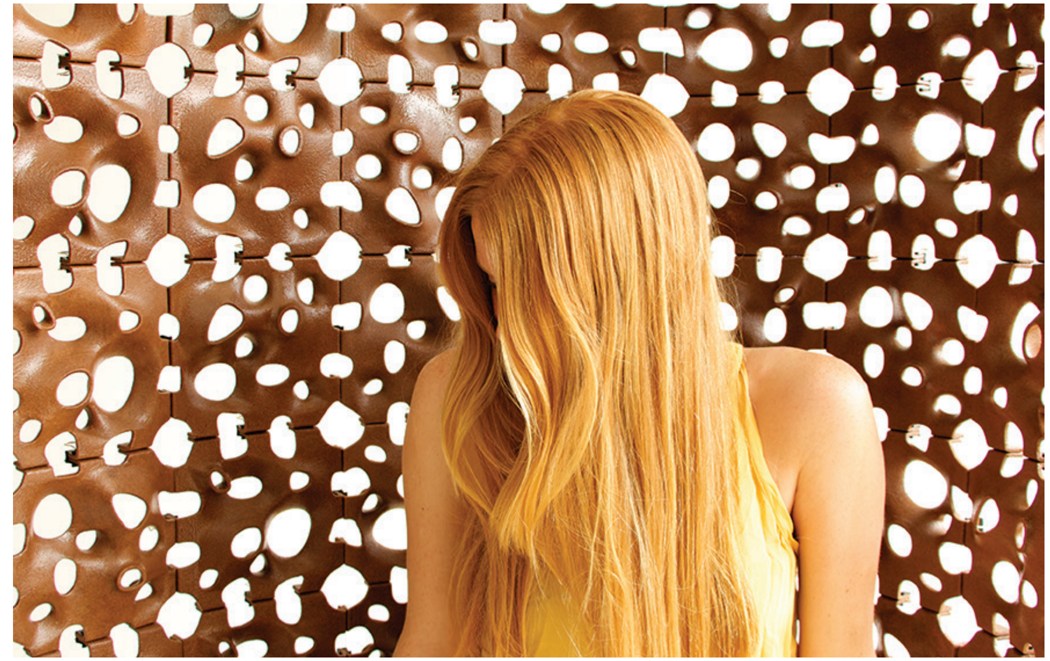
3D printing with sawdust has some similarities to the manufacture of recycled engineered wood products, but in many ways, it is also quite different. Whereas many current applications for upcycling sawdust into building products use equal parts sawdust and polymers, our 3D-printed sawdust begins with nearly 85 percent recycled wood and cellulose particles. The remaining percentage is composed of powder-based glues activated by water. It is only after a 3D-printed object emerges that a polymer coating is applied, which gives the printed object a materially rich texture and surface in addition to its strength. The final color and texture is a product of the wood species that is printed. Pine flour produces objects lighter in color and softer than hardwood fillers such as maple or walnut, which can appear almost like rusted COR-TEN steel. Surprisingly, the layers that are a product of the additive manufacturing process impart a grain similar to natural wood, as if the wood wants to return to its original state and express its internal growth.

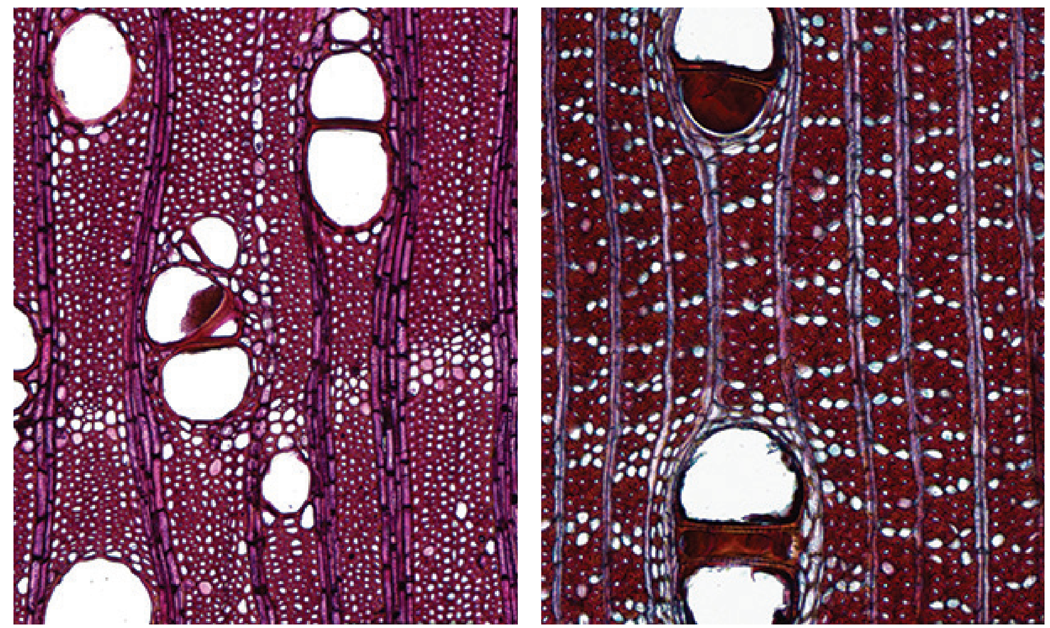
Sawdust isn't the only material that can be used to 3D print wood-like objects. Nutshells, husks, and seeds are all agricultural by-products that can be ground into fine powders and flours and used to make 3D-printed objects that have similar colors and properties.

The Sawdust Screen, for example, is made of pulverized walnut shells and sawdust, and retains a layering effect from the additive manufacturing process, simulating natural wood grain. The screen is composed of individual 3D-printed wood components that are affixed together to form a variably dimensional enclosure and surface. Its porous pattern is inspired by the vessels found in a microscopic analysis of the anatomy of hardwoods. When viewed from the end grain, these vessels demonstrate the porosity of

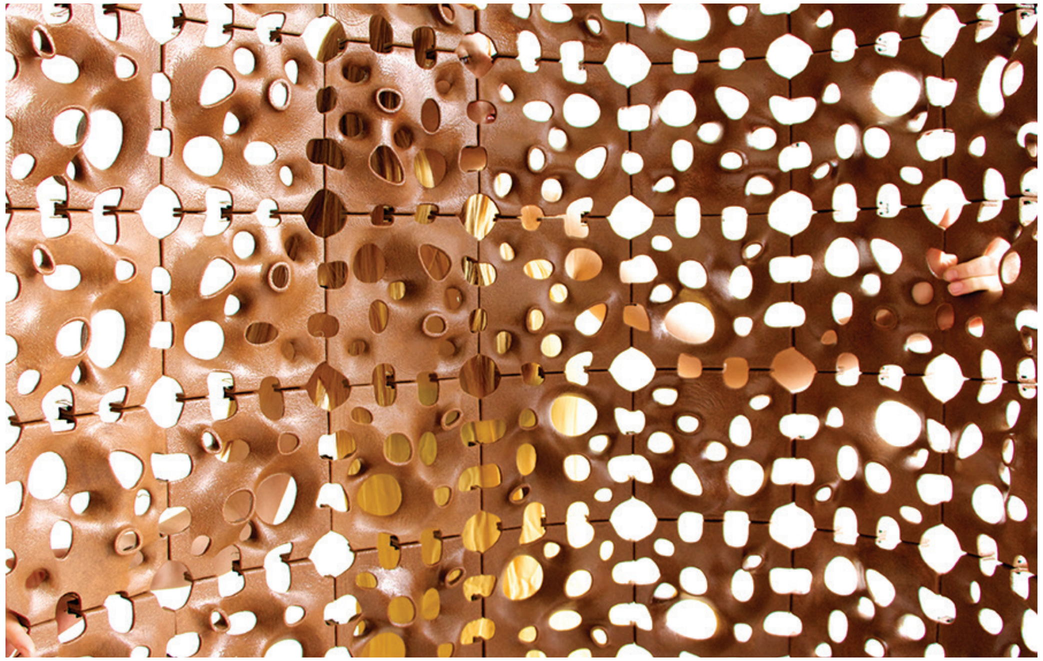


Digital model of Sawdust Screen tile





Transverse wood section of *Dalbergia retusa* and *Swietenia humilis*



wood. In a live tree, they serve as pipelines within the trunk, a transportation system for water and sap. In the *Sawdust Screen*, the vessels serve as an opportunity for visual porosity. The subtle curvature of each vessel accentuates the openings as convex or concave apertures, making the screen both a visual and haptic experience. The *Sawdust Screen* is evidence that 3D printing with sawdust and other agricultural by-products has the potential to transform the inherently subtractive process—which begins with trees and ends with dust—into an additive process that upcycles this widely available material into architectural components.

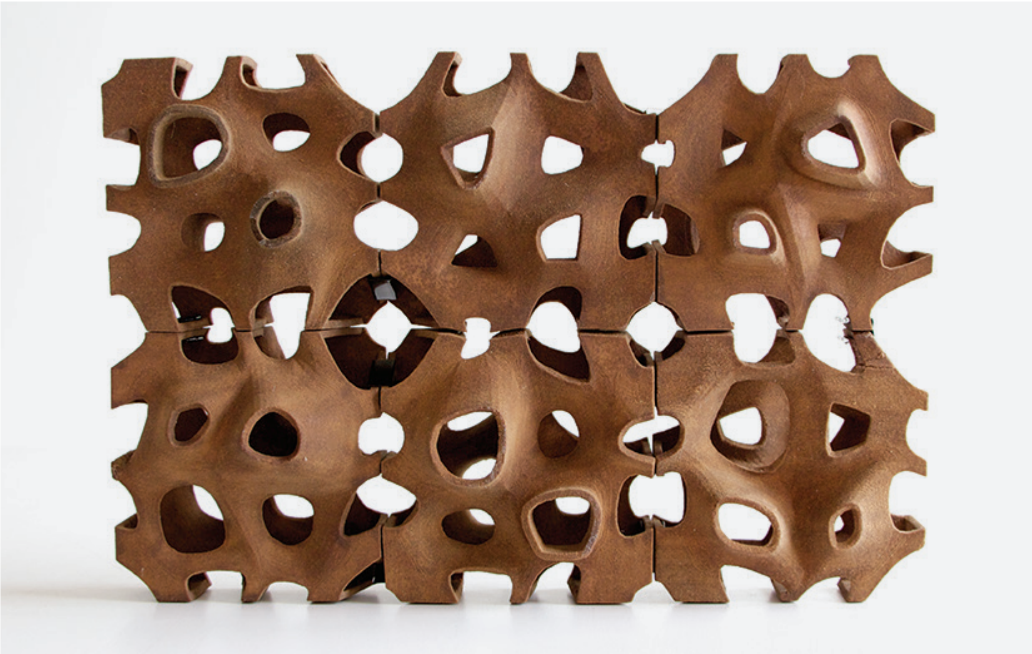
Sawdust, in addition to being a by-product of the construction industry, is also the by-product of certain animals, birds, and insects that live in wood, such as the woodpecker, wasp, and carpenter ant. It is said that the idea of using wood to make paper was inspired by observing wasps. Paper wasps scrape away small particles of wood and mix them with their saliva when making their geometrically complex paper nests.

Paper, specifically newspaper, today is made of ground-up wood pulp. For 3D printing, the newspaper is shredded, mixed with water, dried, and ground up into a fine powder mixture much like papier-mâché. The final product has a velvety, granular appearance and is soft to the touch.

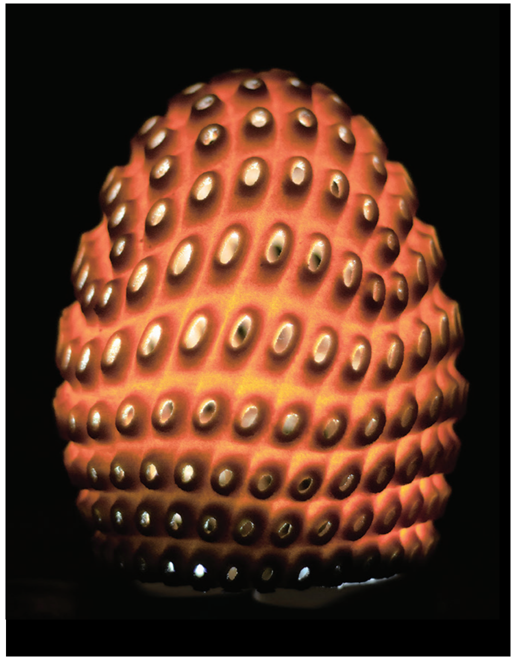
3D-printed newsprint objects

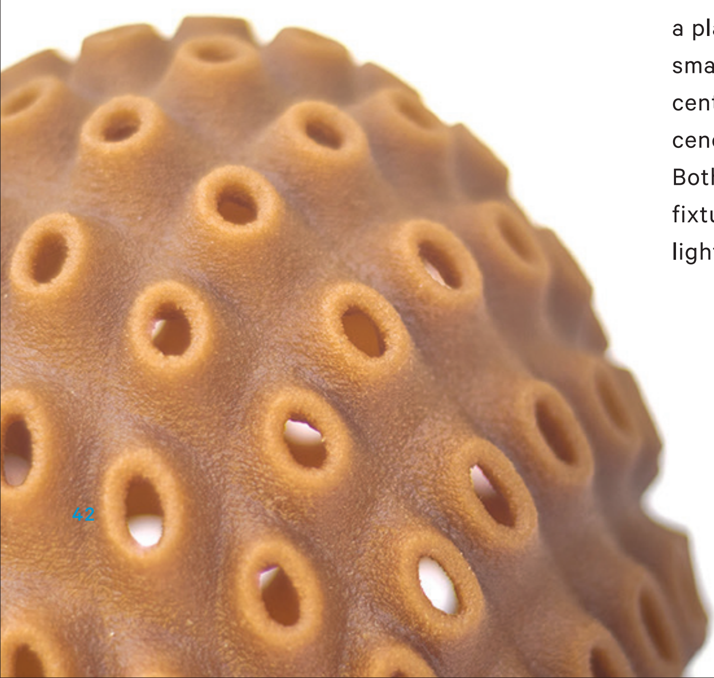
Sawdust Objects

Poroso is an experiment in block aggregation using a specially formulated walnut shell material combined with sawdust. The blocks are double sided, with a hollow interior. There is no front or back; each face of the *Poroso* assembly is unique, allowing for a rich, layered effect when one looks through the wall. The patterns are designed using the Japanese *karakusa* method, in which the pattern of each tile connects to that in every adjacent tile, creating a labyrinthine and uninterrupted motif across the surface that can expand with continuous variation.



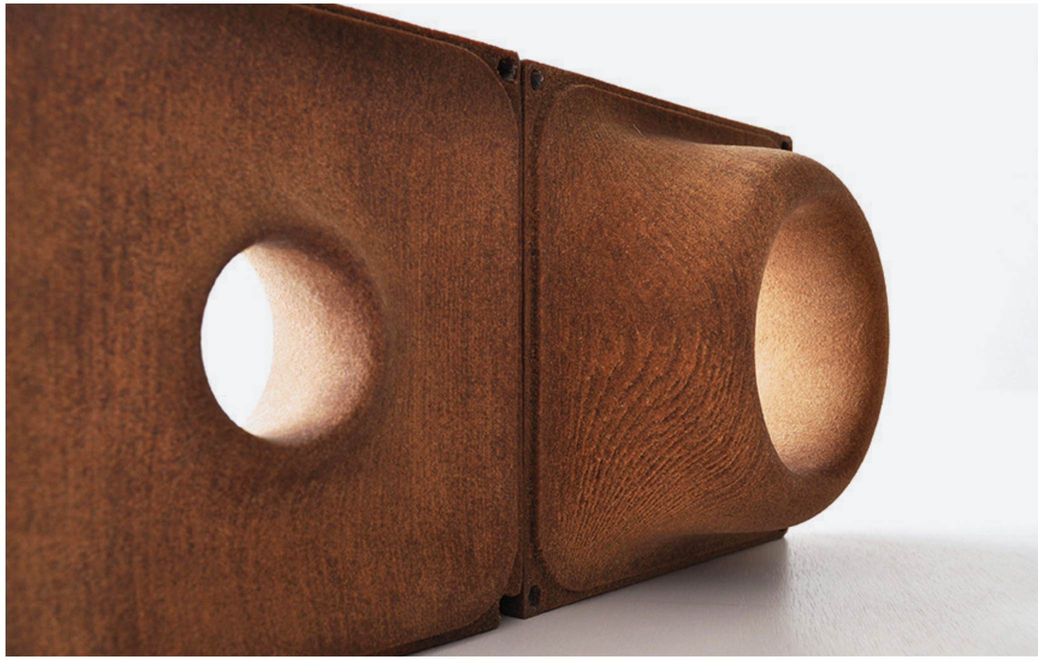
The Burst Tiles demonstrate 3D printing's potential for variation and ornamentation. The flowers on the tiles' surface can have varying degrees of openness. The petals on the flower's surface are parametrically constrained to 30-degree increments of openness, for three unique possibilities (although they might just as easily have been constrained to 1 degree, for ninety possibilities). The petals in their most open and most closed positions develop undercuts and geometries that would be challenging to carve using traditional methods. Because of the complex form and potential for unlimited variation, 3D printing is the best method for producing these designs.





The Lamprocyclas Raelsanfratellis light fixture is made of 3D-printed maple sawdust. The pores, or openings, in the fixture exhibit a play of brilliance or sparkle because of their small size. The 3D-printed wood is translucent and glows, giving off a softer luminescence than that of the sparkling openings. Both the design and the materiality of the fixture contribute to the dual nature of the lighting effect.

A burl is a tree growth in which the grain has grown in a deformed manner. It commonly takes the form of a rounded outgrowth on a tree trunk or branch that is filled with small knots from dormant buds. Burls usually result from a tree undergoing some form of stress, such as an injury, virus, or fungus. In this case, the burl is a product of the 3D printing of wood, exploring the forms and dimensions possible with wood waste as an emerging material in additive manufacturing. Like a burl found in nature, the Burl Bowl contains cracks, deformations, and dense layers of growth rings—a product of the layers of manufacturing.



The Wood Block, designed by Anthony Giannini, uses 3D-printed cellulose powder as a building material that can be mass customized. The additive-layer process of binder-jet printing creates a grain similar to natural wood, which is expressed in the curvature of the block. The wood material is composed of recycled agricultural waste. The texture and subtle translucency of this material give the block a warmth, texture, and luminosity under certain lighting conditions, but it also can appear similar to rusted COR-TEN steel. The *Wood Block* can be used to construct a curtain wall or as a customized masonry unit.

The Haeckel Bowl shown here is 3D printed in walnut shells. Nylon fibers have been added to the powder matrix to increase tensile strength.

Coffee, Tea, and Wine

Coffee, tea, and wine are three of the most-consumed beverages around the world. Each beverage has played a substantial role in the modern era of colonization: tea shrubs, coffee trees, and grapevines were planted by Europeans in India, Australia, and North and South America beginning in the fifteenth century, as European migration and occupation spread around the planet. These plants experienced one of the earliest mass "assisted migrations" (a deliberate relocation to a new habitat) in the history of the world. Because of the global proliferation of these plants, and the extensive beverage industries that have grown up around them, vast amounts of agricultural waste are generated each year as by-products of their cultivation.

The production and consumption of coffee offer many opportunities to harvest waste, beginning in the field where the coffee beans are picked. The coffee bean can be found at the center of the coffee cherry (the coffee tree's fruit). The bean goes through a process of drying or washing as it is separated from the cherry's pulp and outer skin. As the bean continues on its path to roasting, the cherry becomes a waste product. It often is dumped into rivers or left to rot in heaps. In 2016 the world produced 2.886 billion kilograms of coffee cherry fruit and skin waste.[1] In an effort to upcycle the coffee cherry, coffee flour, made by collecting, drying, and pulverizing the cherry fruit into a fine powder, has been developed as a new baking product.

Another source of coffee waste lies in the industrial production of instant coffee. To create instant coffee, coffee must be first brewed and subsequently dehydrated, which means that tons of spent coffee grounds are produced by large producers. The grounds left over after pots or cups of coffee are made in restaurants, coffee shops, and homes around the world are also significant waste.

Coffee grounds can also be used to add color and texture to other materials in the built environment. The grounds can be mixed with vinegar to stain wood, giving it an aged appearance, and used coffee grounds can be mixed with ironite and oil to give concrete a brown tint.

Remarkably, there is an innovative yarn made of recycled coffee grounds that can be knitted or woven into sustainable fabrics that offer enhanced odor absorption, moisture control, and UV light protection.[2] The yarn blends coffee residue with a polymer to produce a coffee/plastic thread. Fabrics can be

Spent coffee grounds

backed with the coffee-residue thread; they can have a micro-encapsulated, baked coffee residue applied to their surface; or they can contain micro-encapsulated coffee essential oil. The material is further composed of a carbonized or "burned" coffee nanoparticle that is made by sieving coffee residue, removing organic contents from the sieved mixture, and then retrieving carbonized particles from the mixture to apply to the fabric as an odor absorber. The end result is a super-high-tech eco-fabric that can be used for clothing or upholstery.

Similarly, the nonprofit design company Re-worked uses coffee waste to make furniture.[3] Used coffee grounds are combined with recycled waste plastics to create a composite material that is durable, waterproof, and easy to form into sheets that can be cut and milled.

Engineers in Melbourne, Australia, at the Swinburne University of Technology, are using spent coffee grounds from local coffee shops to develop sustainable pavement materials for use in road construction.[4] They dry the coffee grounds in an oven at 120 degrees Fahrenheit (50 degrees Celsius) for five days, then sift the grounds to filter out lumps. The sifted coffee grounds are mixed with rice husk ash and blast furnace slag in a 7:2:1 ratio. (The rice husk ash is a by-product of rice production, and the slag is a by-product of steel production.) A liquid alkaline solution is added to bind everything together. The outcome is a coffee-ground geopolymer that leads to a cleaner environment.

Much like coffee, tea generates vast amounts of waste during its cultivation, brewing, and consumption processes. During the harvesting of tea, mature leaves are rejected and left in the field to rot, as are the stems and stalks of the tea bushes. Later, more waste is created when tea is refined and packaged. A by-product called “tea fluff,” a fine dust of broken tea leaves, accumulates on the factory floor and is discarded. Similar to what occurs in the production of instant coffee, the manufacturing of instant tea generates mountains of recyclable brewed leaves, and billions of pounds of tea leaves are disposed of every morning in tea shops and homes around the world, creating a vast network of waste-material sources.

Recycled tea leaves have been used to manufacture synthetic resins, which can be used in building applications. Upcycled tea leaves are also used to create “tea boards,” which are used to make tatami mats and plaster boards that may be used for interior insulation and as finished interior surfaces.[5] These recycled-tea building products are known to have antibacterial and odor-killing effects.

Pomace is the solid remains of grapes after the fruit has been pressed to make wine. It contains the skins, pulp, seeds, and stems of the fruit. Grape pomace has traditionally been used to produce brandies such as grappa, which the Italians have made since around 1000 CE, but even after this second use, remnant material remains. Pomace can be used as fodder and fertilizer, but much like the coffee cherry, grape skins and seeds are often unproductive and remain a waste product of wine production.

Red grape pomace, also called “marc”

3D Printing with Coffee, Tea, and Wine Waste

The waste material generated by coffee, tea, and wine production is abundant, inexpensive, and readily available in almost every region of the world and is suitable for 3D printing. What's more, the 3D-printed objects made of these materials have unique visual and aromatic properties that emerge from their material origins. Pieces 3D printed from coffee possess a dark, rich umber color that patinas and darkens as it ages. Black tea produces a reddish, tawny tone. The skins from different grape varietals produce different colors as well, ranging from chardonnay, which creates a rich brunette color, to cabernet sauvignon, which is almost black like the raisin it was destined to become if left to dry. Coffee, tea, and wine aromas emanate from the 3D-printed objects themselves, and they retain the scent of their raw material for an exceptionally long time, especially coffee and tea.

We have created a series of material formulations with the by-products of coffee, tea, and wine production for 3D printing and fashioned "meta" drinking utensils including a teapot, teacups, coffee cups, ice bucket, and wine goblets. And while it may seem novel and rarified to make drinking utensils out of agricultural materials, it is, in fact, quite traditional. Before the introduction of glassware and ceramics as we know them today, people in East Asia made drinking utensils and vessels out of agricultural fibers and resin, what we commonly know as lacquerware. The production of lacquerware has been ongoing for over ten thousand years—since the Neolithic era.[6] Lacquered vessels are very light and are typically woven of fine strips of bamboo wrapped around a wood mold. The bamboo strips are then coated with sap obtained from tree bark. The vessels are allowed to harden before they are finished with a mix of calcined bone dust, pulverized rice husks, and teak sawdust.

The technique of using broken-down and pulverized agricultural materials strengthened with a resinous material was employed to make many of the oldest drinking utensils, especially teacups, and remarkably, it is similar to how these materials can be combined to make 3D-printed drinking and serving utensils today.

The by-products of coffee, tea, and wine are sourced or pulverized into a fine powder and fiber for 3D printing. Other organic materials are introduced into the matrix that adhere together when the jetted binder is sprayed to solidify the objects in the printer's

build bed. The solid printed vessels are then coated and infused with a food-safe epoxy, resulting in a collection of sustainable and beautiful vessels made from the ingredients that they serve.

Would be helpful to have an image here...

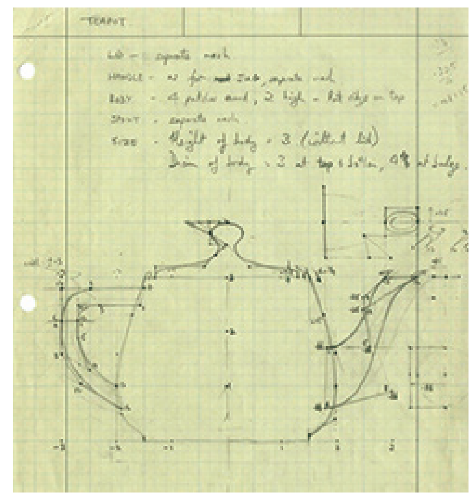
Image of lacquered vessel?

other?

<< Images like these will have edges go to white...

Coffee, Tea, and Wine
Objects

The *Utah Teapot*, also known as the *Newell Teapot*, was one of the first objects ever depicted as a three-dimensional object in the computer. Created in 1975 by the pioneer computer graphics researcher Martin Newell at the University of Utah, this humble teapot has become a standard reference object in the computer graphics community. The *Utah Teapot* for decades remained trapped in its translation from physical object to virtual object; through 3D printing we have liberated the object from the screen. While the original teapot was ceramic, its translation to the physical manifested in a teapot 3D printed out of actual tea! It would not make sense to have a teapot without teacups. These teacups, naturally, are also printed from tea. Furthermore, if you have a teapot and teacups, an obvious necessity would be teaspoons. Of course, the *Tea Spoons* are also printed using tea and hold exactly the volume of a single teaspoon (4.92 cubic centimeters), two teaspoons, and a tablespoon. Therefore the Utah Tea Set is printed from a meta-material, and the object is doubly self-referential—meta—and then meta again.



Martin Newell's drawing of the Utah Tea Pot

The Sugar Teaspoons are 3D printed in sugar and also sized by volume with several quantities available—1 teaspoon, 2 teaspoons, ½ teaspoon—depending on your preference, since these sugar teaspoons can be stirred down and dissolved into one's tea or coffee cup.

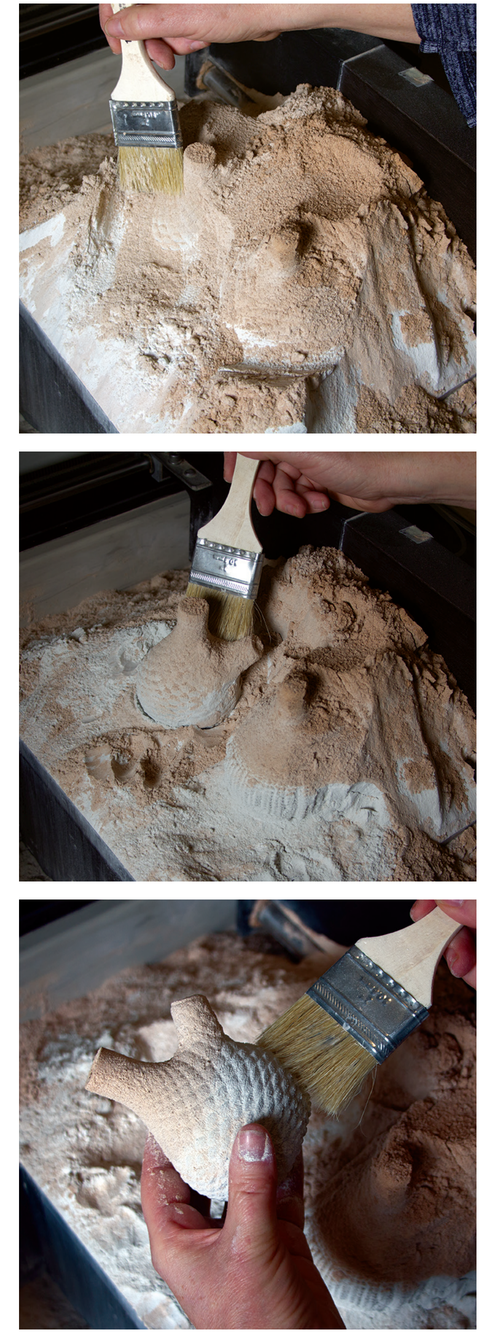
The Coffee Coffee Cups and saucers are 3D printed from upcycled coffee grounds. The grounds are finely pulverized, held together with a water-based binder, and formed into cups as part of the meta-material series of objects. Over time, the cups patina to a rich dark brown, reminiscent of the aroma they exude.

A goblet is a drinking cup with a foot and a stem, typically filled with wine and used during special occasions. Throughout history, goblets have been made of many different materials—earthenware, gold, silver, and glass. Continuing the meta-material series, these Chardonnay Wine Goblets are printed from upcycled chardonnay grape skins and seeds. The skins and seeds are collected from vineyards in Sonoma County, dried in a kiln, and pulverized to the consistency of flour. Both the wine and the goblets themselves can be studied for color, viscosity, texture, notes, and body.

Manufactured using chardonnay grape skins as the 3D-printing material, the Marc Metamorphosis ice bucket was designed by Andrew Kudless/Matsys for Perrier-Jouët. It is composed of seven leaves that rotate around a central circular base. The pattern on the tiles of the ice bucket references the wrinkled skin of a raisin, so that the ice bucket reproduces the texture of a grape as it dries, creating a beautiful and meaningful textured surface tied directly to the wine-making process.

An ombré occurs where there is a smooth transition from dark to light or one color to another. The Ombré Decanters are part of a series of experiments that examine material ombrés. A material ombré creates a smooth and seamless transition from an agricultural material to a geologic material without joints or fasteners. The *Ombré Decanters* demonstrate a graduation from 3D-printed chardonnay to 3D-printed cement.

Excavation of *Ombré Decanters*



The forms of the decanters are inspired by ancient ceramic wine carafes and amphorae, and the surface textures are inspired by the diamond-pressed texture frequently found in wine glasses and decanters.

Cement is sometimes used in vinification culture. Wine can be fermented in concrete vats; because of its thermal mass, concrete allows wine to ferment at a slower pace to retain the flavor of the fruit. The concrete's porosity allows the vats to breathe, naturally fermenting the wine. The oldest fermentation vats from ancient Greece and Rome were made of ceramic materials; thus, the return of cement-based materials for the storage and serving of wine is a look backward and forward at the same time.

Rubber

Automobile tires are one of the planet's biggest waste problems. In fact, the world's largest tire graveyard, in Kuwait, is so vast that it contains over seven million tires and is visible from outer space.[1] Worldwide, almost one billion tires are discarded annually—and 290 million of them come from the United States alone. In the United States, about 80 percent of these tires are recycled, but that still leaves 60 million tires heading to the landfill every year.[2] Discarded tires are extremely problematic because of their inability to degrade and the fact that they contain components that are environmentally damaging. Tires are made of five main ingredients: natural rubber, synthetic rubber, carbon black (a material produced by the incomplete combustion of heavy-petroleum products such as coal tar), metallic and textile reinforcement cable, and numerous chemical agents. These different materials are layered and bonded together to create a product that is flexible, airtight, watertight, and far more resistant to abrasion than steel. Almost no other material in the world can claim this kind of robustness.

Natural rubber comes from mature rubber trees, *Hevea brasiliensis*, which are grown largely on plantations in tropical regions around the world. Originally, rubber could be found only in the Brazilian Amazon rainforest and was first called *cauchu*, or "weeping wood." The Olmec, who inhabited this region, were the first to harvest rubber—the name *Olmec* literally means "rubber people."[3] The Olmec were the first civilization to develop a sport using a rubber ball, and depictions of the game date back 3,500 years.[4] Rubber was used for making sandals, for waterproofing cloth, and for making drumstick ends, and was also burned as incense and used for glue.

By the end of the eighteenth century, the dawn of the Industrial Revolution, rubber had become one of the world's foremost indispensable commodities. It was used to make waterproof fabric, airtight hot-air balloons, and rubber hoses, as well as a vast array of other products, but it still had its problems. The material had a terrible odor, and if warmed too much it became gooey, and in cold temperatures it became brittle and hard. In 1839 the technological genius Charles Goodyear radically transformed industrial rubber. He innovated a process to "vulcanize" rubber (named after Vulcan, the ancient Roman god of fire) by mixing it with sulfur at high temperatures. This process profoundly changed the material's properties, enabling it

Tire landfill

to withstand extreme heat and cold, as well as eliminating its noxious smell. This invention opened the door for rubber to be used in many new ways, including in the production of tires.

Pneumatic tires were first invented in 1887 by John Boyd Dunlop, for his son's tricycle. Another keen cyclist, a Frenchman named Édouard Michelin, tried Dunlop's tires on a bicycle ride from Paris to Rouen and adopted the pneumatic tire for use on motor vehicles, thus creating the single largest market for raw rubber.[5] By the early 1900s American companies such as the Goodyear Tire & Rubber Company and the Firestone Tire & Rubber Company were using millions of tons of natural rubber to make tires. However, at the onset of World War II, the United States was cut off from the natural rubber supply of Southeast Asia, which accounted for 90 percent of production. This caused the United States to embark on a journey to create an inexpensive synthetic rubber, building on experiments already taking place in Europe and Russia. In 1941 the Standard Oil Company of New Jersey, Firestone, Goodrich, Goodyear, and the United States Rubber Company signed a patent- and information-sharing agreement under the supervision of the Rubber Reserve Corporation, founded by President Franklin D. Roosevelt.[6] The new synthetic rubber, engineered under the Rubber Reserve Corporation's oversight and jointly by its member corporations, is composed chiefly of a petroleum by-product, butadiene. Today 70 percent of rubber used in manufacturing is synthetic,[7] and about 60 percent of the rubber used in the modern tire is synthetic.[8]

Rubber is frequently used in the construction of buildings, and increasingly recycled rubber is being developed for products for the construction industry, including rubber O-rings, gaskets, foamed insulation, bearings, and silicone beads to make watertight seals.

Recycled rubber tires are also used in building construction, both formally and informally. For example, the architects Vaillo + Irigaray in Navarro, Spain, have made recycled rubber tire gabions into an office building facade that allows for the passage of dappled light into the building interior, and the Israeli pavilion in the 2015 Venice Biennale was clad in recycled rubber tires. Both show how tires can be used as building materials by designers who are simultaneously addressing aesthetics and environmental issues. Discarded rubber tires are also used to make crude "earthships"—buildings constructed of stacked rubber tires filled with rammed earth to stabilize the tires against movement and to serve as a thermal mass. The stacked-tire walls are often stuccoed to conceal the fact that the earthship is made of recycled tires.

Recycled rubber tires can also be used to make refined building products such as floor tiles, carpet padding, roofing tiles, and waterproof membranes. Most recycled rubber products are made of rubber crumb. A common way to manufacture rubber crumb is to freeze chipped tire pieces in a bath or shower of liquid nitrogen. At -80 degrees Celsius the rubber becomes as brittle as glass, and the frozen rubber is pulverized using a hammer mill. This process reduces the rubber to particles ranging from ¼ inch to 600 microns. Cryogenic grinding avoids heat degradation of the rubber and produces a high yield of product that is free of almost all fiber or steel, which is extracted during the process using magnets and screens. The resulting material is shiny and clean—a raw material, ready to be transformed into something new.

Recycled tire gabions
by Vaillo + Irigaray

3D Printing with Rubber

The Emerging Objects rubber used for 3D printing is ground into even finer particle sizes that are as small as 50 microns.[9] The rubber powder is inert and therefore is mixed with other additives to make it printable; the mixture is adhered together with an organic binder. Thus, through 3D printing, end-of-life tires can be transformed into high-value sustainable products for the built environment, such as outdoor furniture, embossed rubber flooring, and custom tiles for wall cladding.

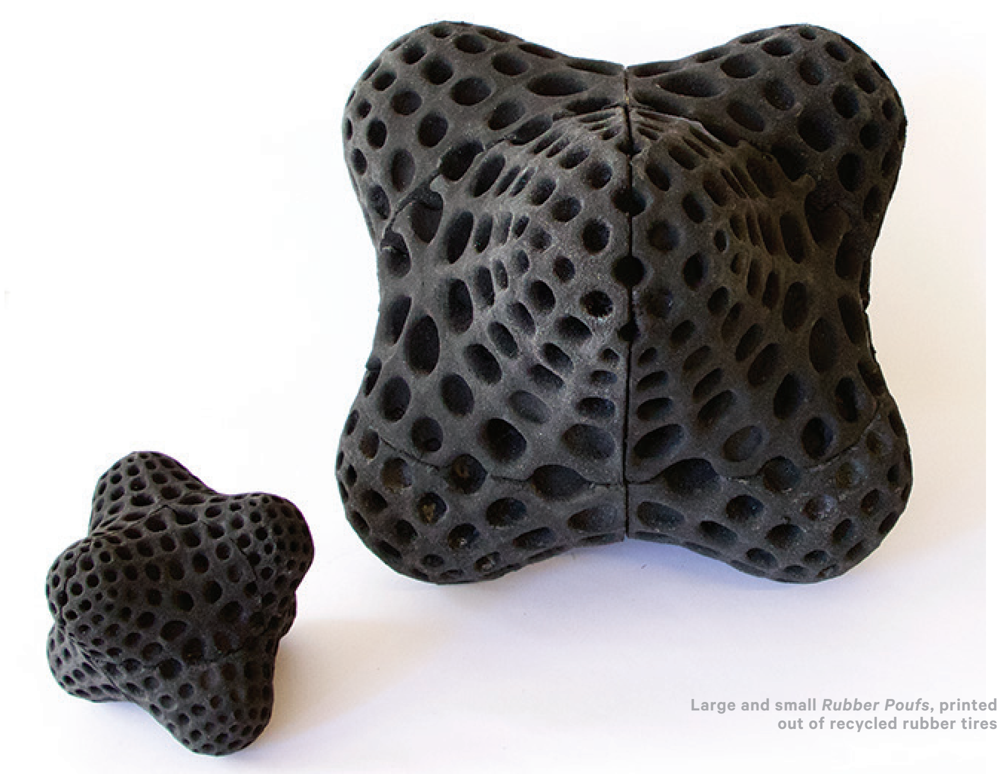
Any image to expand this section?

Image of fine rubber particles?

Architectural example(s) of rubber?

Rubber Objects

The Rubber Pouf is a playful piece of furniture that can be used as a low seat or footstool. Its form resembles a six-pointed star with rounded heads on the ends of all six points. The pouf is printed in eight parts that are adhered together to make one solid object. The detailed, beveled texture on the pouf's surface gives the appearance of button tufting, which makes the piece look padded and soft and contributes to its overall materiality and playful quality.



Large and small *Rubber Poufs*, printed out of recycled rubber tires

The Haeckel Bowl was one of the first objects 3D printed in rubber. One of the most exciting aspects of 3D printing with rubber is that the rubber particles retain their pliability.

Additional photos showing exciting pliability of rubber Haeckel Bowl?

:)

Rubber Objects

Bioplastic

Bioplastic, a synthetic material made from organic polymers, has been used in the built environment for thousands of years. For example, natural plant gum was traditionally used as a wood glue in the construction of houses, and in early oceanic exploration, natural plant gum was applied as a waterproof coating to boats. However, natural plant resins were never chemically modified until Charles Goodyear vulcanized rubber in 1839, thus creating the first man-made biopolymer.[1]

Patented in 1857, Parkesine was the first commercial-grade man-made plastic. It was made from cellulose, a wood fiber, which was treated with nitric acid and a solvent to create what is known as "synthetic ivory." Objects such as combs, buttons, and cutlery handles were crafted from this earth/man-made plastic. Parkesine's successor was celluloid, the material that transformed the film industry. Celluloid is considered the first thermoplastic because of its ability to be easily molded and shaped into any form: filmstrips, phones, toys, jewelry, and furniture are just a few examples of how this transformative material has been used.

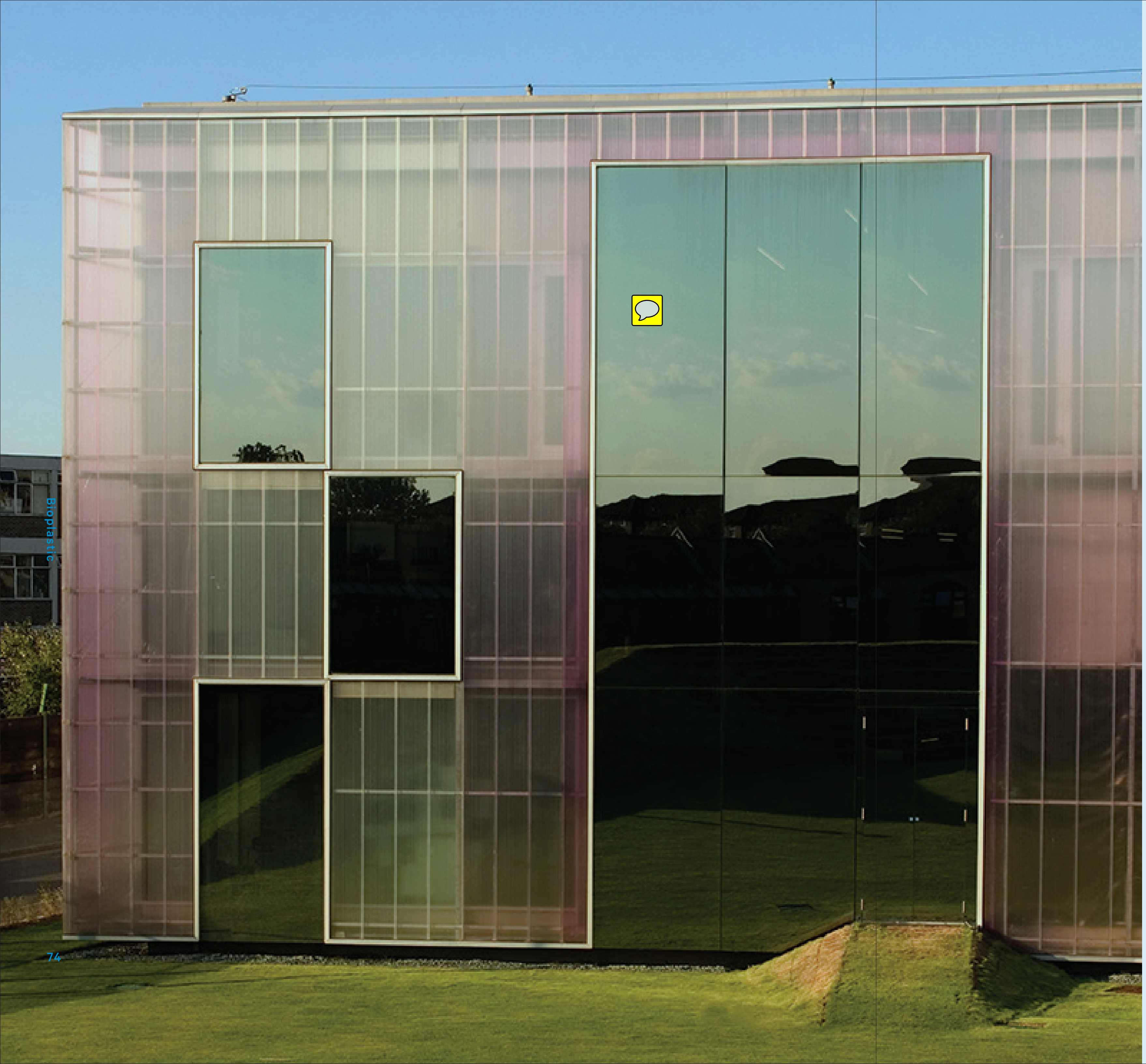
In the early 1900s synthetic polymers were developed, and there are now hundreds of thousands of them in use. Synthetic plastics are strong, cheap to produce, and lightweight, and can seemingly last forever. Unfortunately, the attributes that make plastics so popular are also the ones that make them so problematic. It is estimated that the world produces almost three hundred billion tons of plastic a year, and only 10 percent of that is recycled.[2] Much of it ends up as floating junkyards in our ocean's gyres, as litter on our streets, and in landfill. Plastic pollution is a serious issue worldwide; the production of plastic from oil-based materials releases carbon dioxide into the air, contributing to global warming, and most oil-based plastics take hundreds, if not thousands, of years to degrade. For example, a credit card will take almost exactly one hundred years to degrade, compared with an apple core, which takes only three months.[3] Ideally, all plastic products need to degrade naturally at the end of their life and not cause adverse effects to the environment. The use of cellulose-based materials, rather than nonrenewable crude oil–derived materials, has proved to be an important solution for creating plastics with a low environmental footprint.

Polylactic acid (PLA) is a bioplastic derived from renewable resources such as cornstarch, tapioca roots, and sugarcane; it is biodegradable. PLA was discovered in the 1800s and was designated a prepolymer (a polymer that has undergone a partial chemical reaction but could in fact be further manipulated because of its low production and low purity values). Today, PLA is one of the most widely produced, biodegradable plastics made with renewable materials. It is principally made of carbon, oxygen, and hydrogen, so as it degrades or is incinerated, it releases only those elements into the atmosphere or the soil. PLA can be used for extrusion, injection molding, film and sheet casting, and spinning, which means there are many ways to turn this material into products. It is also one of the most common feedstock materials used in desktop 3D printers today.

For decades PLA has been used primarily in biomedical applications—for bones, screws, plates, pins, and meshes—because it is a bioreabsorptive material that is transformed into innocuous lactic acid in the body in a time frame between six months and two years. Outside your body, PLA can break down in forty-five days in a composting facility. However, under stable environmental conditions, it takes hundreds of years to biodegrade, which means that it shows promise as a long-term building material in applications where temperatures are not excessively hot.

Plastics are frequently used in construction. One can find plastic pipes, insulation, window frames, roofing, screws, hinges, flooring, wall coverings, waterproofing, and

Corn harvest for bioplastic production



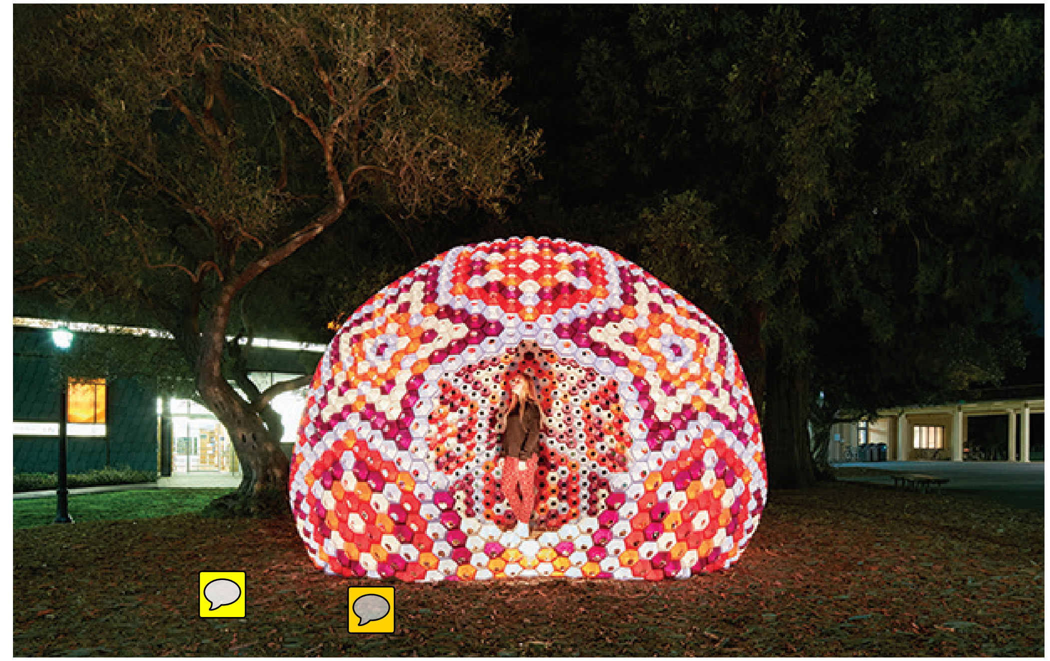
even plastic doors in almost every building. We don't always see the plastic parts of buildings, as they are sometimes hidden (e.g., in the foam core of a door), but buildings today are increasingly made of plastic. In some buildings, plastic is celebrated as the building material. The Laban Dance Centre in London, designed by Herzog & de Meuron, is clad with plastic panels made of impact-resistant polycarbonate, and the Eden Project, designed by Grimshaw Architects, is a series of domes covered with inflated plastic pillows made of ethylene tetrafluoroethylene, or ETFE, which is corrosion resistant and very strong, even in response to temperature fluctuations. These projects from the turn of the twenty-first century that embrace the use of plastic as a cladding material have paved the way for bioplastic buildings of the future.

The Laban Dance Centre
by Herzog & de Meuron

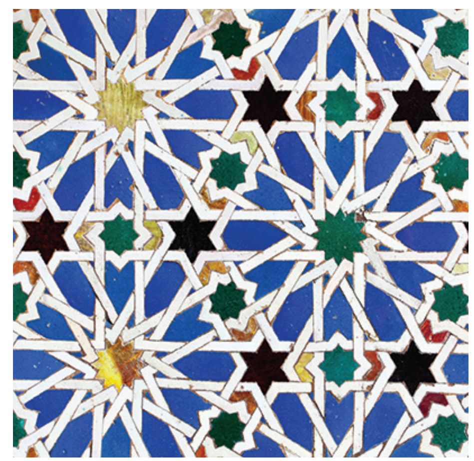
3D Printing with Bioplastic

Branch Technology, based in Tennessee, recently 3D printed a large bioplastic structure for Design Miami 2016 called “Flotsam and Jetsam.” The structure was printed using KUKA robot arms and PLA made from bamboo. The Amsterdam-based architecture firm DUS Architects is building a Canal House from biodegradable plastic parts that are entirely 3D printed, then filled with a lightweight foamed concrete to provide structural reinforcement. The Canal House is being printed on a machine called the *Kamermaker*, quite literally “roommaker,” a room-sized printer that extrudes PLA pellets into forms that are up to nine feet tall. Oak Ridge National Laboratory in Tennessee has a Big Area Additive Manufacturing (BAAM) machine capable of 3D printing components up to twenty by eight by six feet. This device has produced the largest 3D-printed object in the world to date—a trim-and-drill tool that weighs 1,650 pounds, to be used in the production of Boeing airplanes.

The cellulose-based materials that go into PLA include an ever-widening range. It is now possible to 3D print with PLA made not only of cornstarch but also hemp, bamboo, and barley. Additionally, materials such as coffee, glass, and powdered metals can be added to PLA to give it special properties, including color, strength, and sheen, respectively. Dyes can also be added to the PLA filament to offer a wide range of colors that are integral to the material.



Arabic tile star pattern



Emerging Objects fabricated one of the largest PLA-based 3D-printed structures built to date, the Star Lounge. The freestanding, doubly curved dome is eight feet, six inches tall, with a footprint that measures about eleven by eleven feet. The dome is composed of 2,073 hexagonal blocks printed in twenty-eight translucent colors; each color corresponds to one particular block type. This helps simplify the construction process and also creates a beautiful, yet logical, pattern of twenty-one stars and hexagons in an assembly of twenty-one larger panels that are riveted together. The pattern is inspired by cut-tile Arabic star motifs and mid-nineteenth-century American star quilts. The color-coded facade is an aesthetic choice but

also encodes the instructions for fabrication and assembly. In addition to the color coding, each block has a number printed on its interior surface to locate it within the overall dome.

The *Star Lounge* is unique among large-scale 3D-printed structures in that it demonstrates the architectural potential of using a farm of small, inexpensive desktop printers. The hexagonal blocks that make up the large panels were printed using a “bot farm” of over one hundred 3D printers. The design of each individual component maximizes the efficiency of the printer and the print volume. Two blocks could be printed per printer without support material in just over an hour. Holes for rivets were also printed into the blocks. The *Star Lounge* demonstrates that prefabricating small-scale, hand-size, efficiently designed 3D-printed parts for architectural assembly is feasible and cost-effective. This process opens the door to creating 3D-printed bricks, tiles, walls, ceilings, partitions, and cladding for a sustainable architecture of the future.

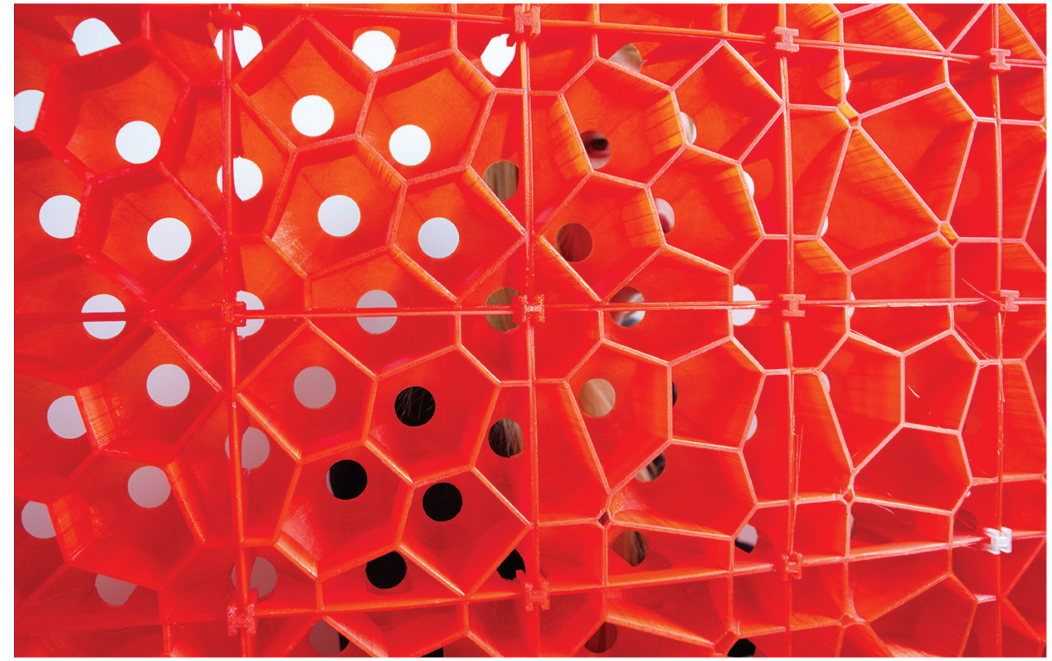
***Star Lounge* assembly**

Bioplastic Objects

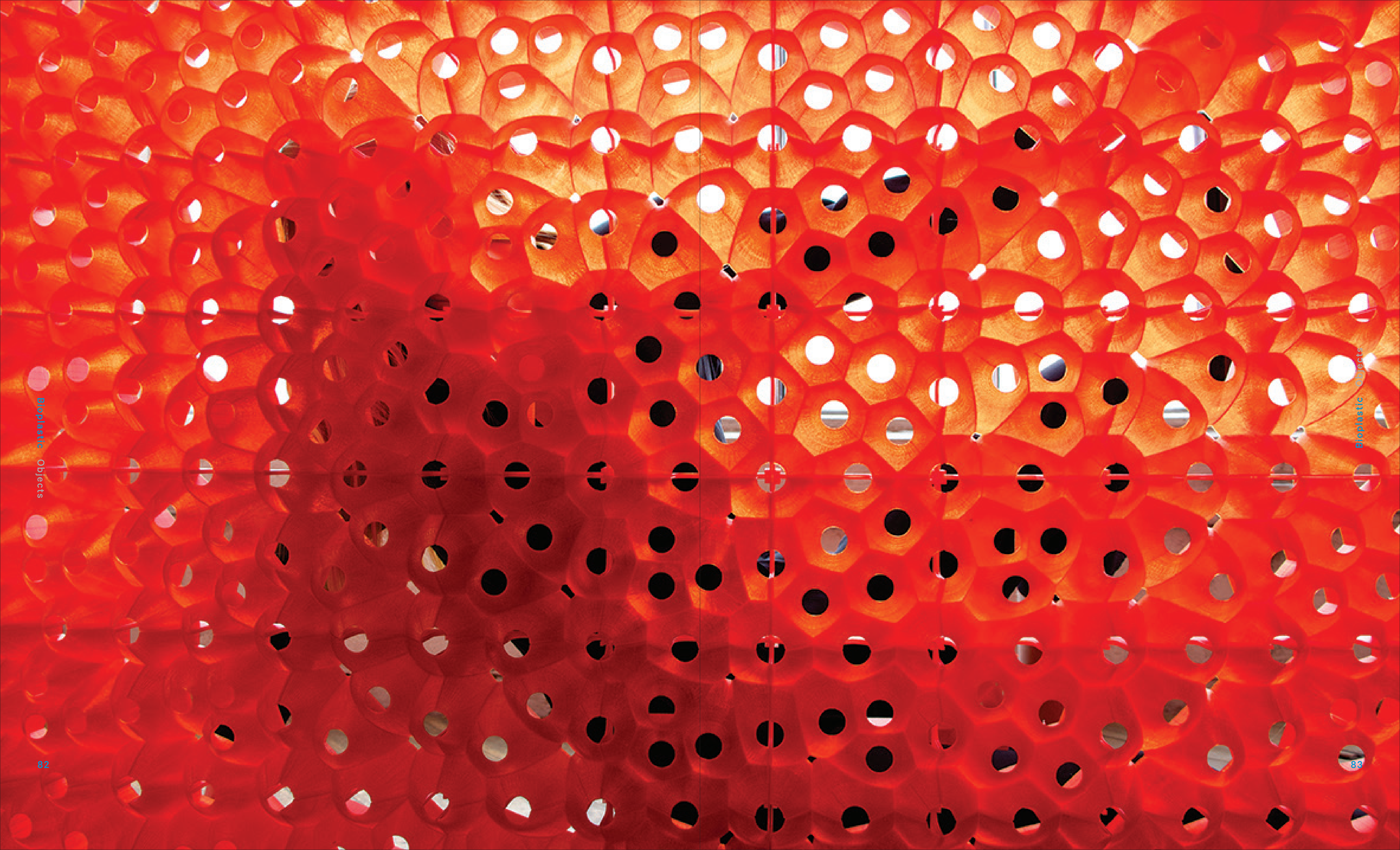
[Starlight](#) is the experimental precursor to the *Star Lounge*. Building on the knowledge generated in the Romanesco studies, it combines the intention of creating a spherical structure out of the minimum number of parts with that of generating diffuse light through woven patterns created by custom G-code. The *Starlight* comprises twenty hexagons and twelve pentagons and is a buckminsterfullerene, or “buckyball.” The difference between a buckyball and the *Starlight* is that the geometry of the *Starlight* extends beyond the ball to make stunning, light-filled cones. The pictured *Starlight* is 3D printed in PLA mixed with fine aluminum particles to give it luster and reflectivity.

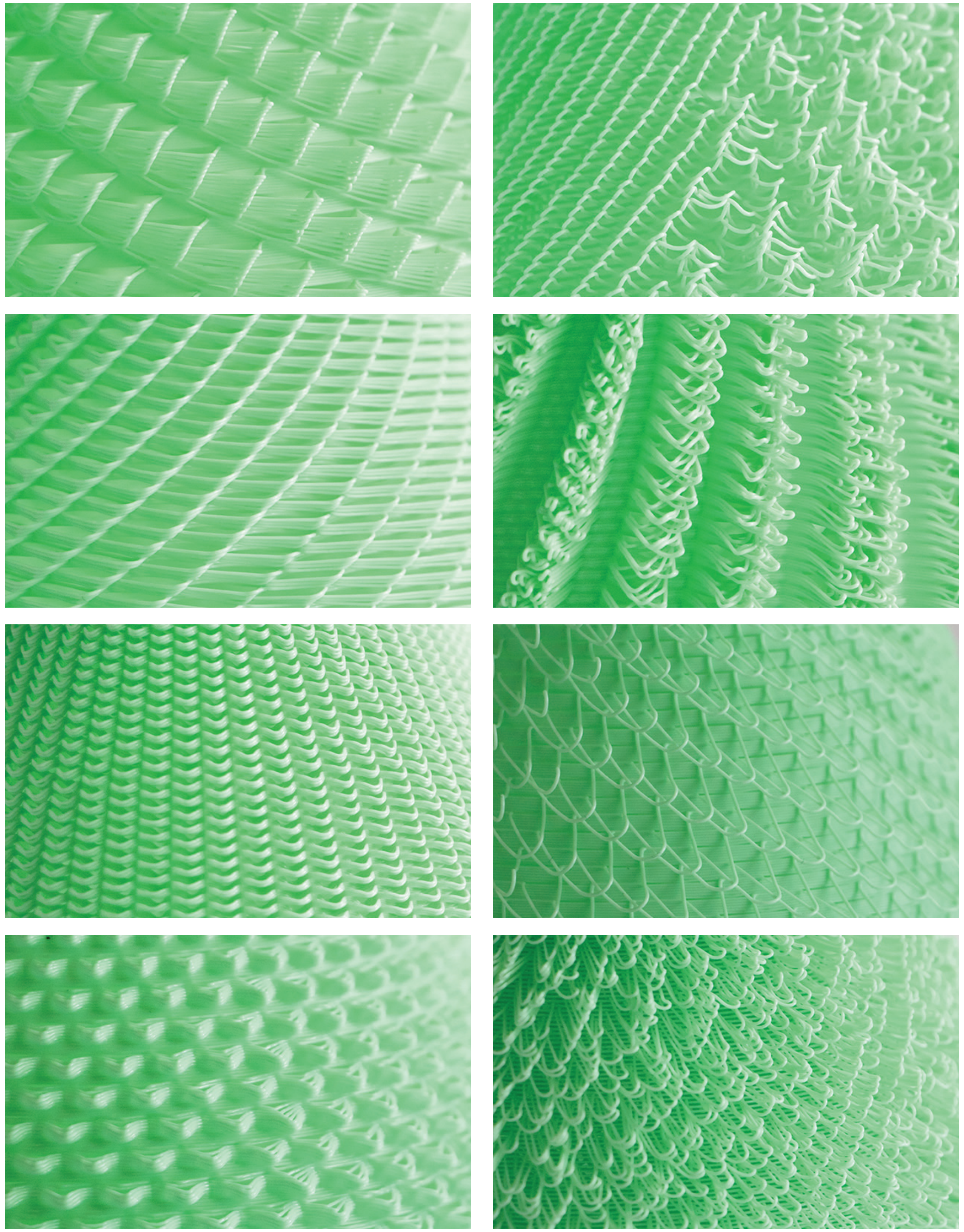
A fine-woven mesh generated by the G-code creates a loopy, textile-like surface with a soft texture. The object glows because of the translucency of the material but also permits direct light to shine through the surface of the cone itself.

Back of *Picoroco Wall*, showing 3D-printed PLA clips



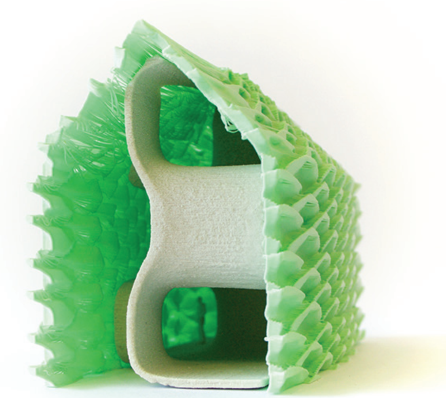
The [Picoroco Wall](#) is constructed using the *Picoroco Block*, a 3D-printed building block for modular wall fabrication printed in translucent orange PLA. The wall comprises blocks with a dimension of 5.75 by 5.75 by 2.75 inches. Three different blocks, with two, three, or four holes, are used in the construction of the wall. Each block can be rotated randomly to create the variable pattern found in the wall. The blocks are held in place with 3D-printed orange PLA clips, which have four prongs that connect the blocks at the corners. The wall takes advantage of the translucency of the bioplastic, giving it a softly scalloped, diaphanous quality when light filters through.





These study models, called Romanescos, are the first experiments conducted by Emerging Objects using customized G-code (the computer language that directs a 3D printer) to inform the surface texture of a 3D-printed object. By controlling each line of filament, we are able to take these lines for a walk in a zigzag, sawtooth, sine wave, or step pattern. The repetition, offsetting, cycling, and amplitude of the line create unique and often porous textile-like surfaces using a minimum amount of material.

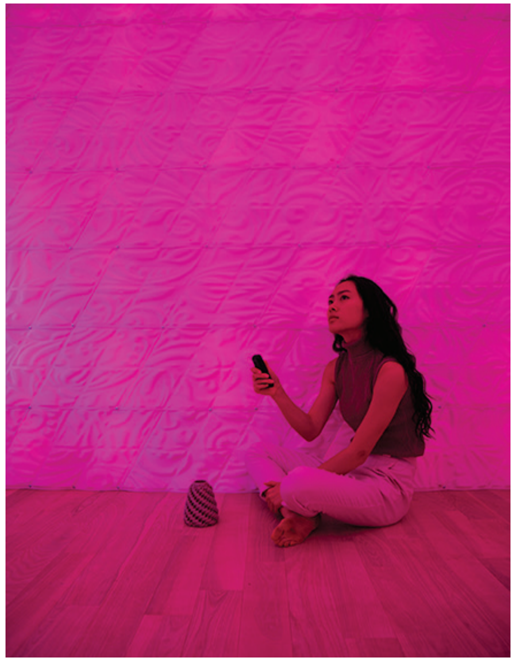
Will silhouette all / make consistent

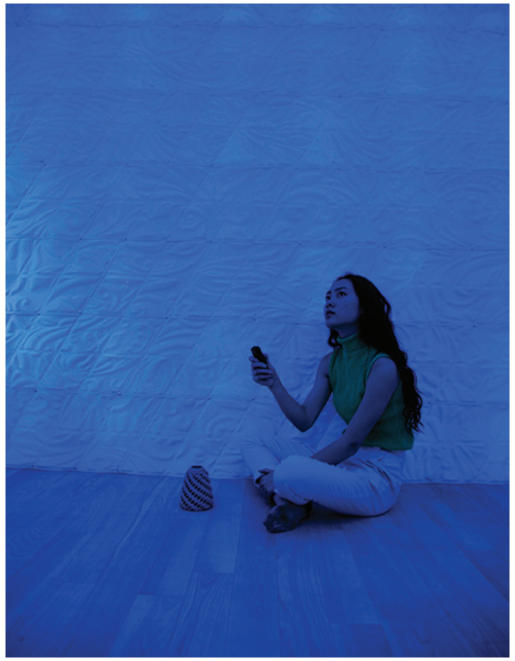


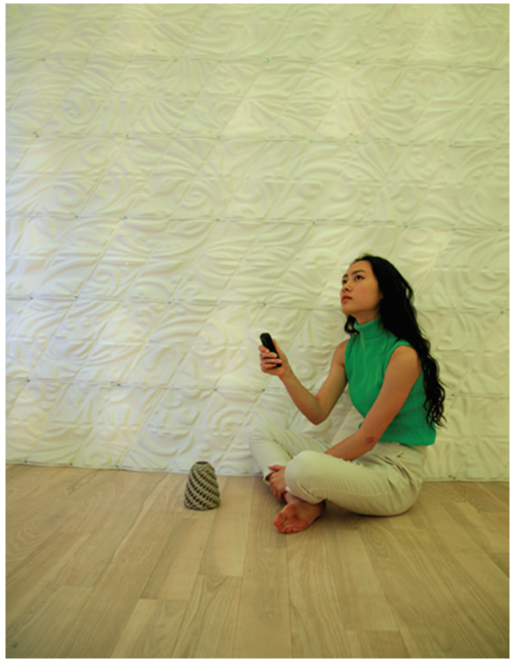
The Hut Was Never Primitive is a series of conceptual study models for houses. They explore how G-code can act as the mediator between machine and architecture, interior and exterior, and wall and ceiling. *The Hut Was Never Primitive* conceptualizes the most fundamental components of 3D-printed architecture—wall, floor, roof—and foretells its emergence. Each hut explores surface, texture, material, form, space, light, color, and shadow and serves as a point of reference for speculation about the essentials of 3D printing buildings. G-code, slicing, customization, hacking, and parametrics represent some of the first strategies for 3D printing a house; the techniques used in the 3D-printed huts build on technologies that have been in development for ten thousand years of human civilization, such as puddling, rusticating, embossing, shagging, vermiculating, and thatching, all of which have the potential to be reinterpreted through the lens of additive manufacturing.

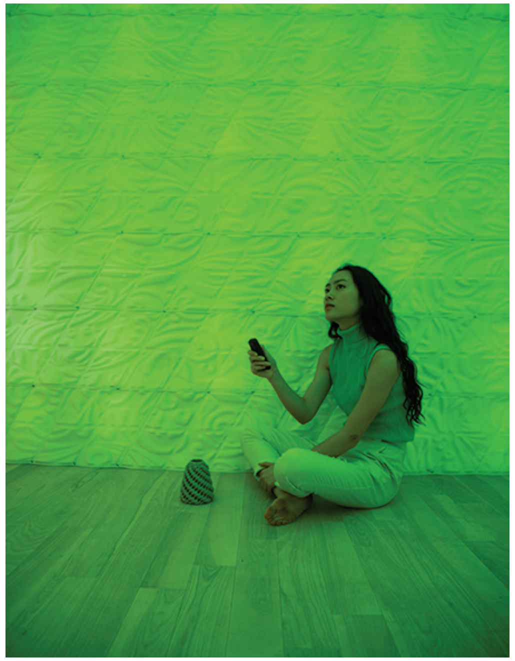
The Chroma Curl Wall references traditional pressed tin-walls and ceilings from the Victorian era. In the late-nineteenth and twentieth centuries in North America and Australia, pressed-tin tiled ceilings were a popular alternative to the exquisite plasterwork one could find in Europe. Sheets of tin were stamped one at a time using cast-iron molds, and were often painted white to give the appearance of hand-carved or molded plaster. The sheets were used as ceilings and wainscoting on walls, with the designs embedded in each sheet repeated across the surface to form an intricate pattern.

Through 3D printing, we are able to achieve the same effect of a highly intricate and sculptural surface, which might from a distance resemble molded plaster or pressed tin but in reality is something entirely new. The digital nature of 3D printing allows each tile in a wall to be uniquely patterned and shaped. It is therefore no longer necessary to make expensive molds that can produce only one tile design. The 3D-printed bioplastic *Chroma Curl Wall* is opaque when washed with light from the room interior during the day, but at night, color-changing LED lights backlight the translucent bioplastic and the wall becomes luminous, taking on the color of the light behind it and animating a surface that transforms chromatically and texturally.





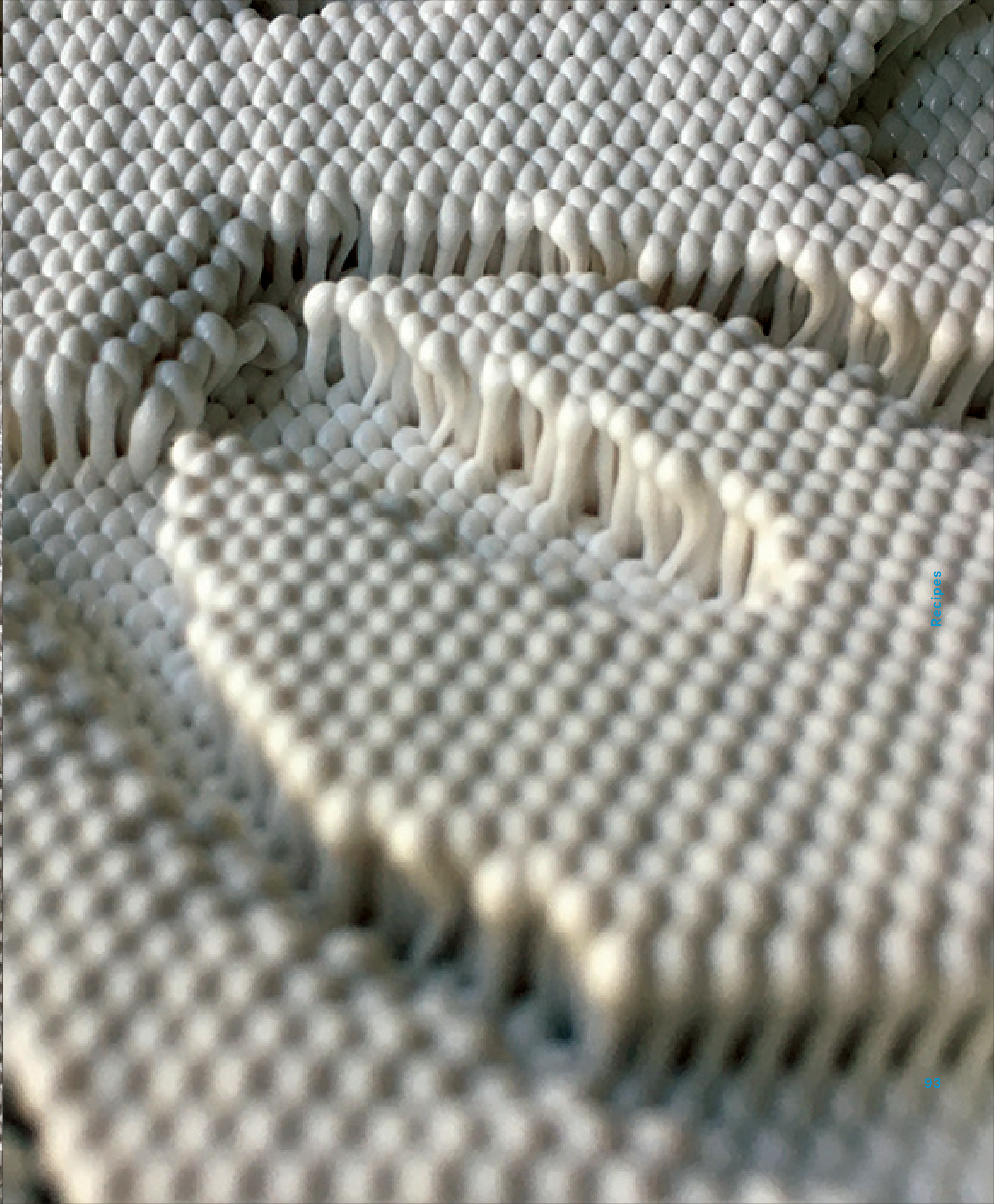




The first damasks used a satin-weaving technique to create areas of different sheens in a cloth, revealing raised animal and botanical patterns. Because it was a three-dimensional weave, the textile was always reversible. Traditionally, damask textiles were always monochromatic; patterns were distinguished by the way light played off the warp (vertical) and weft or (horizontal) filaments. Some damasks even look different depending on the time of day.

Damask was invented in China around 300 BCE. These richly woven textiles were traded along the Silk Road, which stretched from the Far East to the Mediterranean, and may have gotten their name from Damascus, one of the cities merchant caravans passed through en route to Europe. Damasks have had a long-standing status as a luxury fabric because they were originally made of silk filament, which was very expensive. In the 1700s, at the height of their popularity, damask patterns could be found on walls, furniture, and curtains filling entire domestic interiors of the wealthy. The Industrial Revolution ushered in mass production, making woven and printed fabrics more affordable for the growing middle class. Later, during the Arts and Crafts movement—whose advocates saw machine-made designs as inferior and dishonest—damasks were once again handcrafted, often depicting stylized images of plant and animal life.

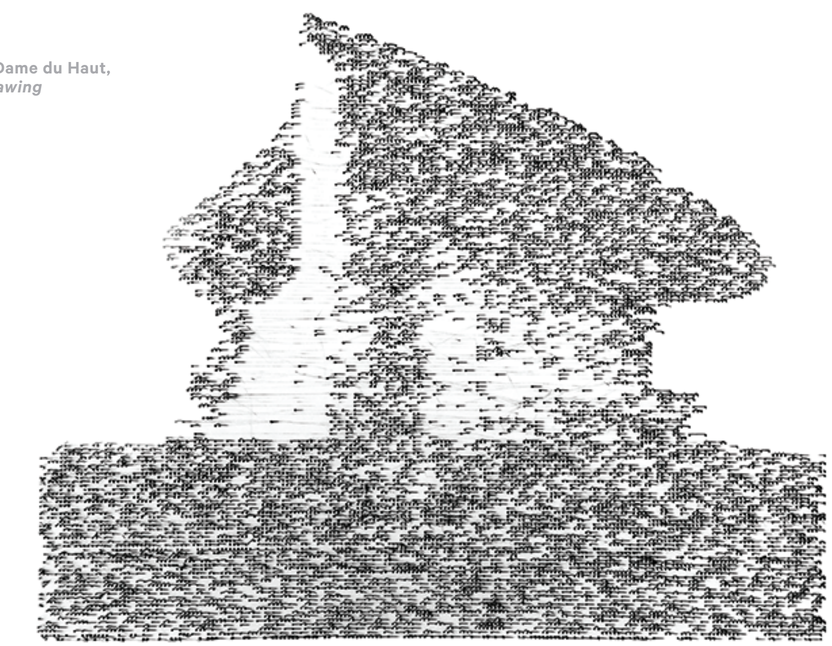
Over the last century, the definition of damask has expanded to include fabrics made with two or three colors and other filaments, such as cotton and wool. Even more recently, patterns that are 2D printed to look like damask have been considered "damask," but these, of course, are not reversible, and they are not three-dimensional. The three-dimensionality and reversibility of the original damask, however, have been revived through 3D printing using new filament: PLA. The 3D-printed PLA Damask Wall is also quite rigid and strong. The pattern or motif gives the fabric structure and rigidity, embedding new functionality. The pattern or motif is not merely applied to the surface of a wall or a piece of furniture but literally becomes the wall or the furniture itself.



Hair, fur, and fibers have long been incorporated in architecture as textural elements. Flocking can be traced back to circa 1000 BCE, when the Chinese used resin glue to bond natural fibers to fabrics. Fiber dust was strewn onto adhesive-coated surfaces to produce flocked wall coverings in Germany during the Middle Ages, and in France, flocked wall coverings became popular during the reign of Louis XIV. Nomadic cultures today continue to gather camel and yak hair, either by shearing or combing; these fibers are felted or woven to create a durable textile for tents.

If architecture can be hairy, how might we draw hairy drawings? In 1925 the architect Le Corbusier asked the twenty-one-year-old artist Salvador Dalí if he had any thoughts on the future of architecture. Dalí retorted, with some disdain (as he viewed Le Corbusier as the inventor of the architecture of self-punishment because of his use of harsh concrete forms), that the architecture of the future would be “soft and hairy.” Hairline Drawing explores the use of custom G-code scripting for 3D printing to create a surface not unlike a technological flocking or a bioplastic weaving. The drawing depicts Notre Dame du Haut, a work where, perhaps influenced by Dalí, Le Corbusier expressly sought to deny the machine-age aesthetic of his previous work—a return to the soft, drawn here with a 3D printer as hairy.

The Notre Dame du Haut,
Hairline Drawing



Sand

Natural sands are eroded or weathered particles of rocks. Sand is made by simply grinding up rocks into increasingly smaller pieces, and glaciers do it best. Sand can also be made out of living creatures, from shells and other organisms of the living world, and many beaches are composed of pulverized animal shells. Sand grains can originate from catastrophic geologic phenomena, as when molten lava erupts from volcanoes and shatters in the air, scattering particles across the oceans to land as tiny grains. This black volcanic sand can be found throughout the world, as on the black beaches of Hawai'i. But by far, most sand grains are made of quartz, one of the earth's most common ingredients, and are formed every single day, on every exposed piece of land, by the process of weathering.[1]

Sand is found in every country of the world and is used to make the most mundane and the most technologically advanced products, from toothpaste to microchips. Sand is a material in flux, blowing in the wind and creating shifting sand dunes, but it is also an important global commodity on which nations are built. For example, Singapore is 22 percent larger today than it was in the 1950s because billions of metric tons of sand have been added to the existing island since that time. Singapore is planning to expand its territory by another fifteen thousand acres over the next fifteen years.[2] However, the increase in size of one nation means the decrease of another. In Indonesia, some two dozen islands have disappeared since 2005 because of sand mining—largely by Singapore.[3]

3D Printing with Sand

The writer Jorge Luis Borges declared, "Nothing is built on stone; all is built on sand, but we must build as if the sand were stone."[4] And we do. Sand is one of the most important aggregate materials for the building and construction industry. Wet sand is workable; it can be combined with water, gravel, and portland cement to be transformed into one of the most durable and most ubiquitous building materials in the world: concrete. When water is mixed with sand, its properties change remarkably; the two fluids become a formable solid, and very little liquid is needed to make this happen. That's the reason 3D printing with sand and other sand-size material is possible. There is enough surface tension between the liquid and the particle to make them neighborly and stick together.

Sand is found in fluvial riverbeds and floodplains, shorelines, deserts, and dunes, as well as man-made sites that include mines and quarries. Sand is everywhere and has the potential to be a valuable local material resource for 3D printing, especially sands that are not currently being used in construction or for reclamation.

In the context of 3D printing, sand is most commonly used in large-volume printers that produce sand molds for industrial metal casting. Molten metal is poured into the 3D-printed silica sand molds to produce automotive and aerospace components such as engine blocks and airplane propellers. Another example of 3D printing with sand can be found in Markus Kayser's desert Solar Sinter project.[5] This example is exciting from a technological standpoint and also from a material resource perspective because most sand being mined for the construction industry does not come from deserts. Desert sand particles are round; therefore, they don't closely pack and so are less desirable in concrete construction. In Kayser's project two elements dominate: sun and sand. The sun offers a vast, free, and powerful energy source of huge potential; desert sand (silica in the form of quartz) is unlimited in supply. Silica sand, when heated to melting point and allowed to cool, solidifies as glass. The process of converting silica via heat into a solid form is known as sintering and has in recent years become a central process in the design prototyping known as selective laser sintering (SLS). SLS printers use laser technology to create extremely precise 3D objects from a variety of powdered plastics and metals—and in the case of Kayser, sand. By using the sun's rays instead of a laser and sand instead

Detail of *Earthscrapers*, showing nylon fibers in sand print

of plastic, Kayser has invented the basis of an entirely new solar-powered machine and production process that takes advantage of the abundant supplies of sun and sand found in the world's deserts. The objects that he prints with large particles of desert sand have a gritty, rough texture that connects them to their material source; they aren't simply white and smooth like most resin SLS prints, which seem to have no connection to context, material, or culture.

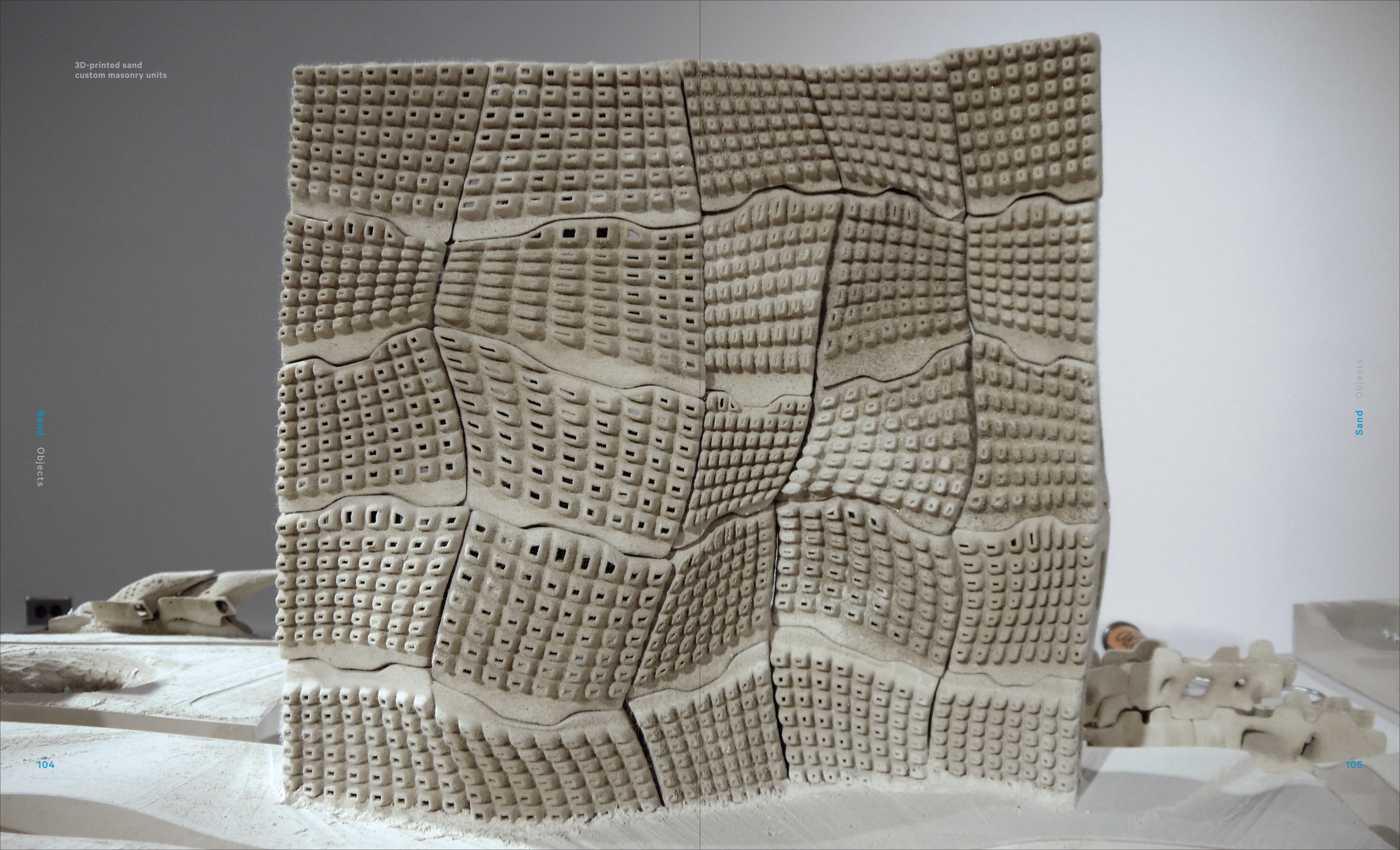
Emerging Objects innovated binder-jet sand 3D printing to imagine future architectural landscapes where the building and its material source are seamless. This is not a new concept; it is possible to find communities all over the world where buildings are constructed, quite literally, from the ground beneath their inhabitants' feet. For example, buildings are made of salt in the Salar de Uyuni in South America (see chapter 1), igloos made of ice are built on the frozen seas and across the arctic tundra, and buildings made of earth exist in arid landscapes in many regions around the world.

The automation of this method of building is imminent, and we imagine a scenario where a mobile 3D printer roves across the landscape, scooping up local sand, pumping it through a nozzle, and organizing it into contours and forms that become the building blocks and walls for a new paradigm of architecture. The sand is mixed with an organic liquid binder, causing the particles to stick together to form a new kind of sandstone, a strong and local building material that doesn't require intense energy usage or the transportation of industrial materials around the world.

[Earthscrapers](#) imagines a world where 3D-printed sand is a scalable technology—one that dissolves the distinct professions of designer and builder. In *Earthscrapers*, which we exhibited at the 2010 Biennial of the Americas, we conceptualized how sites of mining, desertification, dredging, and erosion are a few of the many natural and anthropogenic locations where processes that shape the landscape could provide the material sources, sites, and contexts for the forms and spaces created. A roving 3D printer could be controlled by a designer in situ or remotely. Acquiring information directly from a CAD file, the designer could make changes to 3D-printed sand as it is being deposited. Using sand for 3D printing proposes a future where designer, builder, and geomorphologist merge—a landscape where the earth is architecture and the architecture is earth.

3D-printed *Earthscrapers* installation at the Biennale of the Americas in Denver, CO, 2010

3D-printed sand
architectural model



3D-printed sand
custom masonry units

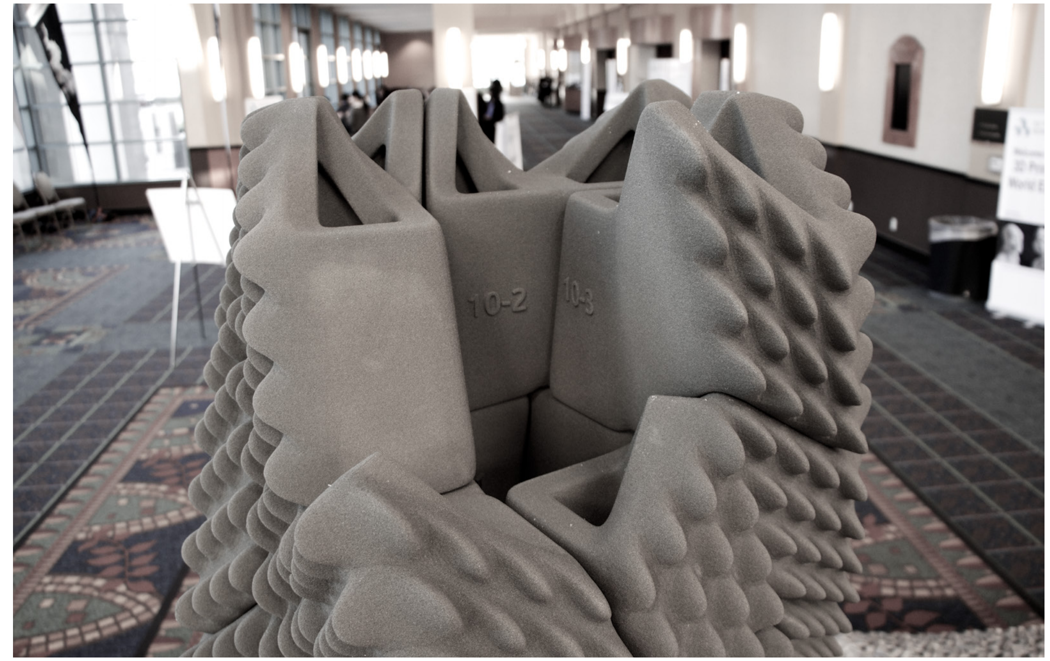
3D-printed sand architectural model

Objects Sand

Sand
Objects

By using 3D-printed building components, we can create seismically resistant structures that use masonry principles to diffuse the force of an earthquake through the interlocking components of a wall or column. The Quake Column draws from traditional Incan ashlar masonry techniques to explore this possibility. Peru is geologically unstable, and for centuries the mortar-free construction appears to have been more earthquake-resistant than using mortar. The interlocking structure of the dry-stone walls built by the Incas could move slightly during an earthquake and resettle without collapsing, a passive structural control technique using both the principle of energy dissipation and that of suppressing resonant amplifications. Inca walls also tend to incline inward by three to five degrees, and their corners are r[illegible]-ed, which contributes to their stability. [illegible]

Incan stone wall

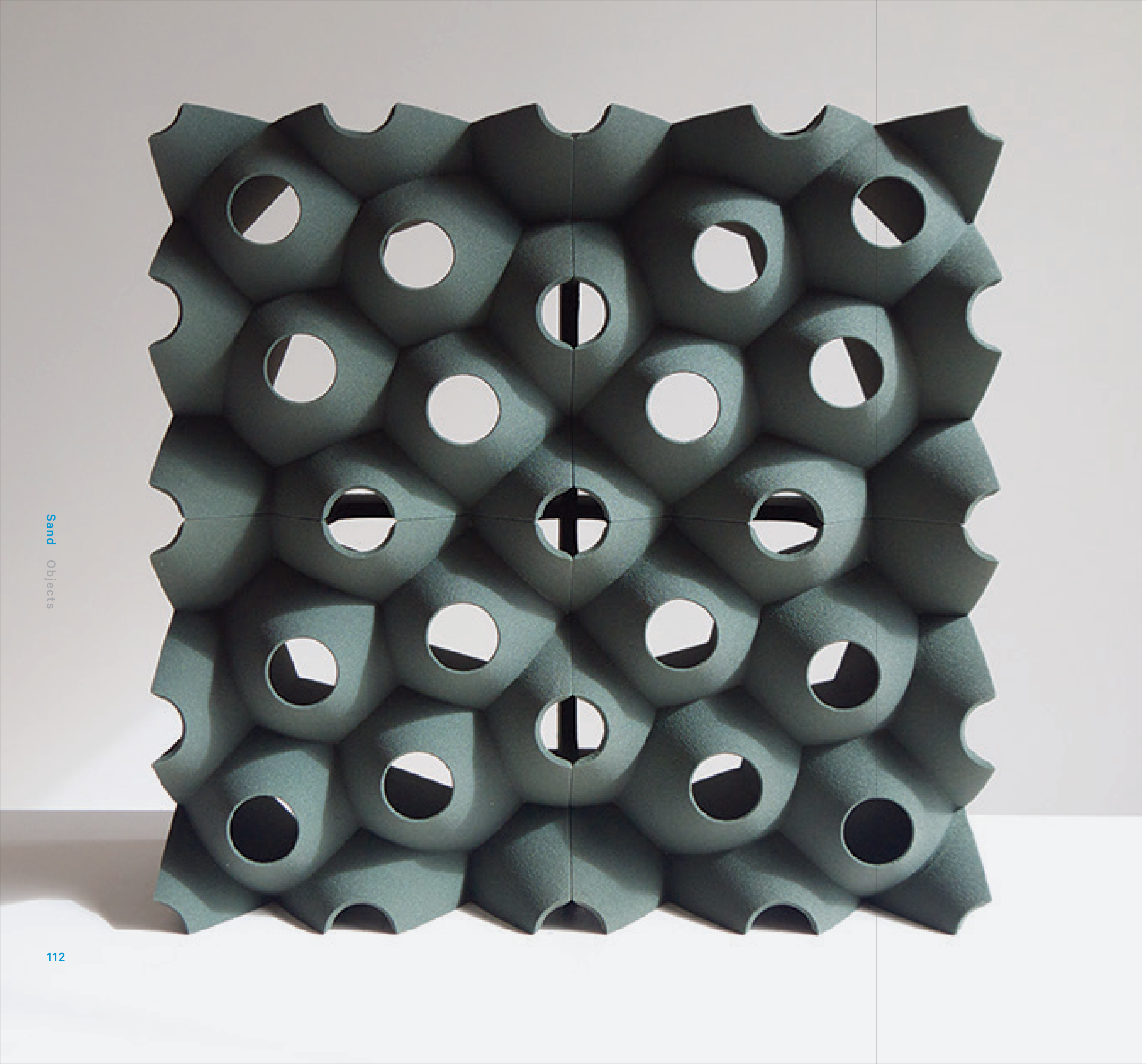


“stone” that makes up the *Quake Column* interlocks perfectly with neighboring blocks. Whereas the cyclopean blocks of Incan construction are massive and weigh several tons, the 3D-printed blocks are comparatively lightweight and hollow. Each block is numbered to designate its place in the construction sequence. Additionally, each massive, 3D-printed stone has a built-in handle for easy lifting, control, and placement.

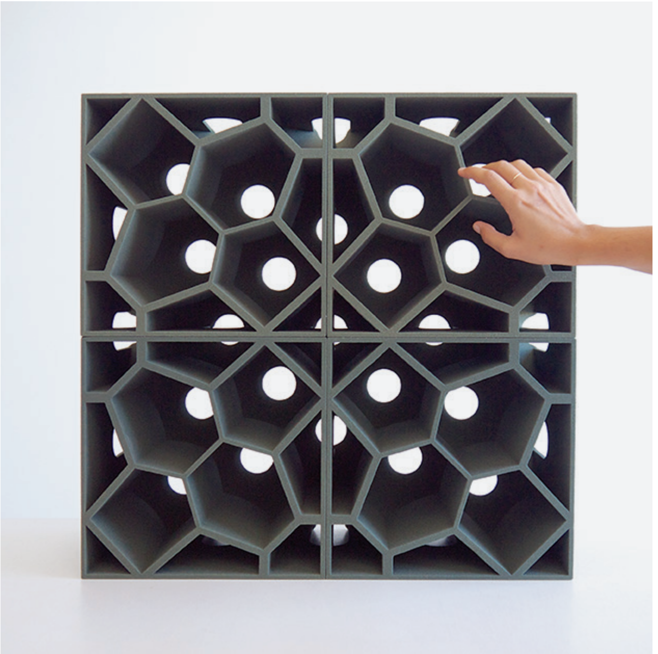
Quake Column at the 2014 3D Printer World Expo in Los Angeles, CA

The Involute Wall is a prototype for the study of thermal mass and acoustic dampening in a massive 3D-printed sand structure. The involuted surfaces reduce resonance in the room by absorption and redirection of sound waves. The enormous, six-hundred-pound 3D sand print permits surfaces to serve as thermal mass while keeping much of the wall in shade—ideal for hot climates with extreme temperature shifts.

Involute Wall at the 2014 3D Printer World Expo in Los Angeles, CA



The Picoroco Block is a modular building block for wall fabrication that is 3D-printed in sand. Each block is a twelve-inch cube in this permutation; dimensional variability is possible using the 3D-printing process. The joints between the blocks become invisible because of the porous pattern that rotates along their surface. This allows for a seemingly continuous surface, even though the wall is modular. The back of the wall clearly expresses the joints and the underlying geometry of the design.



Cement

The word *concrete* comes from the Latin word *concretus*, meaning compact or condensed and grown together. The most basic recipe for concrete comprises aggregates of various sizes that form a compact mass, portland cement, and water. When combined with aggregate and water, the portland cement crystallizes and fuses the matrix into a synthetic stone.

The development of concrete has evolved for over two thousand years. The Romans were among the first to build with concrete, using a mix of quicklime, volcanic ash, and rubble for structures such as the Pantheon. After the fall of the Roman Empire in 476 CE, the techniques for making concrete were lost for almost a thousand years, until the discovery in 1414 of manuscripts describing those forgotten methods rekindled interest in building with concrete.

It wasn't until the late 1700s, however, that the technology took a big leap forward. In 1744 John Smeaton rediscovered concrete in England by mixing hydraulic lime and powdered brick as aggregate for the Eddystone Lighthouse in Devon. Smeaton's mixtures produced concrete with a comprehensive strength comparable to the basic mixes that we use today, and his recipe for hydraulic lime became what is known as portland cement. Around the same time, in France, attempts were being made to improve traditional rammed earth by introducing cements and limes into the compaction of soil between formwork.

Concrete became a common building material in Europe in the late nineteenth century and was pushed into prominence by engineers such as François Hennebique, who pioneered reinforced concrete by introducing metal to the technology to increase its tensile strength. By the twentieth century, concrete had become a global material—generic and normalized, and used in almost every country in the world. Today, in the twenty-first century, concrete has become the dominant material used in construction in Asia (primarily China and India) and has become, by far, the most widely used building material in the world.[1] According to the United Nations Environment Program, in 2012 alone the world used enough concrete to build a wall eighty-nine feet high and eighty-nine feet wide around the equator.[2] From 2011 to 2013 China used more concrete than the United States used in the entire twentieth century.[3] It is estimated that ten billion tons of concrete are produced worldwide each

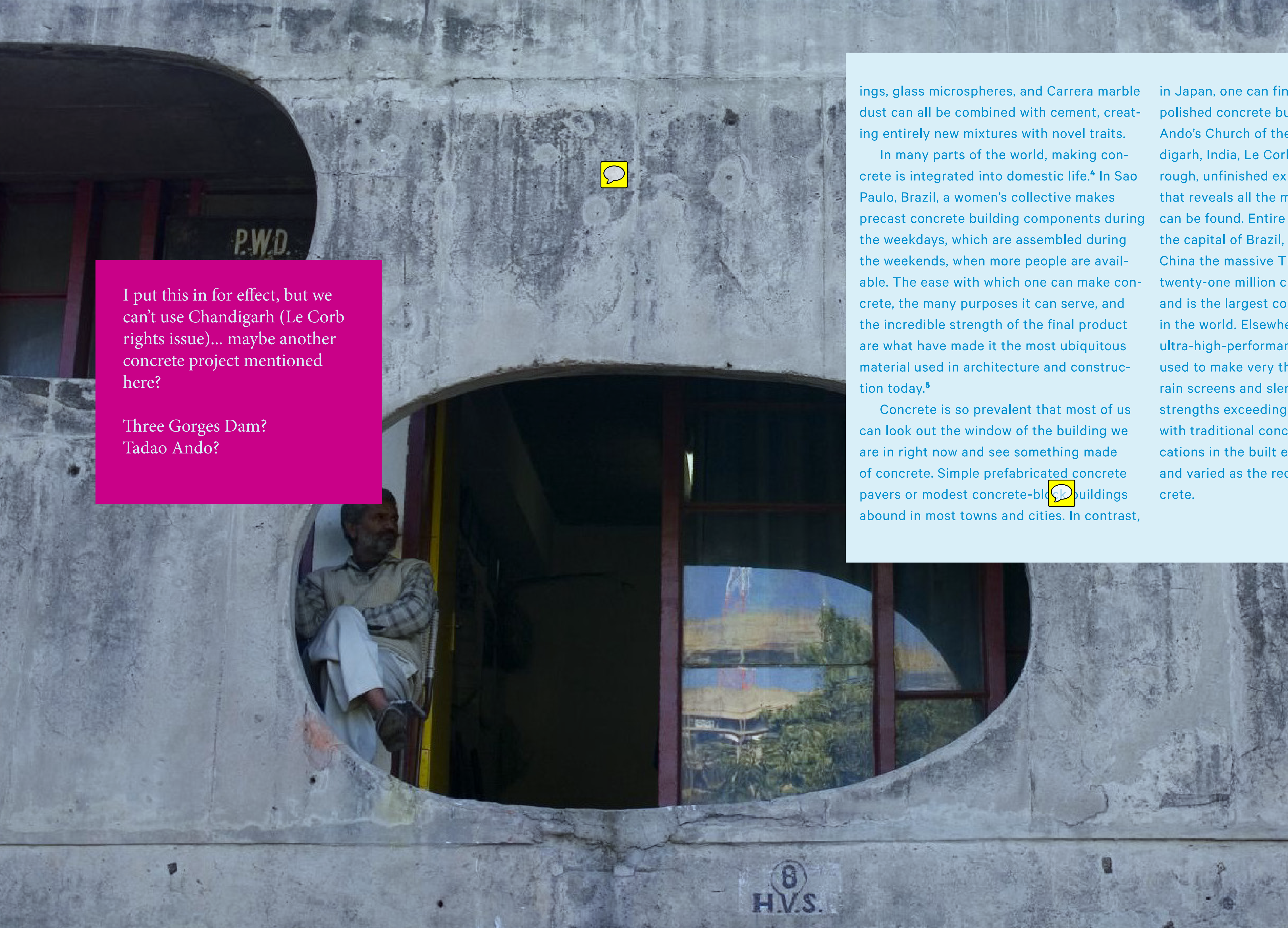
Cement factory

year, which translates to two tons of concrete per person per year in the United States.

This means unrivaled amounts of natural resources are being depleted to produce concrete. Of equal concern is that the production of portland cement releases enormous quantities of carbon dioxide into the atmosphere. Additionally, one billion cubic meters of water are used each year to produce concrete, demanding an urgent call for concrete design and production to become more ecologically responsive in the twenty-first century, as the planet cannot continue to consume concrete at the current rate.

Advanced concrete was initially developed through trial and error and not purely scientific knowledge, and this continues to be a unique characteristic of concrete. It is an ever-evolving material, and endless testing occurs in buckets on job sites as well as in sophisticated laboratories. Unlike with steel and glass, anyone can experiment with concrete to create original results.

There are countless recipes for customizing concrete. A standard formula is never a given; it is always made from scratch—homemade. Ingredients can be mixed, poured, vibrated, and cured to launch a chemical reaction that turns liquid into solid—rather like baking. Experienced workers are even known to taste the admixture to identify its stage of development. Aggregates can be used to change the weight and visual properties of cement, and recycled sawdust, metal shav-



I put this in for effect, but we can't use Chandigarh (Le Corb rights issue)... maybe another concrete project mentioned here?

Three Gorges Dam?
Tadao Ando?

ings, glass microspheres, and Carrera marble dust can all be combined with cement, creating entirely new mixtures with novel traits.

In many parts of the world, making concrete is integrated into domestic life.[4] In Sao Paulo, Brazil, a women's collective makes precast concrete building components during the weekdays, which are assembled during the weekends, when more people are available. The ease with which one can make concrete, the many purposes it can serve, and the incredible strength of the final product are what have made it the most ubiquitous material used in architecture and construction today.[5]

Concrete is so prevalent that most of us can look out the window of the building we are in right now and see something made of concrete. Simple prefabricated concrete pavers or modest concrete-block buildings abound in most towns and cities. In contrast, in Japan, one can find examples of the most polished concrete buildings, such as Tadao Ando's Church of the Light in Osaka. In Chandigarh, India, Le Corbusier's *béton brut*, the rough, unfinished exposed concrete surface that reveals all the marks of the formwork, can be found. Entire cities, such as Brasília, the capital of Brazil, are made of concrete. In China the massive Three Gorges Dam used twenty-one million cubic yards of concrete and is the largest concrete construction in the world. Elsewhere, fiber-reinforced ultra-high-performance concrete is being used to make very thin, delicate, latticelike rain screens and slender bridges that have strengths exceeding that of structures made with traditional concrete. Concrete's applications in the built environment are as many and varied as the recipes for making concrete.

3D Printing with Cement

Traditional concrete can be poured continuously on-site, precast off-site, sprayed, or tilted up. All concrete, however, requires formwork, the making of which is a laborious skilled construction process. Formwork can vary dramatically, from lumber and plywood fastened together using hand tools to large, prefabricated structures that require heavy machinery to set into place. There is a redundancy that is fundamental to concrete construction: a wooden building is constructed, into which concrete is poured, and afterward it is dismantled—and this comes at an environmental and economic price. In the United States, formwork costs up to 60 percent of the total cost of construction, and often it is discarded after use.[6] However, in the case of 3D-printed concrete, there is no formwork, which means that its potential advantages include lower labor costs, increased complexity without specialized labor, greater accuracy, less waste, and less use of water. All add up to make 3D-printed concrete potentially more sustainable and accessible to a wide array of concrete gourmands.

A variety of methods are currently used to 3D print concrete at the construction scale. These include both extrusion and jet-binding techniques. Contour Crafting, an extrusion technique developed and patented by Behrokh Khoshnevis at the University of Southern California in 1996, initially began as a novel ceramic extrusion and shaping method, designed as an alternative to the emerging polymer and metal 3D-printing market. In 2000 Khoshnevis and his team began to focus on construction-scale 3D printing of cementitious pastes. Contour Crafting works by quickly creating cement outlines in the shape of a room, then building in a layer-by-layer fashion that gradually increases in height to form walls.

At the same time that 3D-printed concrete and cement have been developed by engineers and scientists in laboratories at major research universities, students and home enthusiasts also have been hacking robots and 3D printers to develop new recipes for 3D printing concrete. Andrey Rudenko, a contractor, used open-source software to build a concrete 3D printer in his garage and printed a small backyard castle for his children. Students at the Bartlett in London developed a fabrication method that combines the two already existing concrete 3D-printing methods: extrusion printing and powder printing. A robotic arm extrudes a linear path of concrete, which is then supported by granular material until the concrete cures.

3D-printed castle
by Andrey Rudenko

Powder-based 3D printing of portland cement polymer was developed and patented by Ronald Rael, of Emerging Objects, at the University of California. In powder-based printing, all binding particles used in the concrete mix must fit through a 35-picoliter print head, and all cement, aggregate, and reinforcement must be smaller than one-hundredth of an inch. These dimensions seem extremely small, but the end result is that the plastic nature of both concrete and 3D printing offers up a powerful material solution to recent generative design processes in architecture, which often feature organic, doubly curved surfaces; complex ornamentation and detail; structural thinness; and translucency. Materials are stronger and lighter than typical concrete. Typical concrete cures to 3,000 pounds per square inch (psi), but powder-based cement polymer cures to 4,700 psi in compression when mixed with fiber reinforcement. Cement 3D printing generates zero waste, and each 3D-printed cement part can be customized without the need for expensive, unique, or disposable formwork.

Bloom is an experimental pavilion that employs 3D-printed portland cement at an architectural scale. It is a nine-foot-tall freestanding tempietto with a footprint that measures about twelve by twelve feet and is composed of 840 customized 3D-printed cement blocks. The floral motif embedded in the surface of *Bloom* is derived from traditional Thai flower patterns and is mapped

Bloom with Wurster Hall (a concrete building of the Brutalist era) on the UC Berkeley campus

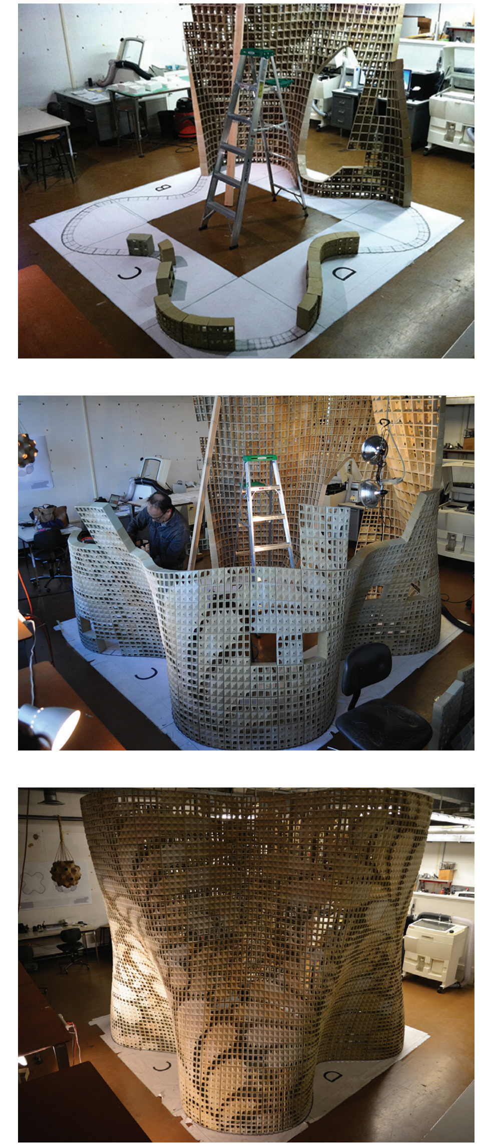
cylindrically onto the surface of the structure. Openings in the surface create a figural pattern that produces stunning visual effects of light, shade, and shadow on the exterior and interior. The exterior pattern is most striking from a distance or when viewed through the screen of a digital camera. On the interior is an internal structural grid that carries the forces of the weight of the cement blocks to the ground.

The individual blocks were printed on a print farm of eleven powder 3D printers, with a special cement composite formulation composed of iron oxide–free portland cement. Iron oxide imparts a gray color to cement, and its removal makes these 3D-printed blocks much lighter in color.

The blocks are numbered to designate their position in the overall structure and stacked to make sixteen large, lightweight prefabricated panels, which can be assembled in just a few hours. Cement that is 3D printed requires no formwork and produces no waste; the support material can be reused to produce more blocks. Coupled with the portland cement is an ecologically derived UV-resistant polymer that uses plant-based materials that do not compete with food sources or displace food-based agriculture. Producing this material reduces greenhouse gas emissions 50 percent compared with conventional petroleum-based epoxies. Each 3D-printed block is coated in the UV-resistant polymer for additional strength.

The curvilinear form of *Bloom's* overall structures provides added stiffness to the

Bloom assembly



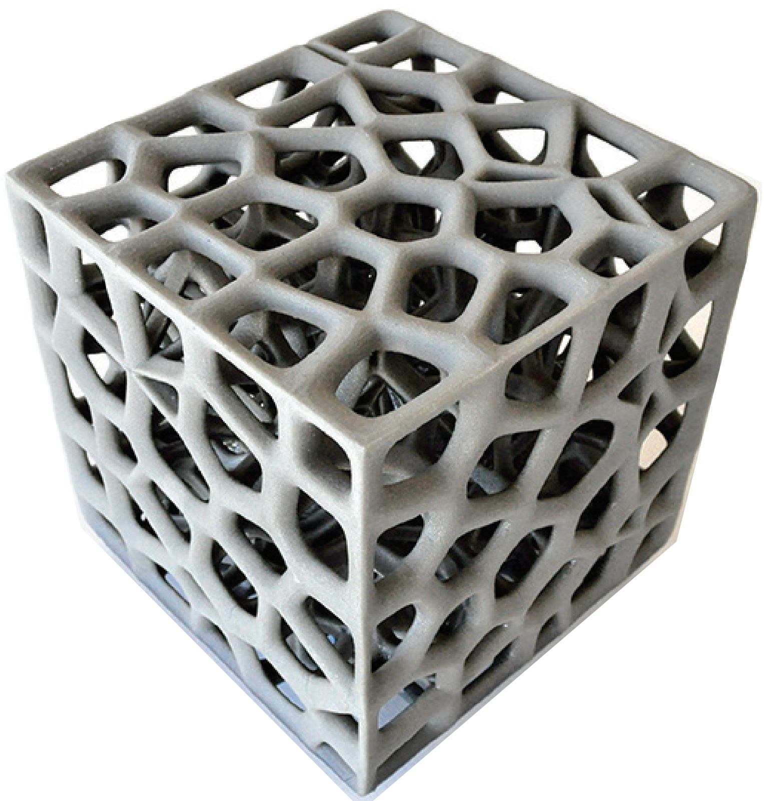
Cement Objects

thin, lightweight shell. The early phases of its development were inspired by the thin masonry structures of the Uruguayan architect and engineer Eladio Dieste (particularly Iglesia del Cristo Obrero—), Thomas Jefferson's serpentine brick walls at the University of Virginia, and the *Torqued Ellipse*, by Richard Serra. In plan, *Bloom* is a curved cruciform that rises nine feet to meet the same shape rotated forty-five degrees, creating a torqued *X* with an entrance forty-five degrees off its primary axis. The undulating form and spaces recall an elephant's foot or, when coupled with the flower pattern on the surface, the traditional mud houses found in the Tiébélé village in Ghana—a reference to the earliest inspirations for 3D printing by Emerging Objects.

Bloom is an excellent example of how portland cement combined with very little water can be used to create intricate 3D-printed structures that have strengths comparable to more traditional concrete constructions. As we move into the future of cement-based building, this material proves yet again its suitability for being continuously reengineered—endlessly tested and retested to achieve multiple levels of performance. Thousands of years of evolution have demonstrated its robust characteristics, and it will continue to evolve as techniques in additive manufacturing become more commonplace in building and construction.

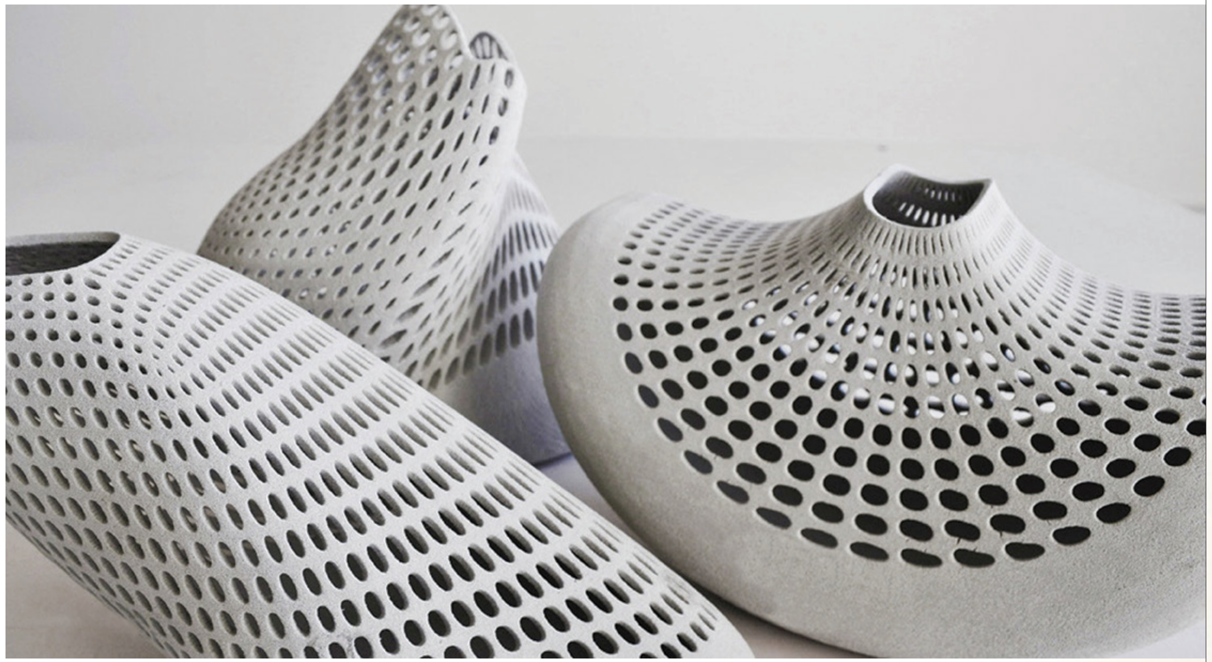
Cement Objects

The SCIN Cube is a cellular solid—a transmaterial grouping characterized by high strength-to-weight ratios—made from 3D-printed cement polymer. The cube is composed of a network of digital cellular bodies that are first relaxed to produce a more uniform field and then structurally differentiated in relation to their distance to the outside surface. The inner core's cell edges are extremely thin and fragile; they are protected by multiple layers of increasingly more robust edges closer to the cube's outside boundary.



Starlight is made up of thirty-two parts assembled from 3D-printed iron oxide–free portland cement with a patina-inducing agent that creates an uneven, aged finish on the surface. The thinness of the print allows for material translucency, and the cement has a soft glow. Components are held together with nylon hardware.

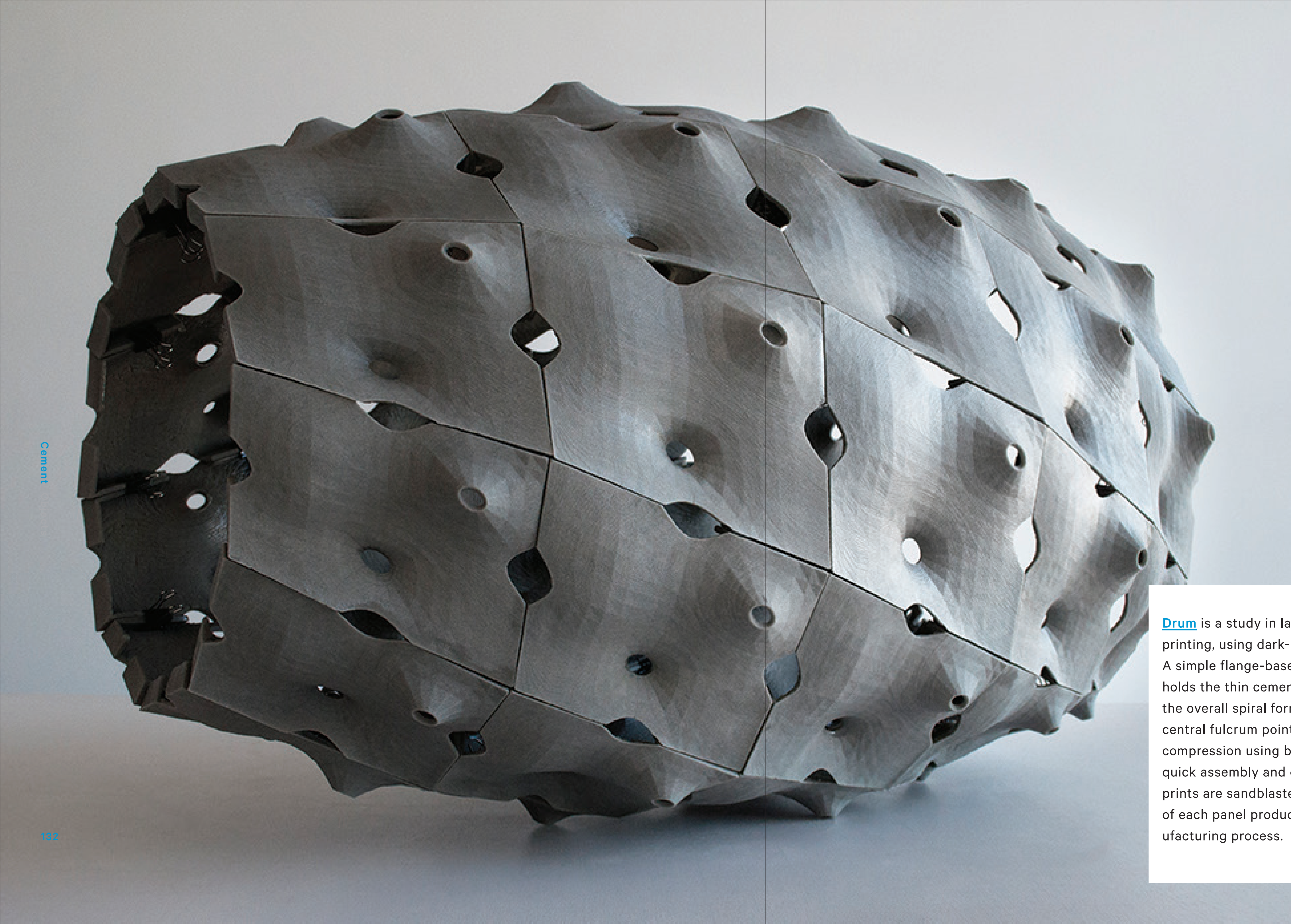
These Grab Tiles are designed with deep undercuts and doubly curved surfaces, which would make them difficult, if not impossible, to cast using conventional methods. The looping and curving relief pattern on top of the tiles provides various ways to interact with them. Users in elder-care facilities, for example, who may need assistance in getting up or in preventing falls, can insert their fingers and hands in the tiles to use them as handles.



The designs for the Rocker Vases are some of the first objects made by Emerging Objects for 3D printing with cement. The vases test thinness, excavation techniques, detail, resolution, and the cantilevering strength of unsupported and unpolymerized material.

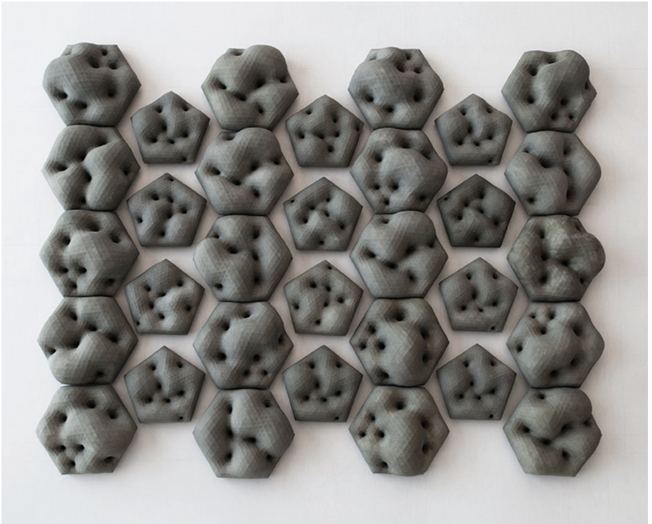
The *Rocker Vases* are intended to be balanced when empty. When plants or water are inserted into the vases, they tip one direction or another, depending on the weight and distribution of the flower display.

The Seat Slug is a biomorphic interpretation of a bench. Its form is inspired by *Flabellina goddardi*, the most recent species of sea slugs discovered off the coast of California, and by the infinite tessellations of Japanese *karakusa* patterns. The *Seat Slug* blurs the lines between biology, technology, and furniture design and is an exploration of function and form. It is constructed of 230 unique 3D-printed cement blocks that are coated with organic resins to create a reflective, finished surface.



Drum is a study in large-scale, lightweight 3D printing, using dark-gray expansion cement. A simple flange-based connection system holds the thin cement panels in compression; the overall spiral form cantilevers from a central fulcrum point. Each panel is held in compression using binder clips, allowing for quick assembly and disassembly. The cement prints are sandblasted to bring out the grain of each panel produced by the additive manufacturing process.

The Seed (P_Ball) is 3D printed in gray cement polymer and sandblasted to appear matte and soft. *Seed (P_Ball)* is the latest object in Andrew Kudless's *P_series*, projects that explore digital and physical processes of self-organization. In this prototype, a geodesic sphere is digitally inflated yet constrained by multiple points. This tension creates a series of undulating surfaces across the larger geodesic framework. The 3D-printed prototype was created to help understand the visual, geometric, and fabrication issues involved in producing a larger cast-concrete installation for the University of California Botanical Garden at Berkeley. Twenty 3D-printed cement hexagons and twelve pentagons converge to form the sphere.



The Planter Tiles are 3D-printed cement hexagonal tiles that close pack. The overall pattern combines six different tile types, four of which can hold plants. The three-dimensional petal motif visually ties together all the planter and nonplanter tiles. The tiles are printed with varying admixtures of aggregate combined with portland cement to produce varying shades and tints; using these different formulations creates a rich and textured surface effect.

Clay

Some of the oldest objects crafted by humankind are made of clay; the human body is often the subject of these early cultural artifacts. The Venus of Dolní Věstonice is a twenty-six-thousand-year-old ceramic figurine from the Paleolithic era discovered in the Moravian basin south of Brno, Czech Republic. This literal clay body was fabricated using local terra-cotta mixed with powdered mammoth bone. (The introduction of bone ash from cattle bones was an innovation also used tens of thousands of years later, in the invention of bone china in late eighteenth-century Britain.) Not only does the Venus from the Dolní Věstonice site represent the earliest known ceramic technology, she also represents one of the earliest known depictions of the female body and the earliest known use of animal bodies in the making of ceramic objects.[1]

Clay is the basic building block of contemporary civilization. The oldest permanent cities, constructed some ten thousand years ago, were built from unfired mud bricks. Scientists theorize that this humble material also composes the fundamental building blocks of life itself. One particular type of clay, montmorillonite, is considered the material segue between matter that is not alive and life, which began as a muddy stew of clay and water transformed into living matter by electrical charges from lightning, forming the first microscopic structures that one finds in living cells.[2]

Clay is a combination of alumina, silica, and chemically bonded water. Particles of clay are extremely small, .7 microns in diameter and .005 microns thick, and they are usually easily found in riverbeds and deltas. Clay particles are flat, two-dimensional, and electrically charged. They touch on only two sides; when flooded with water, a strong attraction occurs, which is what makes clay particles bond to each other. The water also lubricates the particles, which is what allows them to slide and makes the clay plastic and malleable.

Clay can be found in almost all parts of the world. It's cheap, if not free. Its colors range from white to red to black, with every shade and tint in between, and when fired, clay turns back into a stonelike material that lasts indefinitely. Most clay is fired at around 2,000 to 2,300 degrees Fahrenheit (1,090 to 1,260 degrees Celsius), which is a similar temperature to most magmas. The kiln's heat reenacts the geologic processes that create stone.

While the first clay objects made by humans were figurines, the next were pottery vessels. These vessels were baked in outdoor bonfires to be watertight and rock hard. Anthropologists speculate that women would put a fine layer of mud in their woven baskets to make them impermeable, so they could hold water or fat, as some of the earliest remnants of clay pottery show impressions of woven baskets. Subsequently, women began using the coiling technique to make pots by hand for storing water, grains, and cooking fat. Evidence of the first clay pots appears in Japan around 10,000 BCE in the agrarian culture of the Jamon.[3] Simultaneously, around 10,000 BCE, the first houses were being made of mud bricks in the Mehrgarh region of what is today Pakistan. Mud bricks were made of loam, mud, sand, and water mixed with a binding material such as rice husks or straw. These houses coalesced into communities and cities made of mud brick that housed up to an estimated five thousand people in the Indus Valley civilization.

The oldest existing earthen buildings are in the abandoned city of Shahr-e Sukhteh in present-day Iran, built around 3200 BCE. Eventually, people started to build clay furniture in the form of benches and beds next to a clay oven or fire pit. An early form of Egyptian pyramid constructed of mud brick is called the *mastaba*, which means "mud bench." For thousands of years, in villages and cities all over the world, people lived in buildings made of clay—buildings that

Matauri clay pit
in New Zealand

Tepetate Wall at the Center for the Blind and Visually Impaired by Taller de Arquitectura-Mauricio Rocha

surrounded hearths made of clay, where pots and vessels made of clay could be found for cooking and storage, creating entire domestic environments made of clay.

In northern Europe, clay pots were inserted into the walls of clay ovens. These pots sometimes faced in and filled up with the hot air inside the oven, to quickly transmit heat into the room's interior, and sometimes faced out and were known as "fist warmers." If your hands were cold and stiff from working outdoors you could insert them into the pots to warm them.[4]

Earth constructions composed of mud brick, rammed earth, cob, and wattle and daub continue to be built all over the world. The largest existing mud-brick structure in the world is the Mosque of Djenné in Mali, Africa. It was built in 1907 and continues to be the center of religious and cultural life in Mali.

Traditional buildings are not the only earthen architecture that exists. The Center for the Blind in Mexico City, a contemporary work by Taller de Arquitectura-Mauricio Rocha, is made of concrete, glass, and naturally compacted clay, called *tepetate*, which is cut out of the ground. The Eden Project visitor's center in Cornwall, England, by Grimshaw Architects is constructed of high-quality china clay taken directly from the site and rammed into walls. Unfired clay is one of humankind's oldest building materials, and it continues to be a viable and sustainable method of construction worldwide.

Fired brick was first used in the Indus Valley around 3000 BCE. Ceramic brick technology later was adopted, commercialized, and disseminated by the Romans. Using mobile kilns, the Romans successfully introduced kiln-fired bricks to the entire Roman Empire. The bricks were stamped with the mark of the legion that supervised their production. They differed from other ancient bricks in size and shape—they were round, square, oblong, triangular, or rectangular and were generally one or two Roman feet long by one Roman foot wide. The Romans favored this type of brickmaking during the first century of their civilization and used the bricks for buildings all over the empire, including at the baths of Caracalla and the Pantheon.

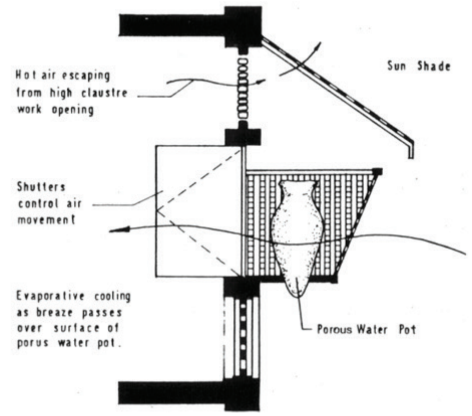
During the industrial era of 1800s England, the production of bricks became mechanized. Bricks could be extruded, pressed, or molded by machines with incredible speed, resulting in the construction of entire cities made of brick all over the world.

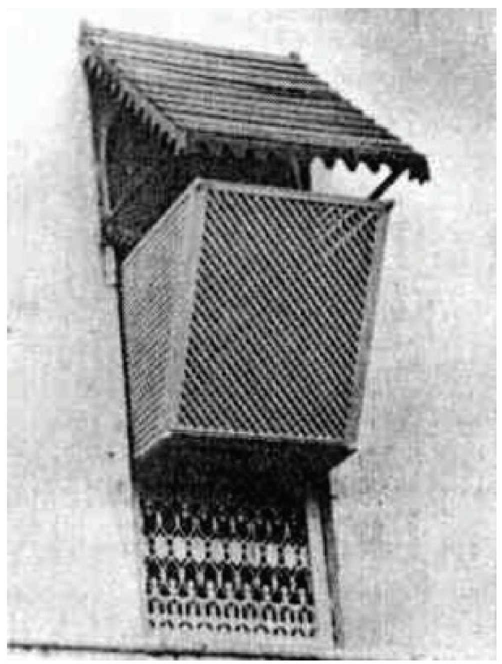
3D Printing with **Clay**

Since the advent of additive manufacturing, clay can be used to make sculptural objects and figures, pots and vessels, bricks, blocks, tiles, and entire earthen buildings. The World's Advanced Saving Project (WASP) uses clay extruders to 3D print large structures such as columns and walls up to twelve feet high, using their BigDeltaWASP printer. Their goal is to build a prototype for a sustainable village composed of 3D-printed mud houses. The mud is sourced locally; little infrastructure and no industrial or expensive materials are required to make the building shell, since the mud is mixed with straw to strengthen it. Like traditional mud brick buildings or puddled mud buildings, the clay buildings 3D printed by WASP will be baked solely by the sun.

Emerging Objects has developed formulas and techniques for 3D printing clay, both with powder-based printers and with paste-extrusion printers that use moistened clay. The Cool Brick takes advantage of powder-based jet-binding printing technology. Because jet binding creates porous objects, the inherent output of the printer inspired the design of the *Cool Brick*.

There are many technologies for keeping interiors comfortable in hot, arid climates.





Muscatese window

Individual Cool Brick

Evaporative cooling is one such technology; it has been used for thousands of years and is still in use today. Called the Muscatese evaporative cooling window, the system employs a porous ceramic vessel filled with water, which is placed in a window. As cool breezes blow over the jug, the water evaporates and humidifies the air, lowering the temperature of the room. This is combined with a wood screen, called a *mashrabiya*, which keeps the vessel and the room in shade, ensuring that both stay cool. The entire ingenious system requires no electricity or ozone-depleting refrigerants.

Inspired by the Muscatese, the *Cool Brick* masonry system collapses the ceramic vessel, wood screen, and window into a single building component made possible by 3D printing.

The *Cool Brick* comprises two scales of porosity. The first is a microporosity that absorbs water through capillary action and stores it in the brick itself. The second is a matrix of openings, in a three-dimensional lattice that allows air to pass through the wall. As air moves through the 3D-printed brick, the water held in the micropores of the ceramic evaporates, bringing cool, humidified air into the interior environment, lowering the temperature using the same principle of evaporative cooling as the Muscatese.

The bricks are modular and interlocking and can be stacked together to make a screen. The three-dimensional lattice creates a strong bond when set in mortar; surface

Cool Brick assembly with mortar

relief creates shade in order to keep a large percentage of the wall's surface cool and protected from the sun, thus improving its performance.

In addition to powder-based printing, paste-extrusion 3D printing has allowed Emerging Objects to explore radical 3D-printing techniques, resulting in the development of a series of objects titled GCODE.clay.

The *GCODE.clay* objects are fabricated using various clay bodies (b-mix with grog, paper clay, porcelain, basaltic clay with manganese, recycled clay, and local clays) to explore the creative potential of designing with G-code. The exploration concerns itself less with the object's shape or profile than with the path that defines the movement of the 3D printer. Through this exploration, the 3D printer is pushed beyond the boundaries of what would typically define the printed object. We have generated a series of controlled errors that create new expressions in clay defined by the plasticity of the material, gravity, and machine behavior.

One outcome of this experiment was the creation of textured surfaces that are reminiscent of textile knitting patterns. Typically, extrusion-based 3D-printed ceramic objects are defined by the striations of the clay layers on the object's surface, but in this case, the surface takes on the appearance of a knitted textile, with clay being looped, purled, and knotted as it droops away from the surface. Occasionally a "dropped stitch" causes a loop to pull away from the surface, making every print unique.

Visualization of g-code

GCODE.Clay collection

In addition to permitting patterning controlled by G-code, paste extrusion offers the possibility of combining clay bodies. During the third debate of the 2016 US presidential election, then candidate Donald Trump said that he wanted to build a wall between the United States and Mexico to keep out the "bad hombres." He was referring to bad men, but what he said sounded more like "bad ombrés"—which connotes something very different. *Ombré*, which translates from the French as "shade," refers to that which progresses from light to dark. An ombré allows for unbroken transitions across borders and between landscapes; it crosses political boundaries fluidly and allows for continuous cultural connections.

In response to Trump's "bad hombres" statement, Emerging Objects created a collection of 3D-printed vessels called *Bad Ombrés*, which smoothly transition from one material to another. The clay bodies used in the Bad Ombrés collection come from different regions around the world and are combined in a single tube that extrudes clay continuously.

The colors and tones of the *Bad Ombré* vessels blend into one another: one clay body graduates into another, from light to dark and from translucent to opaque. Black Mountain and Cassius Basaltic clay, some of the most opaque and black clays available, transition to Polar Ice porcelain, which is mined at the Matauri Bay clay pit in New Zealand and is the world's whitest clay. This unique clay is delicate, resonant, and translucent when

Bad Ombrés in white porcelain
and black mountain clay

struck with light. It is derived from the geologic transformation of volcanic rocks, and the clay body includes alumina-silicates and plasticizers to make it more workable. The Black Mountain clay bodies are a combination of fireclays, ball clays, and red clays that come from pits deep in the southern part of the United States. These clays are blended in California to create a strong clay body that is easily workable.

The *Bad Ombrés* are objects that transcend borders. They are simultaneously rooted in the ground from which they emerge, yet they are global and inclusive. No ombré in this collection will ever be re-created exactly the same way again: randomness, individuality, distinct character, and unique markings are all what make these pieces special. Their differences make them one of a kind, but the ombré itself ties them together.

Bad Ombrés collection

Clay Objects

The Planter Bricks are custom-designed masonry units that counter the heat island effect in big cities through evapo-transpiration and pollution conversion. The plants in the wall help mediate the temperature of the microclimate surrounding the building, buffer sound, and filter the air; the whiteness of the clay reflects light and heat. The fine particles of the 3D-printed clay bricks are held together with an organic binder, and the bricks are fired, burning off the organic materials and leaving behind a strong ceramic object. The *Planter Bricks* are standard dimensions and can fit within existing masonry wall systems. They can be glazed any color.

FLO is a 3D-printed ceramic vessel composed of spheroids that flow into one another, creating a blobby, fluid surface with irregular openings. The spheres appear to be molecules that collide with one another and stick together as they push and pull in a liquid motion, creating an overall form that is continuous and smooth.

"Is it possible to 3D print directly from the ground beneath one's feet?" was the question explored in the development of Wursterware. The bottom floor of Wurster Hall, on the University of California, Berkeley, campus, was undergoing renovation, and an excavation exposed the clay-rich soil atop of which the College of Environmental Design building was constructed. To take advantage of this opportunity, several large buckets of this local clay were gathered, sifted, and reconstituted to create functional earthenware vessels.

Wursterware 1.0

Wursterware 2.0

Wursterware 3.0

The Berkeley-Rupp Architecture Prize
in 3D-printed ceramic, glazed white

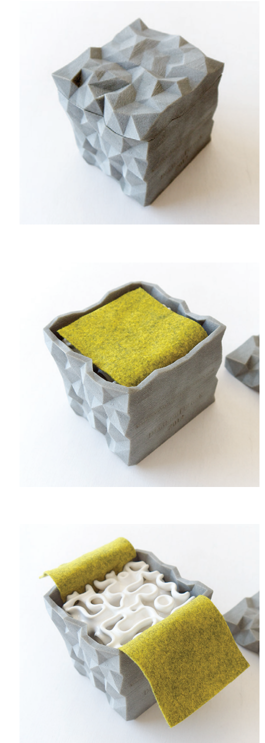
Emerging Objects was honored to have the opportunity to design the physical representation of the [Berkeley-Rupp Architecture Prize](), which awards $100,000 biannually to a distinguished practitioner or academic who has made a significant contribution to promoting gender equality in the field of architecture and whose work emphasizes a commitment to sustainability and community.

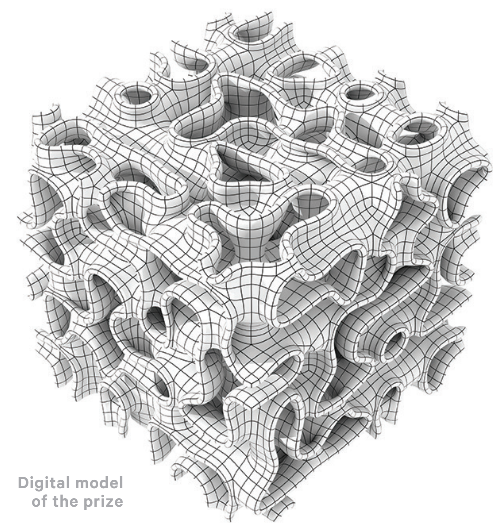
The first medal recorded in history was given by Alexander the Great to recognize military service. Medals were originally intended to be used as jewelry; they were also used as a form of propaganda, often given to politicians to show their support for a particular lobby. Today, all architectural medals are made of precious metals, and their design still reflects the earliest military medals.

In contrast to a medal, the physical representation of the *Berkeley-Rupp Architecture Prize* is crafted from the humblest of materials—clay—and is spatial and nonhierarchical. The design is a three-dimensional object fabricated under the new paradigm of additive manufacturing to represent an updated view of the role of architects in today's society.

The first documented trophy was made of clay—a ceramic amphora filled with oil that was given to the winners of the Olympic Games. The *Berkeley-Rupp Architecture Prize* comes in a contemporary amphora, digitally crafted using materials and processes developed by Emerging Objects.

Unwrapping the prize





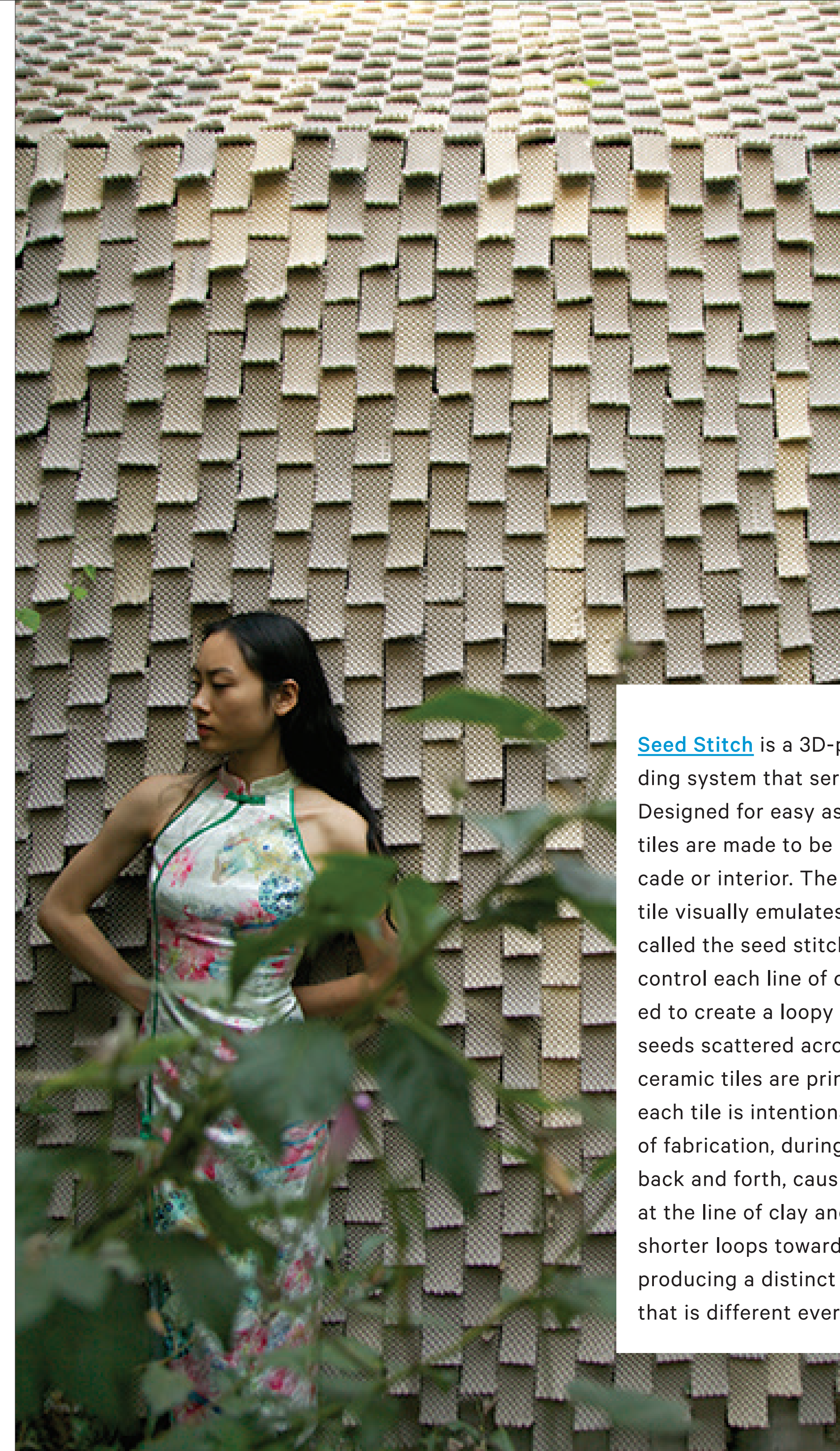
Digital model
of the prize

overlapping

random

random coursed

repeating pattern



Seed Stitch is a 3D-printed ceramic cladding system that serves as a rain screen. Designed for easy assembly, the *Seed Stitch* tiles are made to be hung on a building facade or interior. The surface of each ceramic tile visually emulates a knitting technique called the seed stitch. G-code is used to control each line of clay as it is 3D printed to create a loopy texture that looks like seeds scattered across the surface. While all ceramic tiles are printed from the same file, each tile is intentionally unique as a product of fabrication, during which the tiles wave back and forth, causing the printer to pull at the line of clay and creating longer and shorter loops toward the end of each tile, producing a distinct machine-made texture that is different every time.

Recipes

Many companies and schools around the world own powder-based binder-jet 3D printers (often of the unsupported Z Corporation brand). These printers are quite simple devices; they employ an additive manufacturing process that deposits a binder material onto a thin layer of powder. The liquid binder is sprayed from an off-the-shelf inkjet printhead (hence "3D printing"). These printheads are the same as those used in 2D printers, but when 3D printing, the black ink is purged from the printhead and replaced with a water-based liquid binder that fuses the powder particles together.

The proprietary materials (powders and liquid binders) associated with these printers can be very expensive. But because the liquid binders consist mostly of water, it's easy to use other water-based materials in their place. The powders are also easy to substitute, as long as they are very finely pulverized and have some water solubility.

The ingredients used for concocting the objects throughout this book vary. Different formulations were generated specifically for each material and refined for their performance, flowability, adhesion, precision, and strength. Developing the constituents for each recipe has been a lengthy process involving much trial and error. Nevertheless, anyone can create powder materials for 3D printing.

Here are a few quick recipes to jump-start the process of making open-source liquid binder and powder mixtures for binder-jet additive manufacturing.[1]

!

These recipes have been successful for the authors of this book and are true and complete to the best of our knowledge. All the recipes are made without guarantee on the part of the authors or publishers of this book. The author and publisher disclaim any liability in connection to the use of these recipes.

Liquid Binders

Rice Wine Binder

If you aren't in the mood for cooking, the easiest binder to use is sake rice wine right out of the bottle. Inexpensive, unflavored, and uncolored is best. You may try a few brands, but make sure that there are no particles in the liquid and that it is distilled, clean, and clear (15–20% alcohol). You can open the sake and pour it right into the binder bottle before you purge the printhead. Then run the purge cycle to remove the black ink from the cartridge, and it'll be replaced with the rice wine. You may get an overheat error, but simply rerun the purge cycle. Once you begin printing, you'll notice a beautiful aroma of rice wine filling the air.

Alcohol and Water Binder

A simple recipe for binder requires only two ingredients.

Ingredients

Drugstore brand 91% isopropyl alcohol (280 ml)
Distilled water (920 ml)

Method

1. Mix alcohol and water in a container.
2. Shake or stir as preferred.
3. Pour into the binder bottle and serve.

Powders

Terra-cotta slip

This is a recipe for 3D printing ceramics that can be fired in a kiln.

Inhaling terra-cotta is dangerous. Wear a dust mask and use proper ventilation.

Ingredients

Terra-cotta powder (4 parts by weight)
Powdered sugar (1 part by weight)
Maltodextrin (1 part by weight)

Method

1 Mix the terra-cotta, powdered sugar, and maltodextrin together in a large bucket. This can be done by placing the lid on the bucket and shaking vigorously or, in a well-ventilated area, mixing with a drill mixer.
2 Carefully fill the supply bed of the 3D printer with the terra-cotta mixture.
3 Purge the black ink from the printhead and fill the supply reservoir with rice wine instead of the proprietary binder.
4 Experiment with spraying different binder saturation levels and material layer thicknesses. Settings vary from printer to printer and in different climates depending on ambient humidity.
6 Use established settings to print final object.
7 Wait 24 hours to excavate and depowder the final object.
8 Bisque-fire the air-dried porcelain part for strengthening.
9 Glaze to taste.
10 Fire to full temperature recommended by clay supplier. Enjoy!

Sugar-Sugar Powder

If your sweet tooth beckons, here's a recipe for 3D printing sugar. It can be printed with either binder, and the results are just as sweet. There are only two ingredients in this recipe: sugar and sugar.

Ingredients

Granulated sugar (2 parts by weight)
Powdered sugar, 10x or 12x (1 part by weight)

Method

1 Mix the granulated sugar and the powdered sugar together in a large container.
2 Fill the supply bed of the 3D printer with the sugar mixture.
3 Purge the black ink from the printhead and fill the binder bottle with rice wine. Experiment with spraying different binder saturation levels and material layer thicknesses. Settings vary from printer to printer and location, depending on ambient humidity. A good technique for testing is to make 5 × 5 × 150 mm test bars. Print them and see if the previous layer appears through the current printing layer. If so, it means the two layers are receiving enough binder and are fusing together.
4 Use established settings to print final object.
5 Wait twenty-four hours (a good starting point, but timing really depends on the humidity in the air) to excavate and depowder final object. Use the machine's recommended setting and techniques for excavating.
6 Postprocess with cyanoacrylate, polymer, or wax for strengthening (or don't).

Salt Powder

If you aren't in the mood for sweets, here's something savory: a recipe for 3D printing salt.

Ingredients

Finely powdered salt (8 parts by weight)
Maltodextrin (1 part by weight)

Method

1 Mix the finely ground salt with the maltodextrin, either by shaking in a large, closed bucket until evenly distributed or by combining with a drill mixer. Remember to do so only in a well-ventilated area and to protect yourself by wearing a dust mask or respirator.
2 Purge the black ink from the printhead and fill the binder bottle with rice wine.
3 Experiment with spraying different binder saturation levels and material layer thicknesses. Remember, settings can vary from printer to printer and in different climates depending on ambient humidity.
4 Use established settings to print final object.
5 Wait 24 hours to excavate and depowder the final object.
6 Postprocess with cyanoacrylate, polymer, or wax for strengthening or leave natural.

Note: If finely powdered salt is not available, grind table salt or even coarse road salt in a coffee grinder and sift through 60, 100, 120, and 150 mesh screens until it looks like white dust.

DIY Recipes

There are several steps involved in inventing other materials for powder-based 3D printing. Below is a guide to the steps we undergo when inventing a new material.

Bench testing

Bench testing is used to verify the correctness or soundness of the material formulation.

1 Mix small batches of different ingredients in parts in a small cup, for example, two parts sugar to one part powdered sugar.
2 Pour the batches out on a flat surface in small piles and flatten each pile with a spatula or rolling pin.
3 Spray liquid binder on the top surface of the flattened piles, using a small spray bottle, then leave the mixture to rest for 24 hours.
4 Examine the top layer of the mixture that was sprayed with binder. If it is stiff, hard, solid, and distinct in strength from the loose powder below, you are on the right track to inventing a material. If it crumbles, then it's too weak and the ingredient ratios need to be adjusted (add more sticky stuff).

Test Bars

Test bars are small 3D prints that allow you to examine the strength and dimensional accuracy of the material and to adjust the binder settings. When bench testing has resulted in a formula that shows promise, move to the 3D printer to print test bars using your new recipe.

1 Fill the supply bed in a powder-based printer with 3 inches of the material formulation.
2 Make test bars that are 5 × 5 × 150 mm and orient them horizontally (in the *xy-plane*) in the printer software.
3 Test different layer thicknesses and saturation level settings using the ZPrinter software (or other software if you're not using a Z Corporation powder printer). If the saturation levels are too high, the powder within the printed portion of the bar will smear outside the bar boundaries.
4 Remove the printed bars by raising the build bed in the printer and brushing off the loose powder surrounding the bars. If the bars are solid to the touch and are not warped or crumbly, then the print has been successful. If the bar crumbles, then repeat the process, adjusting the software for greater saturation levels. If the bar is warped, repeat the process with lower saturation levels.
5 Dip or brush the bar with wax, polymer, or cyanoacrylate to process, or enjoy raw!

Developing one's own materials for 3D printing opens the door to new material possibilities and combinations. Some of the advantages include reduced cost, the ability to develop new color variations and textures, and the potential for using local and recycled materials.

The objects, building components, spaces, and structures that are formed through 3D printing can engage the visual, haptic, and olfactory senses, as well as possess extraordinary geometric complexity. The objects below are 3D printed in a combination of curry and cement, and chardonnay and cement—two customized recipes using off-the-shelf materials that demonstrate the ease of creating multisensorial objects. The aromas of the curry and the chardonnay as they are being printed are pervasive and evocative.

This process also raises important questions about the historical and contextual meaning of objects, as well as very simple ones, like why curry and concrete? Asking such questions of objects leads to creativity and speculation about the possibilities of contemporary craft. As pointed out by the British design scholar Gareth Williams, "To retain relevance in the modern world, craft must engage with contemporary concerns. One of the most pressing issues today is the impact of production, consumption and disposal of goods upon the earth's resources and ecological balance."[2] The objects produced by 3D printing are not strictly handmade objects; however, the close connections among design, iteration, technique, material behavior, analysis, and manufacturing suggest that 3D printing, especially when coupled with modes of production that use materials from sustainable resources and waste streams, is a contemporary form of craft with increasing relevance. And if we draw from the craft traditions of the past when speculating about the future, the emerging objects from this nascent technology can inform, shape, and imbue meaning in future forms of architecture, as well as have lasting value for contemporary culture.

Voronoi Cube, 3D printed in chardonnay and cement

Curry Pot, 3D printed in curry and cement

Acknowledgments

The work produced in this volume could not have been possible without the talent, support, and effort of an enormous and diverse group of people, institutions, and sponsors. The genesis of this research was in 2009, with the generous guidance of Dr. Mark Ganter at the Solheim Additive Manufacturing Laboratory in the Mechanical Engineering Department at the University of Washington, who gave us the courage to experiment with printing any material we desired. His knowledge and encouragement early on was instrumental in our ability to improve on and develop the new materials used in this book.

Much of the research was performed at the University of California, Berkeley, and we are indebted to our colleagues there, including Nicholas de Monchaux, who first made us aware of Dr. Ganter's research, and Professor Emeritus Richard Shaw, former head of ceramics at UC Berkeley, who was not only willing to let us in the ceramics department but also helped fund the purchase of the first printer, which we used to test Dr. Ganter's open-source ceramic formulas. An enormous deal of gratitude goes to Ehren Tool, ceramics technician, colleague, friend, and collaborator, who since 2009 has advised on everything from clay bodies, firing temperatures, and glazes to the intellectual and philosophical implications of craft, sculpture, design, and life. Many other colleagues at UC Berkeley are to be thanked for their support of the work, including Greg Niemeyer, Stephanie Syjuco, and Erik Scollon, Department of Art Practice; Professor Claudia Ostertag, Civil and Environmental Engineering; Tom Buresh, chair of the Department of Architecture; and Jennifer Wolch, dean of the College of Environmental Design. Early research in 3D-printed ceramics was conducted in a research seminar at UC Berkeley that helped develop formulas for 3D printing porcelain with students Emily Licht, Colleen Paz, Plamena Milusheva, and Brian Grieb—their efforts laid the groundwork for further experimentation. Several colleagues at San Jose State University are to be thanked for their support of this research, including Brian Kimura, former chair of the Department of Design; Professor Leslie Speer, Department of Design; Professor Shannon Wright; and Cassandra Straubing, Department of Art.

Additional thanks goes to the numerous students at the University of California and San Jose State University who raised critical questions about the relationship between additive manufacturing and architecture in seminars and studios, and the many people who have assisted and inspired the work in countless ways, including Joshua Stein, Jeffrey McGrew, Michael Swain, Nathan Lynch, Andrew Kudless, Jason Kelly, Nataly Gattegno, Thom Faulders, Scott Summit, Jenny Sabin, Bruce Beasley, Bill Kreysler, Reem Makkawi, Lily Shafroth Forbes, Rob Steiner, Molly Reichert, Anthony Giannini, Christine Rael, Margaret San Fratello, Angelo San Fratello, Behrokh Khoshnevis, Andrey Rudenko, Yuri Milo, Mark Kelly, Elli Koutselos, Igor Siddiqui, Dew Tipwimol, Ellen Lupton, Andrew Jeffery, Andy J. Scott, Paul Sacaridiz, Michael Eden, Jonathan Keep, Gerson and Barbara Bass Bakar, Claire Warnier, and Dries Verbruggen at Unfold. We are indebted to Matthew Millman for his talents and generosity for photographing much our work, often for long hours, on short notice, and with immediate deadlines.

The support of several companies has helped us accomplish this work, and we would like to express our gratitude to Carl Bass, Duann Scott, Eyal Nir, Andreas Bastian, Vanessa Sigurdson, and Noah Weinstein at Autodesk; Leonard Dodd and Susana Dodd at Erectorbot; Brad Peebler at Luxology/Foundry; Bre Pettis at MakerBot/Bold Machines; Robert Steiner at MakerBot/Bold Machines/Roboto.NYC; Tom Pasterik at ExOne; Scott Summit, Hugh Evans, Catherine Lewis, and Annie Shaw at 3D Systems; Karen Linder and Aaron Rager at Tethon3D; Spencer Wright at nTopology; Tom Rosenmayer at Lehigh Technologies; and Danny Defelici at 3D Potter.

Research sponsorship was made possible by generous support from the Hellman Family Fund, the Bakar Fellows Program, the Environmental Protection Agency, San Jose State University, the University of California, Berkeley, the Siam Research Group, and the Northern Clay Center.

The talent, insight, hard work, and dedication of our past and present team at Emerging Objects and the printFARM—designers, technicians, research specialists, business partners, and interns, who have established a legacy of the consideration of additive manufacturing in architecture beginning in 2009 through the present—continue to inspire and motivate us. They are: Kent Wilson, Emily Licht, Alexander Schofield, Mona Ghandi, Barrak Darweesh, Logman Arga, Bryan Allen, Alex Niemeyer, Ari Oppenhiemer, Chase Lunt, Chris DeHenzel, Eleftheria Stavridi, Hannah Cao, John Faichney, Maricela Chan, Nick Buccelli, Robert Geshlider, Seong Koo Lee, Stephan Adams, Yonghwan Kim, and our biggest inspiration of all, Mattias Rael—who at seven years of age offers design advice, excavates prints, explains 3D printing to audiences, and reminds us that the present is as important as the future.

Ronald Rael
Virginia San Fratello
2017

Project Credits

removed "the" from "Berkeley-Rupp" and relocated to alpha order

Bad Ombrés
Wursterware
Project team: Ronald Rael, Virginia San Fratello, Phirak Suon Technical assistance: Ehren Tool, Nicki Green (Wursterware) Acknowledgments: Special thanks to Danny Defelici at 3D Potter, Autodesk, Ehren Tool, and the Department of Art Practice at UC Berkeley.

Berkeley-Rupp Architecture Prize
Drum
Haeckel Bowls
Lamprocyclas Raelsanfratellis
Rocker Vases
Starlight
Twisting Tower
Project team: Ronald Rael, Virginia San Fratello, Kent Wilson Wood, chardonnay, rubber, and salt material development: Ronald Rael, Virginia San Fratello

Bloom
Project team: Ronald Rael, Virginia San Fratello, Kent Wilson, Alex Schofield, Sofia Anastassiou, Yina Dong, Stephan Adams, Alex Niemeyer, Ari Oppenhiemer, Reem Makkawi, Steven Huang Cement material development: Ronald Rael Acknowledgements: Bloom was made possible by a partnership with the printFARM (Print Facility for Architecture, Research, and Materials) at the UC Berkeley College of Environmental Design and the Siam Cement Group (SCG Thailand). Additional project support was made through generous sponsorship from 3D Systems and Entropy Resins.

Burst Tiles
Burl Bowl
Chardonnay Wine Goblets
FLO
Finger Tiles
Grab Tiles
Ombré Decanters
Romanescos
Saltshakers
Sugar Sugar Spoons
Utah Tea Set
Project team: Ronald Rael, Virginia San Fratello Wood, chardonnay, salt, and tea material development: Ronald Rael, Virginia San Fratello

Coffee Coffee Cups
Project team: Ronald Rael, Virginia San Fratello, Alexander Schofield, Kent Wilson Coffee grounds material development: Ronald Rael, Alexander Schofield Coffee cherry material development: Ronald Rael, Virginia San Fratello

Cool Bricks
Design team: Ronald Rael, Virginia San Fratello Acknowledgements: This project was made possible by the generous sponsorship of Tethon 3D, which fabricated these parts.

Earthscrapers
Project team: Ronald Rael, Virginia San Fratello, Maricela Chan, Chris DeHenzel, John Faichney, Emily Licht Sand material development: Ronald Rael, Virginia San Fratello Acknowledgments: Earthscrapers was made possible with a grant from the 2010 Biennial of the Americas and was on display as part of the exhibit *The Nature of Things*. Special thanks to Ehren Tool, Professor Richard Shaw, Dr. Mark Ganter at the Solheim RP/RM Lab at the University of Washington, Pax at MediumVFX, and Luxology.

GCODE.clay
Project team: Ronald Rael, Virginia San Fratello, Phirak Suon, Kent Wilson, Alexander Schofield Acknowledgments: Special thanks to Nathan John, Clarke Selman, Douglas Burnham, envelope A+D, Danny Defelici at 3D Potter, Eyal Nir at Autodesk, and especially to the incomparable Ehren Tool in the Department of Art Practice at UC Berkeley.

Geotube Tower
Project team: Ronald Rael, Virginia San Fratello, Kent Wilson Salt material development: Ronald Rael, Virginia San Fratello Design: Thom Faulders of Faulders Studio

Hairline Drawings
Damask Wall
Project team: Ronald Rael, Virginia San Fratello, Barrak Darweesh

Involute Wall
Quake Column
Picoroco Wall in Sand
Project team: Ronald Rael, Virginia San Fratello Acknowledgments: The Involute Wall, Quake Column, and Picoroco Wall in Sand were made possible by ExOne and were on display as part of the 3D Printer World Expo in Los Angeles, CA, in 2014.

Marc Metamorphosis
SCIN Cube
Seed (P_Ball)
Project team: Ronald Rael, Virginia San Fratello, Kent Wilson Cement material development: Ronald Rael Chardonnay material development: Ronald Rael, Virginia San Fratello Design: Andrew Kudless of Matsys

Newsprint
Project team: Ronald Rael, Anthony Giannini Newsprint material development: Ronald Rael, Anthony Giannini

Picoroco Wall in Orange
Project team: Ronald Rael, Virginia San Fratello, Seong Koo Lee Acknowledgments: Special thanks to MakerBot for production.

Planter Bricks
Project team: Ronald Rael, Virginia San Fratello, Molly Reichert Acknowledgments: Special thanks to Dr. Mark Ganter at the Solheim RP/RM Lab at the University of Washington

Planter Tiles
Project team: Ronald Rael, Virginia San Fratello, Kent Wilson, Alexander Schofield Cement material development: Ronald Rael

Poroso
Project team: Ronald Rael, Virginia San Fratello, Molly Wagner, Victoria Leroux Wood material development: Ronald Rael, Virginia San Fratello

The Hut Was Never Primitive
Project team: Ronald Rael, Virginia San Fratello, Kent Wilson, Alexander Schofield

Rubber Pouf
Project team: Ronald Rael, Virginia San Fratello, Voung Dao Rubber material development: Ronald Rael, Virginia San Fratello Acknowledgments: Special thanks to Tom Rosenmayer and Lehigh Technologies.

Saltygloo
Project team: Ronald Rael, Virginia San Fratello, Seong Koo Lee, Eleftheria Stavridi Salt material development: Ronald Rael, Virginia San Fratello Acknowledgments: Special thanks to Dr. Mark Ganter at the Solheim RP/RM Lab at the University of Washington, Ehren Tool at the Department of Art Practice at UC Berkeley, the Department of Architecture at UC Berkeley, the Department of Design at San Jose State University, Mark Kelly, Kwang Min Ryu, and Chaewoo Rhee

Sawdust Screen
Project team: Ronald Rael, Virginia San Fratello, Molly Wagner, Stephanie Murri, Deanna Molkenbuhr, Victoria Leroux Wood material development: Ronald Rael, Virginia San Fratello Acknowledgements: Special thanks to San Jose State University and Lily Forbes Shafroth. Research was made possible by a grant from the Environmental Protection Agency.

Seat Slug
Project team: Ronald Rael, Virginia San Fratello, Emily Licht, Nick Buccelli, Kent Wilson Cement material development: Ronald Rael Acknowledgments: Special thanks to Dr. Mark Ganter at the Solheim RP/RM Lab at the University of Washington, Ehren Tool, Professor Richard Shaw at UC Berkeley, the Department of Art Practice at UC Berkeley, the Hellman Family Fund, Professor Claudia Ostertag at UC Berkeley, San Jose State University, and Luxology

Seed Stitch Wall
Project team: Ronald Rael, Virginia San Fratello, Kenneth Wilson, Alexander Schofield, Phirak Suon Acknowledgments: Special thanks to Danny Defelici at 3D Potter, Eyal Nir at Autodesk, Ehren Tool, and the Department of Art Practice at UC Berkeley

Star Lounge
Design team: Ronald Rael, Virginia San Fratello, Mona Ghandi Fabrication team: Bre Pettis, Rob Steiner, Sam Klemmer, Elizabeth Randel, Geo Salas, Nathan Worth, Steve Gonzalez, Anthony DiMare, Sebastian Misiurek, Meemo Acknowledgments: Special thanks to Rob, Bre, and the bold team at Bold Machines who printed the Star Lounge at the MakerBot BotFarm in Brooklyn, NY

Wood Blocks
Design: Anthony Giannini Wood material development: Ronald Rael, Virginia San Fratello

Notes

UTM suffixes can be removed . . .

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Recipes

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Image Credits (rough estimate)

All photographs are courtesy of Emerging Objects unless otherwise noted.
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Published by Princeton Architectural Press
A McEvoy Group company
202 Warren Street, Hudson, New York 12534
www.papress.com

Printed and bound in China
21 20 19 18 4 3 2 1 First edition

Editor: Sara Stemen Designer: Benjamin English

Special thanks to: Ryan Alcazar, Janet Behning, Nolan Boomer, Nicola Brower, Abby Bussel, Jan Cigliano Hartman, Susan Hershberg, Kristen Hewitt, Lia Hunt, Valerie Kamen, Sara McKay, Eliana Miller, Nina Pick, Wes Seeley, Rob Shaeffer, Marisa Tesoro, Paul Wagner, and Joseph Weston of Princeton Architectural Press —Kevin C. Lippert, publisher

Library of Congress Cataloging-in-Publication Data:
Names: Rael, Ronald, 1971– author. | San Fratello, Virginia, author.
Title: Printing architecture : materials and methods for 3D printing / Ronald Rael and Virginia San Fratello.
Description: First edition. | Hudson, New York : Princeton Architectural Press, 2018. | Includes index.
Identifiers: LCCN 2017035833 | ISBN 9781616896966 (paperback)
Subjects: LCSH: Three-dimensional printing. | Building materials. | BISAC: ARCHITECTURE / General.
Classification: LCC TS171.95 .R34 2018 | DDC 621.9/88—dc23
LC record available at https://lccn.loc.gov/2017035833