

# **Making and Breaking Rules with Algorithmic Forms and Tactile Processes**

**A Technoceramist's Adventures with  
Mathematical Thinking**

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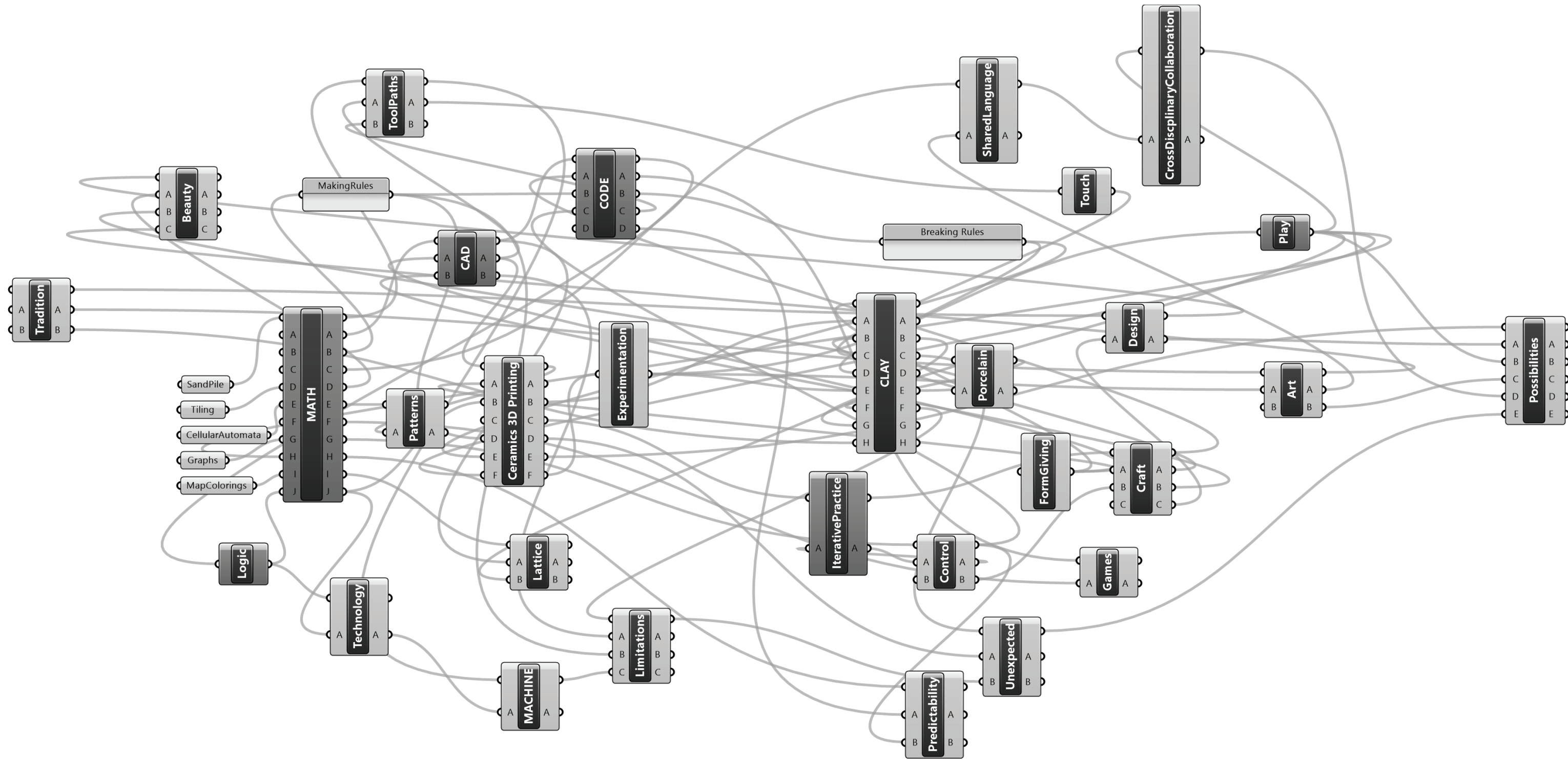
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Chapter Four

# Form Giving





## More on Mathematical Concepts

**LATTICES AND GRIDS** In the collections of art museums around the world, I remember seeing objects created with regularly spaced strips of material, typically some kind of plant fiber. The crisscrossing strips form an open weave pattern made of solid areas and gaps, with triangular, rectangular or hexagonal spaces. These screens of wood, metal, paper or textile materials are lattice works.

In math, though, a LATTICE is understood as an abstract construct that is useful in many areas from geometry to algebra. The mathematical lattice is best defined as a regular array of points on a plane or in 3D space. REGULAR is an arrangement where angles and distances do not change throughout the interconnected structure. A lattice may also be referred to as a grid or mesh, while the points in the lattice are called VERTICES. For the purpose of the mathematical rule-based projects discussed in this book, our game board is always some kind of a lattice. In most instances, I developed the project using a rectangular lattice; in others, like in various tilings, I played around with both rectangular and triangular grids.

In physics and in material science lattices are very common. One might think of crystalline structure as an example, where each atom or molecule is represented as a VERTEX in the lattice. The structure and properties of the material are largely dependent on the mathematical and physical relationship among these points. Clay <sup>01</sup> is a very interesting material to study for its physical structure, a layered lattice, which allows the material to stretch and shrink as well as to transform during the firing. <sup>02</sup>

**WHAT ARE GRAPHS?** A GRAPH is a mathematical structure describing a set consisting of any number of objects and the nature of connectedness among these objects. You may see graphs in the form of a diagram consisting of a network of interconnected nodes. In the mathematical area of graph theory, these objects are depicted and referred to as VERTICES, <sup>03</sup> while the relationship between two vertices is called an EDGE. Edges usually have an orientation to them, marked by an arrow, indicating the direction of some kind of action. This is a VECTOR.

You may have already noticed similarities between graphs and lattices, so it probably would not surprise you to know that in math, there are also entities called lattice graphs, consisting of a series of vertices which form a regular arrangement. Graphs can be used for mapping out the action of the game: for example, to mock up which lattice cell distributes into its neighboring cells in simple chip-firing models.

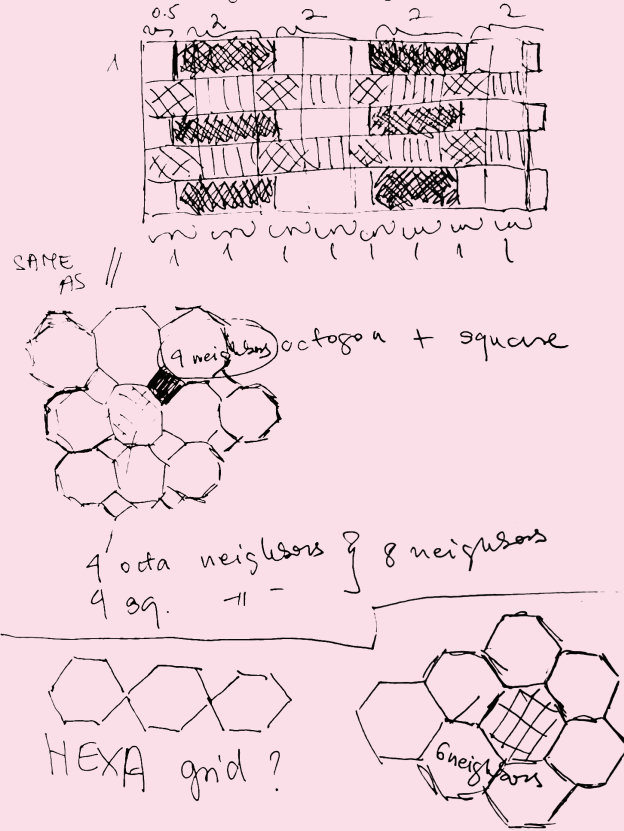
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<sup>01</sup> Heimann, R. B. *Classic and Advanced Ceramics : From Fundamentals to Applications*. Weinheim: Wiley-VCH, 2010.

<sup>02</sup> The first thing every ceramics student learns about clay also has to do with the transformation of its structure from one lattice state to another. This irreversible change—called quartz inversion— happens during the firing. It is what makes clay no longer dissolvable in water, what takes it from raw material into finished pottery.

<sup>03</sup> nodes or connection points

- changing the spacing of cells
- using coloring that is easily discernible
- changing matrix grid to fit layers



MAP COLORING PROBLEMS: FOUR AND FIVE COLOR THEOREMS

On a subdivided surface, in order to tell different areas from one another, colors may be used to distinguish separate territories. I have introduced lattices already, in which the game-board is regularly divided into uniform cells, but we can also extend this consideration to any irregular division of the plain into contiguous regions, which produces a figure called a MAP.

The minimum number of colors needed to color in the entire map, without areas of the same color touching, is an interesting question, which has occupied mathematicians for centuries.

Go ahead, test it out! I too had to wrestle with this problem when designing some of the tiling and sandpile projects.

The five-color theorem,<sup>04</sup> which was proven using graph theory in the late 1800's by Alfred Kempe and later corrected by Percy John Heawood, states that a minimum of five colors are needed for the coloring of any map if we want to avoid two adjacent regions having the same color. Knowing about the five-color theorem was useful when I was creating textures in the 3D design software for ceramics. In order to create a discernable pattern, I needed to develop a vocabulary of four or five shapes, which both looked and felt different from one another when put next to one another. My texture vocabulary consisted of blocks of various heights, for sandpile models, and of various geometric shapes from bricks to pyramids when working on tilings.

Interestingly, in more recent times, computers helped to demonstrate that as few as four colors would also suffice, giving rise to the four-color theorem.<sup>05</sup> Appel and Haken reduced the infinite number of possible maps to just 2,000 variations, which were checked by a computer one-by-one using massive calculations. This first instance of a computer-aided proof has created an enormous controversy among many research mathematicians who were skeptical about the trial-and-error process of testing and experimenting, instead of the parsimonious beauty of an abstract mathematical proof.<sup>06</sup>

<sup>04</sup> Find out more about the math behind this: Jungnickel, Dieter. "Colorings." *In Graphs, Networks and Algorithms*, 261-78. Vol. 5. Algorithms and Computation in Mathematics. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008.

<sup>05</sup> Appel, Kenneth, and Haken, Wolfgang. "The Solution of the Four-color-map Problem." *Scientific American* 237 (1977): 108.

<sup>06</sup> Montañó, Ulianov. "Ugly Mathematics: Why Do Mathematicians Dislike Computer-Assisted Proofs?" *The Mathematical Intelligencer* 34, no. 4 (2012): 21-28.





**TILING** Tiling or TESSELLATION is another kind of division of a plane in which one or more geometric shapes—regular or irregular POLYGONS—are being used. The critical condition of a tiling is that the tiles need to fit together perfectly with no gaps and also lay flat on the plane. REGULAR tessellations use tiles that are all the same. Regular tiles, with every single edge being equal in length with all other edges, exist in only three different kinds: equilateral triangles, squares and hexagons. <sup>07</sup> Regular pentagons though are entirely different. We would not be able to tile a plane in our ordinary Euclidean geometry with them. <sup>08</sup> But certain types of irregular convex pentagons and also a wide range of random shapes can fit together to make irregular tilings. <sup>09</sup>

If a tiling has a repeating pattern, which can be achieved by a limited set of actions called transformations, it is referred to as being PERIODIC. <sup>10</sup> Transformations create symmetries by rotation (moving around a point), reflection (mirroring), translation (sliding over) or glide reflection (made by doing both translation and reflection at the same time). In fact, in math, SYMMETRY and tiling go hand in hand: symmetry being responsible for patterns, like wallpaper, where the same motif appears over and over. <sup>11</sup>

At Slip Rabbit, with the participation of the studio interns, I have been experimenting with a number of fun tessellations for constructing both surfaces and forms. When working in a modeling program, I would typically first make a “texture sticker” on the plane, then proceed to drape this around the surface of a cylinder or some other shape. Each type of three dimensional tile may have the same or a different polygon as its footprint and also a different shape and height. <sup>12</sup>

The thing with clay extrusion printing though is that one

can never know for sure what comes out of such a combination of forms!

Assembled in the design program, the organization of a tiling is re-rendered into layers by the slicer software. By the time it is finally printed in soft and unruly clay, the regularity of the design undergoes another kind of transformation. I found that as long as I kept the footprint of the three-dimensional tiles conforming to the rules of tessellation, the actual shape and scale of the tile could vary widely. Making it bigger or smaller or creating forms with spikes and jagged edges made lots of exciting variations of both texture and form, creating endless opportunities for play.

My experimentation with tessellations preceded the work in rule-based patterns. They had actually led me to think more about building using mathematical rules and to develop a digital workflow that allowed meticulous placement of small textures on three-dimensional forms. I could create precise layouts or push this process towards the wildly experimental, setting the stage for later work with cellular automata and sandpiles.

<sup>07</sup> Note that a hexagon is made of gluing six copies of equilateral triangles together.

<sup>08</sup> A regular pentagon has five edges of equal length. Regular pentagons, when put together, curve out of the Euclidean space. They can only be used for tiling a sphere (think of a soccer ball!) or a hyperbolic plane, such as surfaces similar to corrals or curly leaves of a lettuce. More about these in Taimiņa, Daina. *Crocheting Adventures with Hyperbolic Planes*. Wellesley, MA: A.K. Peters, 2009.

<sup>09</sup> The work of M. C. Escher provides great examples for artistic versions of these irregular tilings. See more in the well-maintained archives of the M. C. Escher Foundation: [mcescher.com/](http://mcescher.com/)

<sup>10</sup> It is also quite possible to create a tessellation that shows no periodicity; a well-known mathematical example is the Penrose tiling. See more about these in Todesco, Gian Marco, and Michele Emmer. "Aperiodic Tiling." In *Imagine Math: Between Culture and Mathematics*, 197-208. Milano: Springer Milan, 2012.

<sup>11</sup> Farris, Frank A. *Creating Symmetry: The Artful Mathematics of Wallpaper Patterns*. Princeton: Princeton University Press, 2015.

<sup>12</sup> this is to get the maximum textural effect.



**CELLULAR AUTOMATON** As introduced earlier, the cellular automaton (CA) **13** is best described as a game on an array of cells arranged to form a grid. These cells exist in specific states, which are described with DISCRETE values, meaning that there is no gradual change possible. When a cell's state changes, it toggles from one condition, for example OFF, to another condition: ON. The game is played using RULES, which specify conditions for when and how the state of the cells might change. The rules take into consideration the cell's original state and the current state of its neighboring cells.

It is a fascinating process to create simple rules and watch them play out on the game board. Small alterations to the rules, for example varying how many neighboring cells may have an effect on the cell's behavior, can introduce unforeseen variations and add further complexity to the system. When the rules are applied, a given array of cells advances to the next state, which can be seen as generative process. Each generation exhibits a different distribution of cell states. In other words, we get a variety of PATTERNS. The process of self-reproductive logical systems and, with them, the theory of the cellular automaton, emerged in the mid-1900's from contributions to cybernetics made by Alan Turning, Stanislaw Ulam and John von Neumann. **14** Interestingly, many of their, as well as subsequent studies, focused on comparing and modeling natural and artificial (computer) automations.

Perhaps the best known of all CA is the one played on a two-dimensional grid, which was popularized by the research of John Horton Conway in the 1970s. Conway's construction, called the Game of Life, references living systems. In it, cells are being alive or dead, and the possible

actions are to be born; to survive; or to die. The game starts with an INITIAL STATE entered. **15**

There are only three simple rules, **16** taking into consideration nothing more but the number of neighbors alive. Once Conway's game has started, it requires no further input outside of the dutiful application of the appropriate rule. This process generates a nearly endless combinations of patterns, showing not only in how many but also in what location we would find surviving generations. **17** The time-based nature of this game lends itself to be visualized more aptly by some form of time-based media, such as an animation, rather than in a plastic form. While I did not end up making the Game of Life into ceramics, its existence provided a very important conceptual anchor and reference in my own work.

The type of cellular automata behavior that did spend a lot of time understanding and exploring with ceramic 3D printing is an even simpler one. It's called the Elementary Cellular Automata for its basic construction being a linear grid. Cells are "scanned" by the rules in triplets, the process moves along the string from one end to the other in a liner fashion. Each triplet determines the condition of the single cell centered just below in the next row. **18**

This type of CA behavior was systematically studied and described by Stephen Wolfram **19** in the 1980's. There are 2³=8 different triplets one may get this way, resulting in a total of 2⁸=256 possible variations for setting up the rules. Starting always with a single ON cell placed in the center of the string, flanked by cells that are OFF, Wolfram devised a way of numbering the rules and classifying the results. **20** Producing thousands of generations from a single string, he

was able to observe four distinct classes **21** of the resulting two-dimensional lattices. Wolfram's title, *A New Kind of Science*, suggests his aspirations to expand the effects made by a simple program from computing to modeling the essential features of all sorts of complex physical, biological and other systems. The primal importance of algorithmic computation, in fact, is in the very heart of Wolfram's theory about the Elementary CA. His ideas might be too far out to some peoples' tastes, but they certainly raise interesting questions about what can be modeled and what cannot, what can be controlled and what cannot. And here is where my interests in rules intersects with Wolfram's argument.

One would need real patience to create an Elementary CA pattern by analogue means, but it's not impossible, since the process of scanning happens in a linear fashion. Often enough, the rules must be repeated for hundreds of generations before seeing some interesting behavior. In the beginning of our research, Sara wrote a script in CoCalc for scanning the strings and plotting the resulting MATRIX. **22** Similarly to the process of creating tilings, I then translated this black and white map of little squares into textures using Rhino.

I later tinkered with scripting variations to the rules. **23** I experimented with applying the rules not only to single starting seeds but to various already existing patterns from representations of language—actual text sources turned into Braille and Morse code—to weaving drafts. I also designed and introduced secondary rules, which we called "viruses," in the hope of breaking the regularity and predictability of the emerging pattern. Our computing

resources seemed to be near exhaustion when it came to making larger matrices, **24** proving that the computation required to run large scale plots was nowhere near simple.

Another interesting concept that arose from this work has to do with the automata behavior itself, which is commonly described as EMERGENT. An economist, Jeffrey Goldstein, coined the term in 1999 in a more general sense and described it as "the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems." **25** Goldstein later replaced emergence with a more expanded notion of "self-transcending constructions." **26** A self-transcending construction is a befitting description especially for those unusual matrices, which show a global state coherent but not predictable from the states preceding it, one that evolves as a result of dynamical interaction in a rather surprising way.

**13** Automata, when referring to them in plural.

**14** Aspray, William. *John Von Neumann and the Origins of Modern Computing*. History of Computing. Cambridge, Mass.: MIT Press, 1990.

**15** Imagine the initial state as the arrangement of cells in ON state on a game-board, with all remaining cells being in an OFF state. Territories of wolves and other predators and cell or bacteria cultures in a petri dish are real life examples of initial states in Game of Life type of conditions.

**16** On a rectangular lattice, each cell has 8 neighbors, including diagonals. The rules are as follows:

Rule #1: A cell will die of under- or over-population if < 2 or > 3 of its neighbors are ON.

Rule #2: A cell will be born or become alive if there are exactly 3 neighbors ON.

Rule #3: The cell that is ON will survive if it has exactly 2 or 3 neighbors ON.

**17** Interestingly, these patterns could be classified into a few basic shape types, which are described in terms of the behavior of change they show: Still life is a pattern type that stabilizes over time and remain unchanged for the rest of the game. Oscillator patterns go through periodic regular transformations. Other kinds of patterns may exhibit an infinite ability to transform but neither stabilize nor go into a cyclical change.

**18** As the scanning process moves down the string, it evaluates the condition of every cell in the context of the state of its neighbors to the left and right. Each cell is being evaluated three times, the resulting cells slowly building the next line and then the next line.

**19** Wolfram, Stephen. *A New Kind of Science*. Champaign, IL: Wolfram Media, 2002. The book is full of amazing illustrations and large- scale matrices of various Elementary CA.

**20** Following Wolfram's designation, ON cells are marked with a black color, while OFF cells are with white.

**21** There are four types of resulting states:

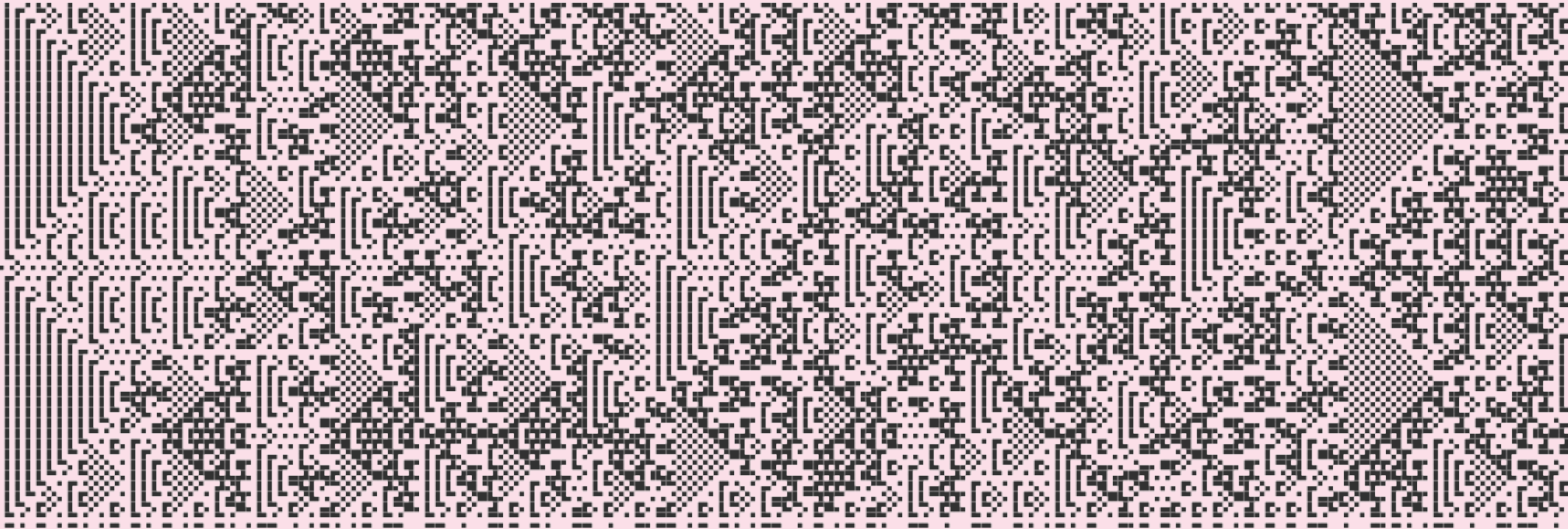
1. A uniform state is being created when one state eventually wipes out the other.

2. Stabilization happens where the resulting pattern continues without change for an infinite number of generations.

3. Random states are those where no particular pattern can be observed.

4. Finally, there are some rather unusual states in which random and stable areas seem to be interacting in unpredictable ways.





**22** Here again, Slip Rabbit intern, Daria Micovic, was tremendously helpful.

**23** A 50x50 cell matrix was the typical size of the plots used for most of the pieces. However, the most interesting patterns started emerging only around a few hundred generations. We were able to solve this problem by plotting in sections and stacking the printed vessels together.

**24** Goldstein, Jeffrey. "Emergence as a Construct: History and Issues." *Emergence: Complexity and Organization* 1, no. 1 (1999): 49-72.

**25** Goldstein, Jeffrey A. "Reimagining Emergence, Part 3: Uncomputability, Transformation, and Self-transcending Constructions." *Emergence: Complexity and Organization* 16, no. 2 (2014): 116-176.

**26** Sandpiles are a relatively young area of research in math. They were developed in 1990 by a theoretical physicist, Deepak Dhar. Similar ideas have been explored much longer, curiously as a tool for teaching probability. Engel, Arthur. "The Probabilistic Abacus." *Educational Studies in Mathematics* 6, no. 1 (1975): 1-22. A good mathematical introduction to the topic can be found here: Holroyd, Alexander E., Lionel Levine, Karola Meszaros, Yuval Peres, James Propp, and David B. Wilson. "Chip-Firing and Rotor-Routing on Directed Graphs." 2008, In and Out of Equilibrium 2, "Progress in Probability" Vol. 60, Pages 331--364 (2008).

**27** Grains of sand are also referred to as "chips" placed on a position. From each position, there are certain "neighboring" positions which can be reached in one step. If a position ever has more chips than neighbors, then it becomes "unstable" and will fire its chips, meaning that it will give each neighbor one of its chips.

**28** A GROUP is a mathematical entity. A group refers to a collection of objects (a SET) that is equipped with a binary operation, such as multiplication. This operation combines any two elements to form a third one in a way that satisfies four conditions: closure (operation returns a member of the set); associativity (the order in which the operations are performed does not matter as long as the sequence of elements stays the same); identity (or identity element is a neutral element, which leaves any element of the set unchanged when combined with it); and invertibility (meaning that every element has an inverse, such as a and 1/a).

**SANDPILE MODELS** One of the most visually interesting areas of mathematical research is sandpiles. <sup>26</sup> Picture this game as an actual pile of sand concentrated at a given location—typically, in the very center—of a game board lattice. The pile is rather unstable. It wants to be extending towards the edges of the game board, thus growing wider. Grains of sand slide down its slopes and are being displaced into neighboring cells unevenly, creating landscape of shifting peaks and valleys as sand continues to roll away from the center. What happens on the macro scale of the entire board is a ripple effect of dynamically changing patterns. <sup>27</sup> On the micro scale of the individual cells or neighborhoods of cells, there is a continuous transformation between high and low states of saturation, which is also referred to as a CHIP-FIRING sequence.

Sometimes, the game results in an infinite loop of firings. Most often though, eventually a terminal STABILIZED state will occur where no position can fire. Looking at the stabilized game boards of sandpiles and chip-firing games, the patterns that develop are quite mesmerizing. Large versions made with millions of sand grains can seem like a cosmic diagram built from concentric layers of circles and rectangles, just like a mandala. Towards their edges, they have a rich fractal-like organization consisting of periodic patches of various patterns made from many colors. The colors, of course, correspond to the state of the cell holding 0, 1, 2, 3 or more grains. This kaleidoscopic beauty seems both perfectly logical for its obvious repetitions and apparent symmetries, as well as mind-bogglingly complex and chaotic. The patterns, which often resemble stars, roses, kites, and more, can be grouped into families based on the type of the distribution.

An interesting mathematical aspect of sandpiles is called an Abelian sandpile GROUP. <sup>28</sup> It describes a set of terminal configurations, which can be reached by adding chips to the fully saturated configuration with some place on the board designated as the SINK. <sup>29</sup> These are configurations that will occur *infinitely often* <sup>30</sup> if you keep adding chips to a sandpile and letting it stabilize again. A beautiful mathematical theory states that if the game ends in the terminal stable state, then the order in which the positions are fired will not change the final outcome. <sup>31</sup> In mathematical terms, the order of firing is COMMUTATIVE.

Sandpile groups are only one aspect of sandpiles which mathematicians study. The sandpile model brings together a lot of different parts of math: graph theory, group theory, number theory, partial differential equations and combinatorics. Researchers also study the distribution of avalanches in the sandpile, the patterns and pattern-families that appear, the density of sand in the pile, and so much more.

Sandpile models can also be studied from a lot of other perspectives outside of math. In fact, this model was first proposed in physics <sup>32</sup> as an example of a DYNAMICAL SYSTEM <sup>33</sup> displaying SELF-ORGANIZED CRITICALITY. Bak argued that complex behavior in nature reflected the tendency of large and complex systems to evolve into a CRITICAL STATE, such as sand piled high and ready to topple. In the critical state, small disturbances can lead to major events, like a landslide or an explosion. <sup>34</sup> Sensing logic in the organization of the critical state—focusing on the overall properties of the whole rather than the individual and localized actions of each grain that make it up—Bak called such complex systems SELF-ORGANIZED.

While many open problems in this area of mathematical research are still unsolved, the fundamental concept is quite accessible to general audiences.

Our WXML research group on sandpile models experimented with several possible scenarios using regular square grids and hexagonal grids. We always worked with a finite lattice, bounded by sinks on every side. As an experiment, I asked Sara to code us a scenario that placed the sink hole onto a single cell in the center while “joining” the right edge of the board to the left and the top to the bottom, effectively turning the game board inside out. We created a counter for analyzing the rhythm by which the pile topples and the distribution of the chips change in major ways. We tried to use known integer sequences to predict the occurrences of critical states. And once again, we played the game by modest hands-on means, using coins and creating animated sequences of small sequential matrix plots. We also generated sandpile distributions in CoCalc using thousands, hundreds of thousands and, eventually, millions of grains of sand. Differently from the Elementary CA where scanning only happens in a linear fashion, in sandpile models, chip firings may also happen simultaneously all over the lattice. Running these simultaneous algorithmic operations tested our available computing resources. Looking at the resulting patterns, that were not unlike images in a kaleidoscope, the existence of reflection symmetries stood out to me, which suggested a potential solution to our computationally expensive workflow. Taking my suggestion to a mathematical application, Eli Johnson wrote a script that ran chip-firing on a small subset of the graph, <sup>35</sup> using reflection to complete the pattern.

I turned several of our smaller matrix plots into tactile objects using a workflow more or less similar to the one used for making the Elementary CA. I would have liked to go even bigger and into more complex designs, but once again, both computational resources and my tools limited the scale of the grid I could use. The finished pieces used wall-paper symmetries of sandpile patterns around cylindrical vessels. It also occurred to me to study the pattern of each distribution <sup>36</sup> independently, and I created pieces with these somewhat sparser sub-patterns. I was surprised by the astonishing resemblance of these to design patterns familiar from textile work, like Norse knit patterns and Hungarian embroidery. Only much later, after our collaboration concluded, could I step away from the math completely and work on a final piece, *Plateaus*, inspired by sandpiles. <sup>37</sup>

<sup>29</sup> The SINK is a place where chips can fall of the board and disappear forever. Sinks can be as small as a single cell (a vertex) or as large as one edge or the entire boundary, all the edges together.

<sup>30</sup> This expression is borrowed from mathematician Ahmed Bou-Rabee, who kindly provided me with feedback on the draft.

<sup>31</sup> Dhar. “Self-organized Critical State of Sandpile Automaton Models.” *Physical Review Letters* 64, no. 14 (1990): 1613-1616.

<sup>32</sup> Bak, P., C. Tang, K. Wiesenfeld, and Brookhaven National Laboratory, Upton, New York 11973 Physics Department. “Self-organized Criticality: An Explanation of the 1/f Noise.” *Phys. Rev. Lett.*; (*United States*) 59, no. 4 (1987): 381-384.

<sup>33</sup> meaning time-dependent, changing.

<sup>34</sup> In this sense, clay, especially porcelain, is the ultimate example of a material in the critical state. Minute cracks and misalignments develop throughout the forming, drying and firing process, only to lead to failure in the most unexpected moment. Many times, a piece was nearly done printing or had just finished, only for me to find it flat like a pancake on the printer’s platform a moment later, collapsed into a helpless heap. What has upset the balance? Where was that critical moment? Where is the exact spot on the form whose weakness is responsible for the destruction?

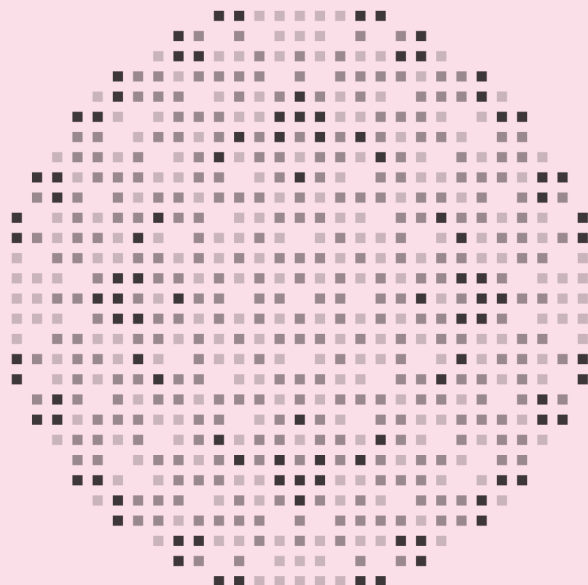
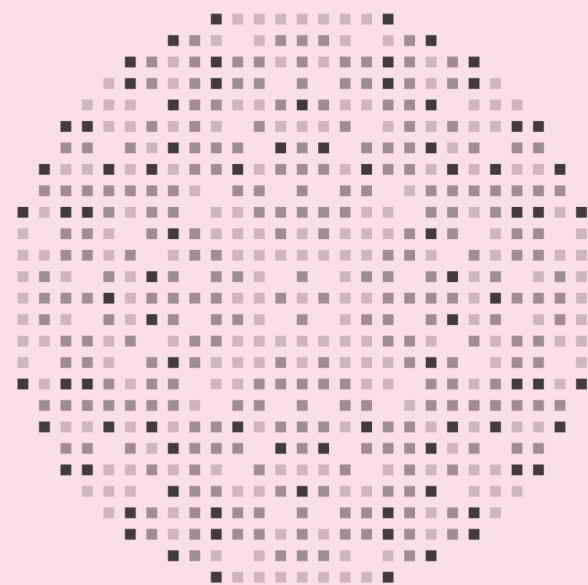
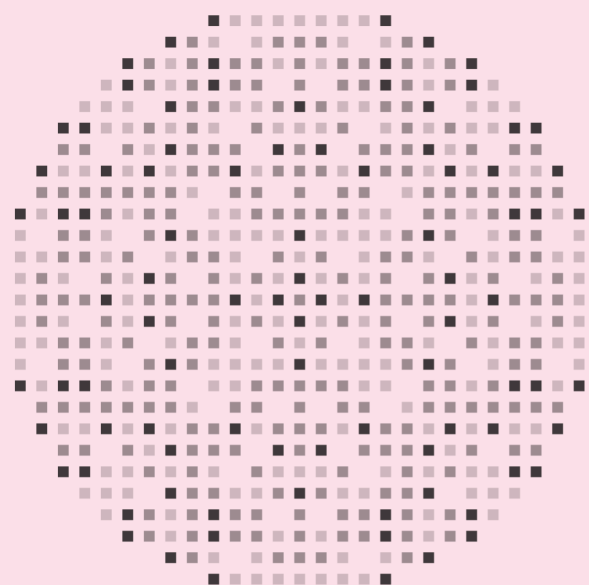
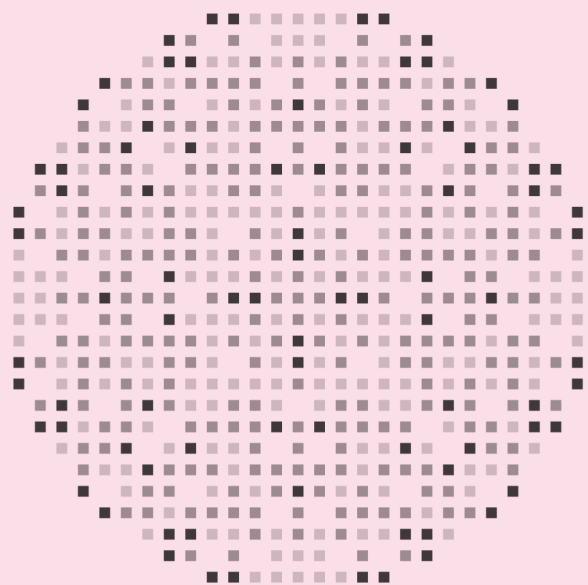
There isn’t usually one. Sure, there was a proverbial straw, an ultimate shove... (Think of the weight of the last grain of sand!) But rather than blaming that for the collapse, I had to recognize the compound effect from multiple tiny irregularities within the layers, imperceptible imbalances of the form and the uneven distribution of moisture throughout the material. On a microscopic level, I probably would be able to see actual clay particles forming clusters and gaps of various sizes. Similar critical state scenarios may happen during drying when moisture leaves clay or during the firing

when the crystalline transformation happens and clay changes from mud to glass. Things may look uneventful for a while, until the critical state emerges and a crack forms. I really enjoyed discovering that there was a scientific way of thinking about all this.

<sup>35</sup> These subsets looked like pizza slices. Eli wrote about the mathematical aspects of this discovery in his thesis.

<sup>36</sup> Making separate matrices for distributions of cells with equal height of sand.

<sup>37</sup> *Plateaus* is a vaguely landscape-like interactive piece, set up as an actual game board with several different types of forms, which may be moved and stacked on one another.



## More on 3D Printing

<sup>01</sup> Here are a few:  
Craftcloud [www.craftcloud3d.com/](http://www.craftcloud3d.com/)  
Shapeways [www.shapeways.com/](http://www.shapeways.com/)  
Sculpteo [www.sculpteo.com/](http://www.sculpteo.com/)  
i.materialise [i.materialise.com/en](http://i.materialise.com/en)  
Stratasys Direct [www.stratasysdirect.com/](http://www.stratasysdirect.com/)

<sup>02</sup> Sintering is a process of fusing powder into a solid material by the application of high heat. Sintering causes the powder to compact and solidify without melting first (without going through a liquid state). The ceramic process of firing in the kiln is a form of sinter. Other forms of sintering may use laser, current and pressure.

<sup>03</sup> Most often, these are used in medical and aerospace industries.

<sup>04</sup> Vitrification makes the ceramic material somewhat similar to glass. It makes clay more dense, gives it structural strength and an ability to hold water.

**TYPES OF 3D PRINTERS** Types of 3D printers constantly change; no listing or classification of them is exhaustive or would stay meaningful for a long time. While many are widely available and quite easy to get started on, price and ease of maintenance can be a big barrier for owning one of the more sophisticated ones. There are professional 3D printing services, either local or worldwide online,<sup>01</sup> where artist and designers may send their files to and have their work produced in a variety of materials. It's important to understand the main differences among the currently existing technologies though, as certain challenging forms may require a particular type of printer, which in turn determines not only the material choice but also surface resolution, structural strength, and even how close your finished object is going to be to the digital rendering on screen.

Material extrusion is the type of printer I use in my work, which has been described previously. This process lets a mass of material through an opening in a controlled manner, either by using heat—as in Fused Deposition Modeling (FDM), also sometimes called Fused Filament Fabrication (FFF)—or by using pressure, as in the various clay extrusion printers that are on the market today.

Vat Polymerization uses a liquid-state photo-polymer resin that is cured by UV light, layer by minute layer. Its various forms are called Stereolithography (SLA) and Direct Light Processing (DLP). It's rather Frankensteinian in appearance, as the form develops upside-down, being pulled out by the platform from a gooey vat under the glowing light. The result is extremely high resolution, with very little surface roughness. There are promising technologies for using ceramic powders mixed with resin in vat polymerization, though the percentage of ceramic material is rather low and

<sup>05</sup> The commonly used term for these programs is CAD (Computer Aided Design).

<sup>06</sup> [www.rhino3d.com/](http://www.rhino3d.com/)

<sup>07</sup> Here is an in-depth explanation of NURBS: [www.rhino3d.com/nurbs](http://www.rhino3d.com/nurbs)

<sup>08</sup> Splines are special functions described piecewise by polynomials. B splines are a special case of Bezier curves. The most important practical thing about B splines is that they can be moved and shaped by dragging their control points, which, when put together, describe a control polygon.

<sup>09</sup> Literally, B splines are infinitely smooth (no bumps, breaks or corners) and can be combined together.

the resulting object needs to be sintered.<sup>02</sup>

There are various printers that use some type of raw material in a powder form laid out in a thick bed. These are called Powder Bed Fusion or Binder Jet (BJ) processes. In Powder Bed Fusion (PBF), a thermal energy source creates a solid object by selectively inducing fusion between powder particles. Depending on the specific process, the types are called Selective Laser Sintering (SLS); Metal Powder Bed Fusion (MPBF); or, when a current is used instead of heat, Electron Beam Melting (EBM). Binder Jetting (BJ) is a 3D printing process where a liquid bonding agent or catalyst is selectively dispensed and binds the regions of a powder bed.

Binder Jetting with ceramic powder is the second most common form of ceramic 3D printing, one that results in typically small-scale but extremely precisely formed objects.<sup>03</sup> The really interesting physical properties of clay—commonly seen in extrusion printing—don't tend to play a role in the resulting object. The finished piece is exceptionally consistent with the digital rendering, making it a reliable option for industrial production. However, just like after vat polymerization, the BJ-printed object still needs to go through a sintering process in order to become VITREOUS.<sup>04</sup>

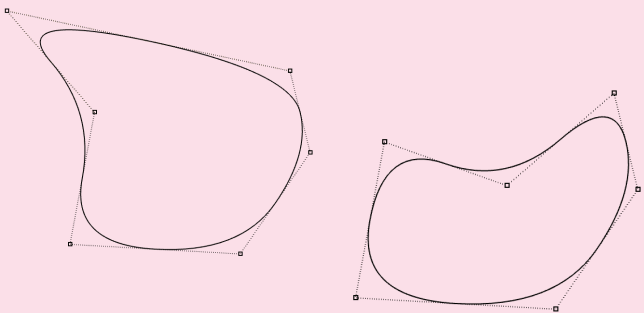
Finally, the most recently developed technique is Material Jetting (MJ) or Drop on Demand (DOD). During Material Jetting, droplets of material, usually a photo sensitive resin or wax, are selectively deposited and cured on a build plate. The result has extremely fine detail and a great consistency with the design, with the added bonus of selective application of color.

<sup>10</sup> Imagine drawing a line by wrangling a set of fishing poles that have a rope tethered to them. You can only move the rods, which in turn will affect the overall shape of the line but you cannot directly manipulate the rope itself.



WORKFLOW AND TYPES OF SOFTWARE FOR 3D PRINTING

Describing the sophisticated math inside of currently used 3D modeling programs <sup>05</sup> goes beyond my expertise and the pages of this book. However, it is important for a learner to distinguish a few basic types processes and the software dedicated to these when designing, refining and preparing printable 3dimensional forms. Perhaps the most commonly used professional software is Rhinoceros <sup>06</sup> by Robert McNeel & Associates. At the time of this writing, I'm using Rhinoceros (or, affectionately, Rhino) version 6. Rhino is based on using NURBS (Non-Uniform Rational B-Splines), which are “mathematical representations of 3-D geometry that can accurately describe any shape” including free-form curves. <sup>07</sup> NURBS, which are a special case of B spline, <sup>08</sup> are sort of omnipotent and ubiquitous in the world of digital 3D. Computationally efficient and extremely precise, they are also used in most computer graphic and animation programs. They are smooth operators! <sup>09</sup> However, NURBS may not always be user friendly for the beginner. <sup>10</sup>



In addition, NURBS are based on computation, <sup>11</sup> resulting in a form, which, while it seems rendered on a screen, may not be of a VALID object. <sup>12</sup> There are possible instances of combining surfaces when the computation does not return a legal value, and parts of the form could not be joined or closed watertight. Fixes and work-arounds exist for all of these problems, but proceeding mindfully during the design process with some understanding and appreciation of the math involved can save you a lot of head-scratching later.

The other widely accessible software type is made by Autodesk, <sup>13</sup> which currently offers AutoCAD, 3DS MAX, Revit, Maya, Fusion 360 and other valuable programs aimed across the board for various 3D modeling needs in architecture, engineering, animation and games industries. A beginner user would probably most likely to encounter Fusion 360, a wonderfully intuitive modeling and sculpting environment, which uses T splines. <sup>14</sup> T splines are based on a reduced number of control points and allow an easier merge of surfaces. T splines don't reach the accuracy of B splines and may not produce the desired smoothness. <sup>15</sup> Ceramic extrusion printing, though, is unlikely to need such precision and detail. Most beginner students prefer the Autodesk interface, which consists of a single viewport, context-sensitive pop-up menus and a sculpt function for free-form modeling. On the other hand, I've watched quite a few students eventually grow frustrated with the degree of flexibility in the sculpting environment. It is easy to turn a surface inside out by pushing and pulling, again leading to a virtual form that appears intriguing on the preview screen but quite impossible to turn into anything tangible.

Software based on PARAMETRIC DESIGN <sup>16</sup> allows retroactive manipulation. Most of the Autodesk products

<sup>11</sup> Computation interpolates points in order to calculate the curvature and smoothness of a curve.

<sup>12</sup> Valid objects are closed meshes. They are WATER-TIGHT, meaning that each seam is zipped together.

<sup>13</sup> [www.autodesk.com/](http://www.autodesk.com/)

<sup>14</sup> T spline is associated with a quad polygon mesh, which responds to shaping by selecting the desired edges and transforming the overall shape by pushing/pulling these.

<sup>15</sup> For example, circles always stay polygons.

<sup>16</sup> Parametric design uses parameters (variables) that can be edited with a great degree of freedom, thus manipulating the end result. In parametric design, the interconnected geometry of the parts forms a hierarchical structure. Changing one variable will affect aspects of the shape further up in the design chain without having to go back to redraw the connected parts.

<sup>17</sup> [www.solidworks.com/](http://www.solidworks.com/)

<sup>18</sup> Grasshopper was created by David Rutten at Robert McNeel & Associates. [www.grasshopper3d.com/](http://www.grasshopper3d.com/)

<sup>19</sup> Look around in any city! Contemporary architecture is unimaginable without this powerful critter.

<sup>20</sup> Even print settings can be inputted into Grasshopper, by passing the slicer and writing GCODE directly from CAD.

have some parametric features. Solidworks, <sup>17</sup> a preferred tool in industrial design, is a solid modeling program that uses parametric features and is best used for assembly products and functional design intent. The most omnipotent parametric modeling program is Grasshopper 3D, <sup>18</sup> a visual scripting environment embedded into the 3D modeling package Rhinoceros. Grasshopper is primarily used to build flexible generative algorithms, to play with data flows and to fluidly change input values in order to create design iterations. Originally embraced by architects, <sup>19</sup> Grasshopper is becoming one of the most used tools in every area of CAD design. It also integrates with other programming languages, providing another magnificently useful tool for those with advanced coding experience. <sup>20</sup>

The final design state of a printable object looks like a mesh, <sup>21</sup> a closed structural network of polygons representing the surface of the designed form through the combination of vertices, edges and faces. The particulars of creating, calculating and optimizing a mesh is the territory of advanced mathematics. Meshes are a computational splurge, and they are impossible to reverse engineer into editable geometry. Working with a mesh in CAD is a bit of guess work. There is no metric space or accuracy to the design. It is difficult to anticipate the exact outcome. On the other hand, mesh modeling and fixing programs, such as Meshmixer, Meshlab, Cinema 4D, Maya and Blender are crucial in computer graphics, 3D scanning and photogrammetry, <sup>22</sup> and they may also be the last resort in fixing a broken mesh from CAD.

Once the CAD object is finished, it is saved into a file type called STL. <sup>23</sup> An STL file describes the geometry of the object by breaking it into a somewhat unstructured

<sup>21</sup> Imagine the mesh as a stretchy fishnet stocking pulled over the form. It is rather easy to make changes to the fishnet locally by pinching and stretching, stitching together, filling a large opening with smaller ones or slashing through a few small ones to form a larger opening.

<sup>22</sup> An easy and affordable method for 3D scanning using a camera to create a methodical record of photographic information about an object. This visual information is stitched together by an image recognition software, which evaluates each point in relationship to the camera and to its neighbors and renders it on a mesh.

<sup>23</sup> STL stands for stereolithography, recalling the idea of both print making (lithography) and of spatial representation (stereo).

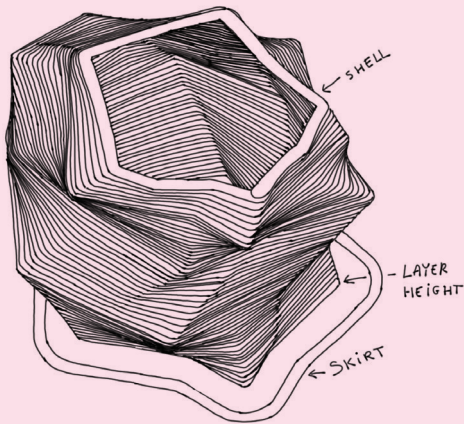
<sup>24</sup> A vector that is perpendicular to each triangular surface and designates the orientation of that.

<sup>25</sup> [ultimaker.com/software/ultimaker-cura](http://ultimaker.com/software/ultimaker-cura)

<sup>26</sup> [www.simplify3d.com/](http://www.simplify3d.com/)

<sup>27</sup> Each pass makes a SHELL.

<sup>28</sup> responsible for building pressure.



SOME LESSONS LEARNED ABOUT WORKING WITH SOFTWARE

KEEP IT SIMPLE, STUPID.

All things of software can get insanely complicated and time consuming rapidly. It may take a while to start feeling confident when learning a new piece of software. I find it rather disheartening to sit over the computer for endless hours, sometimes days, trying yet untested commands or coming up with workarounds for a stubborn CAD problem. Digital art does not have to be a showcase for the latest software update. There is a simple set of commands in Rhino I use regularly and which provide a great amount of versatility. When I need to, I expand on these with the use of a few new commands. Information about each command is freely available through the developer's site along with a discussion forum through which users and developers share questions and solutions. Designing based on what I know works and varying, combining simple geometries is a satisfying process, filled with new discoveries. As Rhino runs on math, each command means another calculation, creating lots of opportunities for alternative workflows en route to the desired outcome. I like approaching each design task through the simplest option, the one that I can reasonably understand and control.

WHEN YOU CAN'T FIX IT, BREAK IT.

Sometimes though, I get frustrated with the software. This is where being an artist helps. I'm free to shift focus or accept the result as a new opportunity. I can explore another path through the workflow, reach for another software or reduce a problem to a solution I'm familiar with already. If I need to, I create a workaround, quick and dirty. *Things don't boolean in CAD?* Smash them together in the slicer. *Pesky holes in the mesh?* Reroute the process through a mesh program and stitch the gaps. *Must generate support in the slicer to make the piece stand?* Make it in parts and assemble or pause the printer and build in clay or foam supports manually. *Getting all kinds of weird toolpaths that are not supposed to print inside of the object?* Printing just the vertical walls onto a premade clay slab might help to debug the slicing.

IN PRAISE OF HACKS

Not knowing the first thing about coding has made me a hacker in some sense. When I first opened a GCODE file, I was pleasantly surprised by the simple logic of it. GCODE consists of sets of instructions and sets of Cartesian coordinates, which serve as destination addresses for the printer. Writing GCODE is as easy as using an etch-asketch. Editing existing GCODE is the most blatant and fun hack that I regularly practice. I made the *ListeningCups* by pausing the printer at select coordinates and designed a Python code, called the *Pathfinder*, which serves to reroute the printer to one of four possible destinations around the original coordinate point. Open a GCODE file and change some of the X and Y values and see what happens. I usually learn a lot from trying out silly ideas.

CHOOSING THE RIGHT WORKFLOW

I'm going to say it again: Not all programs are created equal. Each has their particular method of translating geometry into mathematical functions, and each has different tolerances, restrictions and freedoms. There are also applications, stand-alone or plug-in, that are coming to the market nearly every day. These are pieces of code with a user-friendly interface, which will streamline a certain task or simplify a tedious workflow. They are worth trying as they may be useful or at least a time-saver. But the more accessible these software tools are, the more opaque their workflow is. I worry that being overly reliant on these new apps and plugins risks creating objects which will lack diversity and personality. For my own practice, digital craft means exploring each and every part of the digital-to-material workflow to get a deeper understanding of how it works and where opportunities within the process may arise. It also means making room for simple ideas where I can try things out, without prejudging the outcome. I fail often, but I also trust that I will always find something to be learned from each failure. And while doing that, the next exciting idea will gleam at me.

2818	G1 X46.486 Y-12.223 Z4.681 E53.2878
2816	G1 X45.848 Y-13.985 Z4.669 E50.1059
2814	G1 X44.292 Y-17.456 Z4.645 E43.6475
2813	G1 X45.117 Y-15.732 Z4.657 E46.8911
2812	G1 X42.366 Y-19.807 Z4.621 E37.0856
2811	G1 X40.093 Y-23.981 Z4.597 E30.4529
2809	G1 X38.830 Y-25.485 Z4.585 E27.1199
2808	G1 X37.491 Y-26.924 Z4.573 E23.7817
2807	G1 X36.079 Y-28.294 Z4.560 E20.4427
2806	G1 X34.601 Y-29.588 Z4.548 E17.1073
2805	G1 X33.062 Y-30.802 Z4.536 E13.7792
2804	G1 X31.470 Y-31.933 Z4.524 E10.4636
2803	G1 X29.830 Y-32.976 Z4.512 E7.1640
2802	G1 X28.150 Y-33.930 Z4.500 E3.8854 F2100
2801	G2 E0
2799	; outer perimeter
2798	G1 X25.875 Y-33.680 Z4.488 E397.7383
2797	G1 X24.145 Y-34.442 Z4.476 E394.5289
2796	G1 X22.397 Y-35.109 Z4.464 E391.3520
2795	G1 X20.637 Y-35.682 Z4.452 E388.2106
2794	G1 X18.874 Y-36.161 Z4.441 E385.1005
2793	G1 X17.113 Y-36.548 Z4.429 E382.0482
2792	G1 X15.362 Y-36.846 Z4.418 E379.0323
2791	G1 X13.627 Y-37.057 Z4.406 E376.0633
2790	G1 X11.814 Y-37.189 Z4.395 E372.9786
2789	G1 X9.997 Y-37.234 Z4.386 E369.8935
2788	G1 X8.661 Y-37.210 Z4.375 E367.6255
2787	G1 X6.903 Y-37.105 Z4.363 E364.6358
2786	G1 X5.108 Y-36.911 Z4.352 E361.5712
2785	G1 X3.311 Y-36.628 Z4.341 E358.4826
2784	G1 X1.601 Y-36.274 Z4.329 E355.5181
2783	G1 X0.093 Y-35.981 Z4.317 E352.5516
2782	G1 X-1.827 Y-35.305 Z4.306 E349.4679
2781	G1 X-3.532 Y-34.687 Z4.294 E346.3891
2780	G1 X-5.223 Y-33.980 Z4.282 E343.2785
2779	G1 X-6.891 Y-33.182 Z4.270 E340.1394
2778	G1 X-8.530 Y-32.295 Z4.258 E336.9758
2777	G1 X-10.133 Y-31.321 Z4.246 E333.7903
2776	G1 X-11.694 Y-30.261 Z4.234 E330.5882
2775	G1 X-13.205 Y-29.118 Z4.222 E327.3170
2774	G1 X-14.660 Y-27.897 Z4.210 E324.1472
2773	G1 X-16.052 Y-26.601 Z4.198 E320.9173
2772	G1 X-17.378 Y-25.235 Z4.185 E317.6859
2771	G1 X-18.630 Y-23.805 Z4.173 E314.4587
2770	G1 X-19.805 Y-22.316 Z4.161 E311.2384
2769	G1 X-20.899 Y-20.775 Z4.149 E308.0301
2768	G1 X-21.909 Y-19.188 Z4.137 E304.8373
2767	G1 X-22.861 Y-17.563 Z4.125 E301.6649
2766	G1 X-23.680 Y-15.875 Z4.113 E298.4566
2765	G1 X-24.442 Y-14.145 Z4.101 E295.2492
2764	G1 X-25.109 Y-12.397 Z4.089 E292.0723
2763	G1 X-25.682 Y-10.637 Z4.077 E288.9309
2762	G1 X-26.161 Y-8.874 Z4.066 E285.8288
2761	G1 X-26.548 Y-7.113 Z4.054 E282.7526
2760	G1 X-26.846 Y-5.362 Z4.043 E279.7526
2759	G1 X-27.057 Y-3.627 Z4.031 E276.7856
2758	G1 X-27.189 Y-1.814 Z4.020 E273.6989
2757	G1 X-27.234 Y0.003 Z4.011 E270.6138
2756	G1 X-27.105 Y3.097 Z3.988 E265.3561
2755	G1 X-27.105 Y3.097 Z3.988 E265.3561
2754	G1 X-26.911 Y4.892 Z3.977 E262.2915
2753	G1 X-26.628 Y6.689 Z3.966 E259.2029
2752	G1 X-26.274 Y8.399 Z3.954 E256.2284
2751	G1 X-25.834 Y10.114 Z3.943 E253.2319
2750	G1 X-25.305 Y11.827 Z3.931 E250.1882
2749	G1 X-24.748 Y13.532 Z3.919 E247.1094
2748	G1 X-24.168 Y15.235 Z3.907 E243.9988
2747	G1 X-23.182 Y16.891 Z3.895 E240.8597
2746	G1 X-22.295 Y18.530 Z3.883 E237.6961
2745	G1 X-21.321 Y20.133 Z3.871 E234.5105
2744	G1 X-20.261 Y21.694 Z3.859 E231.3085
2743	G1 X-19.118 Y23.205 Z3.847 E228.0923
2742	G1 X-17.897 Y24.660 Z3.835 E224.8675
2741	G1 X-16.601 Y26.052 Z3.823 E221.6376
2740	G1 X-15.235 Y27.378 Z3.810 E218.4062
2739	G1 X-13.805 Y28.630 Z3.798 E215.1790
2738	G1 X-12.316 Y29.805 Z3.786 E211.9587
2737	G1 X-10.775 Y30.899 Z3.774 E208.7504
2736	G1 X-9.188 Y31.909 Z3.762 E205.5576
2735	G1 X-7.563 Y32.831 Z3.750 E202.3852
2734	G1 X-5.875 Y33.680 Z3.738 E199.1789
2733	G1 X-4.145 Y34.442 Z3.726 E195.9695
2732	G1 X-2.397 Y35.109 Z3.714 E192.7926
2731	G1 X-0.637 Y35.682 Z3.702 E189.6512
2730	G1 X-1.126 Y36.161 Z3.691 E186.5491
2729	G1 X2.887 Y36.548 Z3.679 E183.4888
2728	G1 X4.638 Y36.846 Z3.668 E180.4729
2727	G1 X6.373 Y37.057 Z3.656 E177.5059
2726	G1 X8.106 Y37.189 Z3.645 E174.4192
2725	G1 X10.003 Y37.224 Z3.636 E171.3341
2724	G1 X11.339 Y37.210 Z3.625 E169.0661
2723	G1 X13.097 Y37.105 Z3.613 E166.0764
2722	G1 X14.892 Y36.911 Z3.602 E163.0118
2721	G1 X16.689 Y36.628 Z3.591 E159.9232
2720	G1 X18.399 Y36.274 Z3.579 E156.9587
2719	G1 X20.114 Y35.854 Z3.568 E153.9522
2718	G1 X21.827 Y35.305 Z3.556 E150.9085
2717	G1 X23.532 Y34.687 Z3.544 E147.8297
2716	G1 X25.223 Y33.980 Z3.532 E144.7191
2715	G1 X26.891 Y33.182 Z3.520 E141.5800
2714	G1 X28.530 Y32.295 Z3.508 E138.4164
2713	G1 X30.133 Y31.321 Z3.496 E135.2308
2712	G1 X31.694 Y30.261 Z3.484 E132.0288
2711	G1 X33.205 Y29.118 Z3.472 E128.8126
2710	G1 X34.660 Y27.897 Z3.460 E125.5878
2709	G1 X36.052 Y26.601 Z3.448 E122.3578
2708	G1 X37.378 Y25.235 Z3.435 E119.1264
2707	G1 X38.630 Y23.805 Z3.423 E115.9893
2706	G1 X39.805 Y22.316 Z3.411 E112.6790
2705	G1 X40.899 Y20.775 Z3.399 E109.4707
2704	G1 X41.908 Y19.188 Z3.387 E106.2719
2703	G1 X42.831 Y17.563 Z3.375 E103.1055
2702	G1 X43.680 Y15.875 Z3.363 E99.8992
2701	G1 X44.442 Y14.145 Z3.351 E96.6988
2699	G1 X45.109 Y12.397 Z3.339 E93.5128
2698	G1 X46.161 Y8.874 Z3.316 E87.2694
2697	G1 X46.548 Y7.113 Z3.304 E84.2091
2696	G1 X46.828 Y6.609 Z3.216 E80.6435
2695	G1 X46.911 Y-3.892 Z3.227 E83.7321
2694	G1 X47.105 Y-3.097 Z3.238 E86.7967
2693	G1 X47.210 Y-1.339 Z3.250 E89.7864
2692	G1 X47.234 Y-0.003 Z3.261 E72.0544
2691	G1 X47.189 Y1.814 Z3.270 E75.1395
2690	G1 X47.057 Y3.627 Z3.281 E78.2262
2689	G1 X46.846 Y5.362 Z3.293 E81.1932
2688	G1 X46.274 Y-8.389 Z3.284 E57.6790
2687	G1 X45.834 Y-10.114 Z3.193 E54.6725
2686	G1 X44.660 Y-12.323 Z2.988 E288.3650
2685	G1 X43.997 Y-35.935 Z2.886 E261.8929
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2683	G1 X43.502 Y-35.912 Z2.895 E264.7792
2682	G1 X43.502 Y-35.912 Z2.895 E264.7792
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2657	G1 X43.502 Y-35.912 Z2.895 E264.7792
2656	G1 X43.502 Y-35.912 Z2.895 E264.7792
2655	G1 X43.502 Y-35.912 Z2.895 E264.7792
2654	G1 X43.502 Y-35.912 Z2.895 E264.7792
2653	G1 X43.502 Y-35.912 Z2.895 E264.7792
2652	G1 X43.502 Y-35.912 Z2.895 E264.7792
2651	G1 X43.502 Y-35.912 Z2.895 E264.7792
2650	G1 X43.502 Y-35.912 Z2.895 E264.7792
2649	G1 X43.502 Y-35.912 Z2.895 E264.7792
2648	G1 X43.502 Y-35.912 Z2.895 E264.7792
2647	G1 X43.502 Y-35.912 Z2.895 E264.7792
2646	G1 X43.502 Y-35.912 Z2.895 E264.7792
2645	G1 X43.502 Y-35.912 Z2.895 E264.7792
2644	G1 X43.502 Y-35.912 Z2.895 E264.7792
2643	G1 X43.502 Y-35.912 Z2.895 E264.7792
2642	G1 X43.502 Y-35.912 Z2.895 E264.7792
2641	G1 X43.502 Y-35.912 Z2.895 E264.7792
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2606	G1 X43.502 Y-35.912 Z2.895 E264.7792
2605	G1 X43.502 Y-35.912 Z2.895 E264.7792
2604	G1 X43.502 Y-35.912 Z2.895 E264.7792
2603	G1 X43.502 Y-35.912 Z2.895 E264.7792
2602	G1 X43.502 Y-35.912 Z2.895 E264.7792
2601	G1 X43.502 Y-35.912 Z2.895 E264.7792
2600	G1 X43.502 Y-35.912 Z2.895 E264.7792
2599	G1 X43.502 Y-35.912 Z2.895 E264.7792
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2591	G1 X43.502 Y-35.912 Z2.895 E264.7792
2590	G1 X43.502 Y-35.912 Z2.895 E264.7792
2589	G1 X43.502 Y-35.912 Z2.895 E264.7792
2588	G1 X43.502 Y-35.912 Z2.895 E264.7792
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2583	G1 X43.502 Y-35.912 Z2

## Ceramic 3D Printers

3D printing simultaneously references and updates many historical precedents and modes of production. It does that not by taking away the hand, rather by adding new opportunities to the ceramic workflow. The history of ceramics is strongly connected to the history of domestic objects traditionally made not only by hand but by various tools like the potter’s wheel, the lathe, jigs, presses or plaster molds. Iterative processes such as these have allowed making of consistent multiples, which came to be a staple of industry. But ask any production potter: repetition is in the heart of the craft for them too, not just as a way of gaining expertise but also as a time-saving measure and a necessity in the competitive marketplace.

### CERAMIC PASTE EXTRUSION PRINTING: IT TAKES A VILLAGE

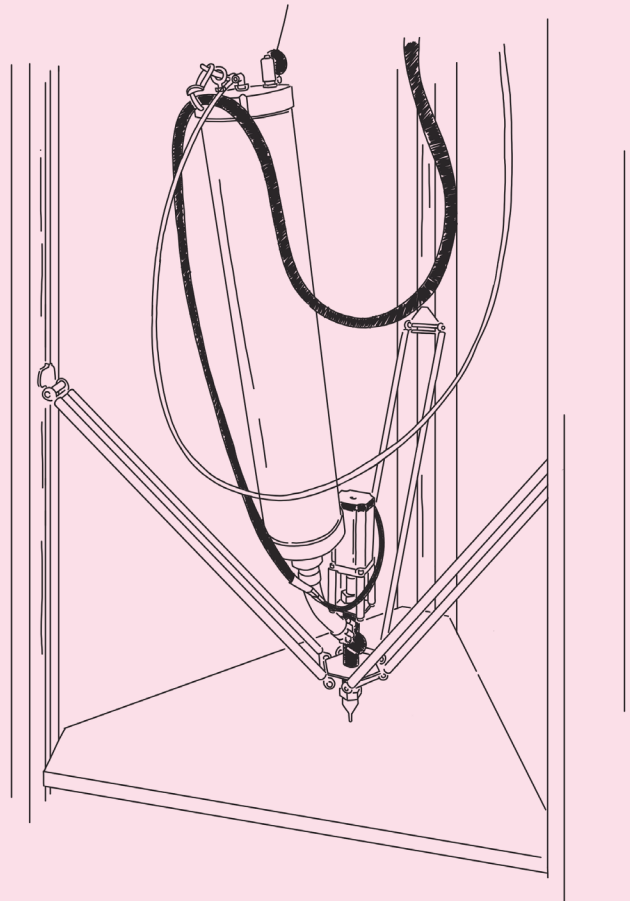
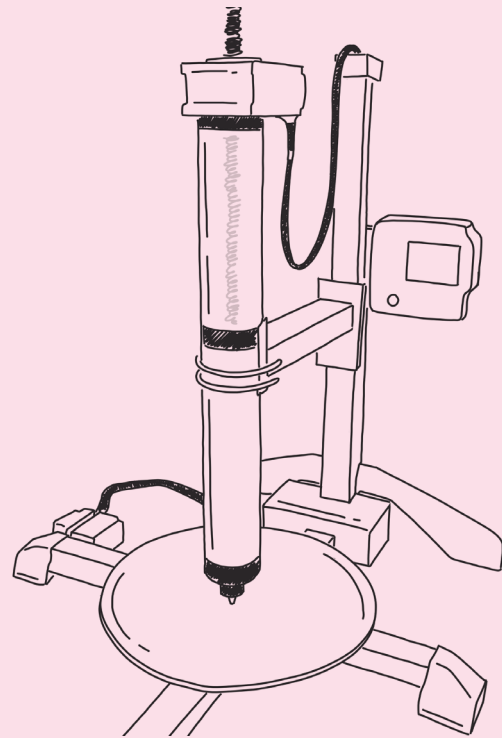
Ceramic paste extrusion printing is a rapidly developing area that is currently finding its way into both art and design practice. Experiments with the process began around 2009 through research initiatives concerning both hardware and software possibilities. Belgian designers Dries Verbruggen and Claire Varnier of Studio Unfold and the British ceramic artist Jonathan Keep were among the first to explore printing with plastic <sup>01</sup> paste ceramic materials and to publicize their research methodology. <sup>02</sup> Olivier van Herpt’s thesis work at the Design Academy Eindhoven in the early 2010’s has elaborated on the utilization of deposition modeling process. Parallel investigations followed rapidly, concentrating around the FabLab of the European Ceramic Workcentre in the Netherlands and at cross-disciplinary research facilities like Ronald Rael’s Emerging Objects at the Berkeley Architecture program. Early experiments around the specific language of plastic printable materials such as concrete; resinous and organic compounds; as well as clay were widely shared among the global community of makers. The introduction of these plastic materials within the automated digital process helped to refocus the dialogue from algorithmic perfection onto the role of imperfection.

At the time of this writing, there are a few small companies <sup>03</sup> who have developed specific types of machines for ceramic printing. These developers function and innovate within a global network of digital makers, whose feedback and workflow, in turn, help to influence the development of new technologies. Ceramic artists Jonathan Keep and Bryan Czibesz, who fabricated their machines from scratch, have also made their machine blueprints available open source.

Makers, developers, artists, engineers, coders, architects and designers form a network forged on a shared interest in using 3D printing differently. This network has demonstrated that artistic projects can help innovate machine technology and vice versa.

<sup>01</sup> Plastic refers to the soft workable quality of wet clay. <sup>02</sup> Jonathan Keep [www.keep-art.co.uk/](http://www.keep-art.co.uk/) has some great resources. Studio Unfold [unfold.be/](http://unfold.be/) has pioneered research in clay printing through many innovative projects and lucid essays. <sup>03</sup> The Italian WASP [www.3dwasp.com/en/ceramic-3d-printing-wasp-clay/](http://www.3dwasp.com/en/ceramic-3d-printing-wasp-clay/); the Dutch Lutum [lutum.vormvrij.nl/](http://lutum.vormvrij.nl/); and the American 3D Potter [3dpotter.com/](http://3dpotter.com/).





#### HOW DO CERAMIC EXTRUSION PRINTERS WORK?

Regardless of the developer, any type of extruder printer consists of a tank, which holds a certain volume of clay under pressure; a build-platform; stepper motors, each of which allows movement on one of the three axes; one additional stepper that is responsible for the extrusion—directly <sup>04</sup> or through an auger system <sup>05</sup>—and a nozzle, which reduces the flow to the desired diameter.

The biggest difference among the functionality of these printers (not counting the obvious size and volume limitations), is the readiness to retract, meaning that when the nozzle disengages, the flow of clay immediately stops. Since each printer model is slightly different, the most exciting consequence of the previous statement is that each machine has its own unique “fingerprint” on the finished object. <sup>06</sup>

I work both with a Delta and a Cartesian printer depending on the specific needs of my project. Cartesian printers owe their name to the Cartesian coordinate system. They have a moving print platform, which tracks on both the X and Y axes, while the Z axis, which holds the extruder, continues to move up. Cartesian printers move quite heavily and they are unable to stop or change direction in an instant. The constant jerking of the platform can jeopardize top-heavy or taller pieces.

Delta printers have a very graceful and agile printhead, which is suspended from three belts. These belts are responsible for triangulating the printhead for each XYZ spatial coordinate point. The build platform is stationary, greatly aiding the stability of the object. However, loading the printer, getting ceramic paste to the printhead and accessing the forming piece during the printing can quite be difficult due to the substantial structure that holds up the belt system.

**LIMITATIONS OF THE TOOL** The what-you-see-is-what-you-get hype of 3D printing is so prevalent that—not surprisingly—it is very common to approach ceramic extrusion printing with little initial consideration for the material. However, it is more helpful to think about the extrusion printer as a nimble and smart clay extruder that is able to follow location directions. While it is possible to get a near-exact object, the most interesting potential is in the unexpected: in the adulterated versions; in the mishaps; and in the chance to take advantage of what this unique material can do best, namely to slump, fold, crack and crease, sometimes elegantly, other times rather dumbly. Clay sticks best to clay, that is one of the most important things to keep in mind. Layers won’t build over a void, and clay will not defy gravity.

<sup>04</sup> Direct extrusion is similar to how a syringe works.

<sup>05</sup> An auger is a rotating helical shaft that is designed to remove (in case of a drill bit) or push down (like a meat grinder) material through a hole.

<sup>06</sup> This fingerprint is evident in traces of pressure changes, air bubbles, interruptions from starting and exit points, remnants of “blind toolpaths”, etc. Blind toolpaths are paths through which the printhead must travel but does not intend to print.



## The Ceramic Process

### THERE IS CLAY. AND THERE IS PORCELAIN.

Ceramics has a rich tradition enmeshed in a hands-on form of play: forming the material by the slightest interaction with the hand or with another object; or by gravity, centrifugal forces and pressure. Clay, as a material, is appreciated for its responsiveness: being both malleable and available. Objects made of clay are a comfortable, non-precious and often-touched part of our everyday environments in the form of dishes, containers, basins, and other types of vessels.

Clay also comes in a form that is historically associated with rarity, secret alchemy <sup>01</sup> and preciousness. Her name is PORCELAIN. Thought to originate from the Han Dynasty <sup>02</sup> and fully developed by the Song dynasty potters, Chinese objects made of porcelain were traded with Europe from the 17th century, where they were desired, collected and treasured. More expensive than gold, porcelain became the object of an obsessive quest <sup>03</sup> in the early 18th century Prussian and French courts, driving a frenzy of R&D. While the process of working with porcelain spread and continued to be refined throughout East Asia mostly through small workshops, European innovations were mostly centered around large-scale factories, where ornamentation, decoration, and sculptural techniques developed. From these diverse roots, porcelain has made its way into the studio ceramics of today. <sup>04</sup>

I work with porcelain almost exclusively. I simply love the stark white unadorned nature of the fired material; its reluctance to conform and respond obediently; <sup>05</sup> its associations with both high and low; <sup>06</sup> and because I am fascinated with its convoluted, dramatic history.

Porcelain’s main component, kaolin, is an especially pure form of decomposed granite rock. Aged in the ground under special circumstances, long enough to be cleansed from any iron, manganese and other metallic residues, kaolin is exceptionally white. By itself, kaolin has a large particle size, and it’s not plastic at all. In order to be usable and have the desired fired qualities, it requires a few more ingredients such as ball clay, silica and feldspars. <sup>07</sup> Bone china, in the mature fired form, is similar to porcelain, but it has different ingredients and compositional ratios. <sup>08</sup> When fired, it is bewitchingly translucent but stubbornly rigid and unyielding as a material to work with. Plastic porcelain feels smooth and sensual, but it still poses many challenges in every stage of the making process. It is sensitive to sudden changes of moisture, not at all forgiving when manipulated, warps when and where it pleases, and has a high rate of shrinkage. <sup>09</sup> I have to build a relationship with the material every time I change to a new type of porcelain: testing, repeating and learning from my own mistakes.

<sup>01</sup> More about this fascinating history involving blood, murder and treachery in this book: Gleeson, Janet. *The Arcanum: The Extraordinary True Story*. New York, NY: Warner Books, 1999.

<sup>02</sup> The Han Dynasty existed 206 BC–220 AD. The Song Dynasty began in 960 AD and lasted until 1279. Kaolin is also commonly called China clay.

<sup>03</sup> Royal alchemists sacrificed not only their careers but literally their own lives while trying to recreate the secret formula for porcelain using locally mined materials.

<sup>04</sup> British potter David Leach’s work and writing are thought to be pivotal in this. His technical book on pottery making has defined clay art for generations. Leach, Bernard. *A Potter’s Book*. New York: Transatlantic Arts, 1976.

<sup>05</sup> No matter what technique is used for giving it form, porcelain has to be cajoled, beguiled and patiently coaxed.

<sup>06</sup> The “high” here refers to fine tableware and “low” refers to sanitary receptacles, from chamber pots to contemporary sinks and toilets.

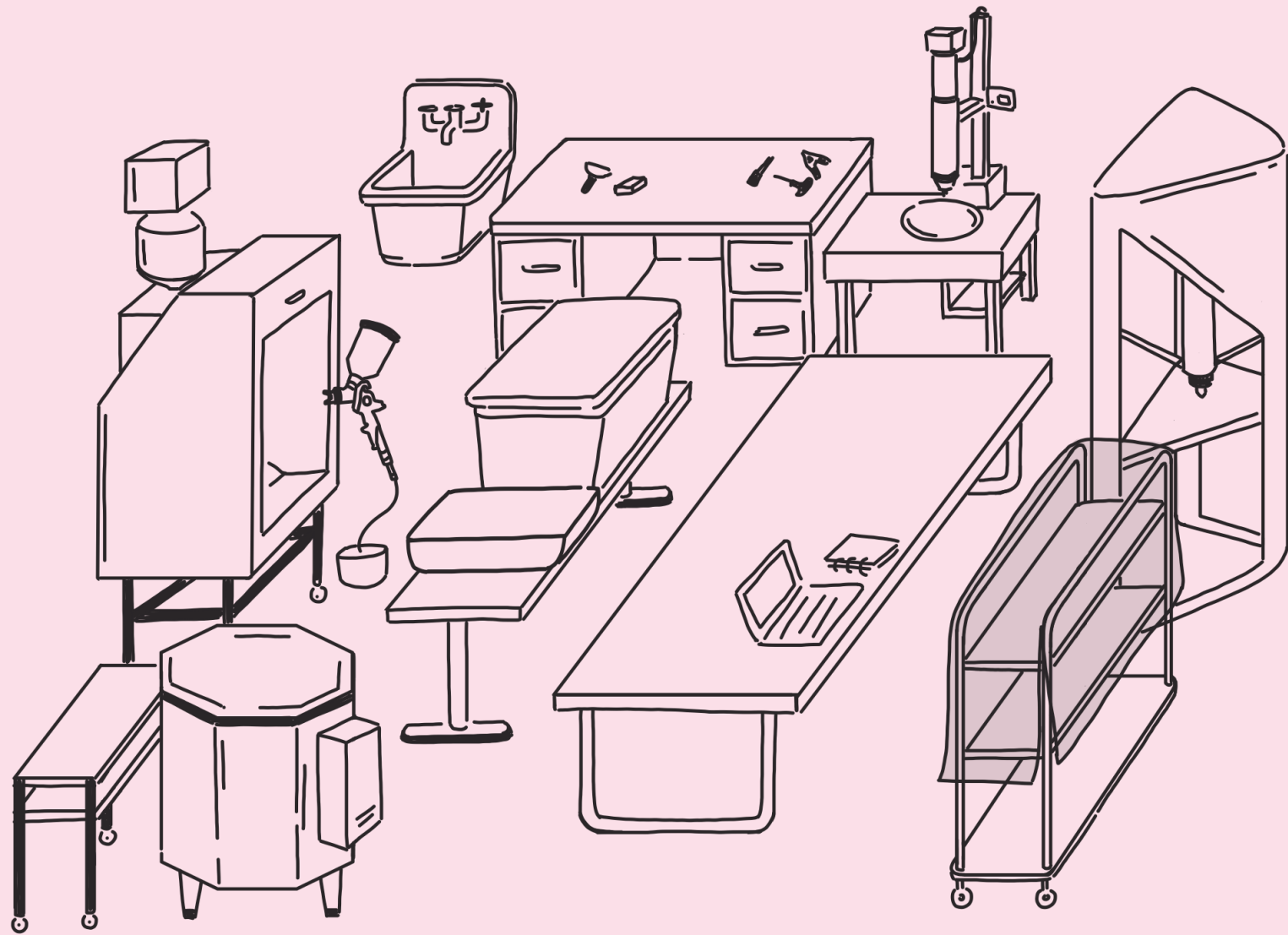
<sup>07</sup> Ball clays are carried from their original source by weathering and erosion. As a result, they are very fine in particle size, making the porcelain mixture more plastic but at the same time, increasing its shrinkage quite a lot. Silica (quartz or flint) is responsible for glass forming and increasing hardness and strength. Feldspars are also glass forming ingredients, but they are also fluxes,

decreasing the temperature at which porcelain matures and increasing its translucency.

More about these materials: Whyman, Caroline. Porcelain. *Complete Potter*. Philadelphia: University of Pennsylvania Press, 1994.

<sup>08</sup> Invented in 18th century Britain for industrial production, bone china has bone ash, feldspars and china clay. It is fired to a slightly lower (1250°C or 2282°F) temperature than porcelain.

<sup>09</sup> Ratio of size change from wet to dry and fired forms. This is a very important data to keep in mind for aspiring designers. The size of the finished object is somewhere between 10-13% smaller than the one printed. The shrinkage is very rarely uniform, expect to see variations as well as some warping.



## PORCELAIN IN THE INDUSTRY AND IN THE STUDIO

Industry has developed many processes and methods <sup>10</sup> specifically addressing the challenges of working with various types of porcelains. Factories and manufactures in any part of the world I have visited, from rural Wisconsin (Kohler Co.) to Arita, Japan to Stoke-on-Trent <sup>11</sup> in England, not only spent great energy on formulating the right blend of ingredients but also amassed a wealth of techniques and tricks for taming this temperamental material and bending it to their will. Industry's goal is, of course, focused on reliability and efficiency during mass production.

I have learned a great deal from watching the artisan workers in these factories. It is clear that studio ceramics as an art form has greatly benefited from industrial techniques for centuries, and artists, in return, have influenced the design ideas of manufacturing.

This mutual relationship between industry and the studio potter now extends to include 3D printing. Surprisingly though, the first 3D printed industrial products were those initiated in architecture and construction, using paste extrusion printing for the making of architectural objects and spaces, such as adobe and concrete dwellings, bricks and cladding. <sup>12</sup>

As it is at the moment, ceramic paste extrusion printing is still a research tool, one with novel outcomes that are difficult to standardize or make cost-effective in the industry. But it is also one with a great promise for artistic and design innovations.

**STUDIO EQUIPMENT** Outside of a printer and a computer, there is very little other equipment needed for the minimalist digital ceramist. At Slip Rabbit, we divided the studio into three main ceramic areas based on health and safety procedures and further sectioned each of those areas to be dedicated toward a particular task. <sup>13</sup>

In addition to these, non-clay work and computers have their own tables, and the studio also has a generous industrial sink and a floor drain for cleaning up.

I use tents <sup>14</sup> and plastic boxes for drying and for keeping things wet longer. These simple pieces of equipment are very effective for controlling the speed by which each piece dries and preventing cracks.

I apply glaze with a spray-gun that is being run by an air compressor. The only health-safe way of using this is in a spray booth equipped with proper ventilation.

And finally, a well-ventilated ceramic kiln <sup>15</sup> is necessary for turning the dried clay object into a vitreous ceramic piece or into brittle, but structurally sound, bisque ware. <sup>16</sup>

<sup>10</sup> There are tools, such as jigs and molds as well as techniques, such as those for drying, assembling and firing.

<sup>11</sup> Home of Staffordshire and Spode, one of the first European factories to crack the mysteries of porcelain. Though they have done that by inventing a completely new mixture for the clay body: bone china.

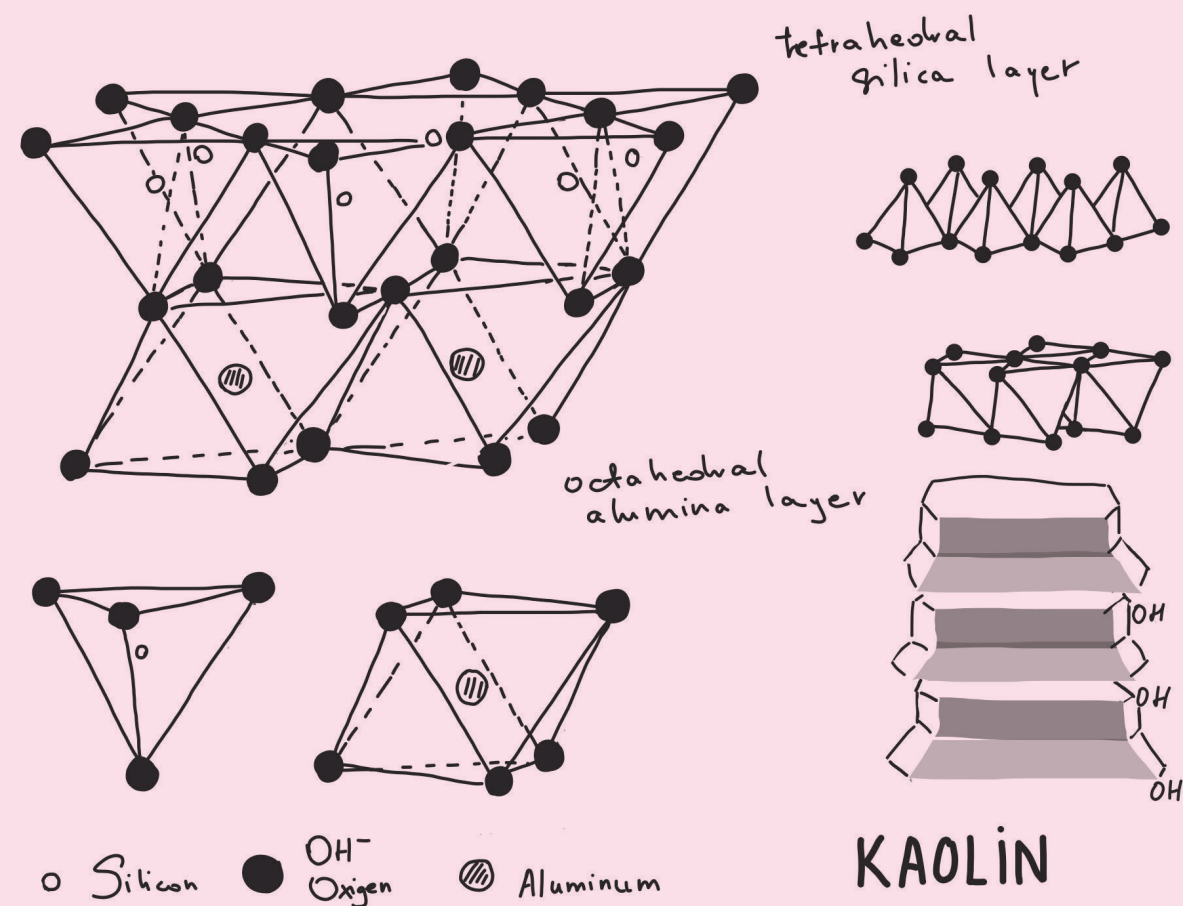
<sup>12</sup> One of the most interesting of these concept experiments is Fossilized by the London-based group Amalgamma. [www.amalgamma.org/](http://www.amalgamma.org/)

<sup>13</sup> The three main areas are: For clay, we have designated tables for the printers, a work bench for clay preparation, and a very large table for post-printing work and hand-building. The glaze area includes spaces for glaze preparation and application, and the firing area has the kilns, vents and racks for kiln furniture. We have storage areas for green, bisque and finished work everywhere else.

<sup>14</sup> These can be made from plastic or from paper constructed on some kind of scaffolding, which prevents the sides of the tent from touching the clay object's surface.

<sup>15</sup> In the US, for most small studios, this is most likely to be an electrical kiln, preferably one with ventilation to the outside.

<sup>16</sup> Bisque or biscuit ware is a term for clay objects which have been heated to around 1800-1900°F (985°C and above) where the clay body goes through irreversible structural changes, which make it suitable for handling. Midrange clays mature (vitrify) around 2150-60°F or 1180°C; high-firing clays mature at 2340-2372°F or 1280-1300°C.



**CLAY PREPARATION** Plastic clays <sup>17</sup> from the manufacturer require preparation as they are typically too hard for ceramic printers to extrude through the small opening of the nozzle. I use a mid-range Grolleg porcelain, which strikes a good balance between my expectations for the desired aesthetic effect and the workability of the material. The chosen ceramic process dictates expectations for choosing the right type of clay body; among other properties, plasticity, shrinkage, dry strength, maturation temperature and tendency to warp or slump are important to consider when planning a new form or exploring a new process.

In ceramic 3D printing, there is a lot of freedom to experiment with the material itself. Mixing clay from scratch, blending in various other ceramic and non-ceramic materials or bringing together different types of clay bodies are not only possible but would be exceptionally fruitful areas for further experimentation. <sup>18</sup> I've done a considerable amount of work using pigmented clay bodies. I found that the color distribution is difficult to control and the pigments change the physical properties of the clay body, making it more brittle. Certain pigments burn out during higher temperatures in the firing; others may lower the melting point and create surprises. Pigments are expensive and require care to be used in a health- and safety-conscious way in a communal studio environment.

Always consult the Safety Data Sheet (SDS) for information on handling, storing and disposing of any ceramic materials, especially, pigments. Test in small batches, wear appropriate safety equipment and protect your kiln furniture. <sup>19</sup>

At Slip Rabbit, we slice the bagged plastic clay from the ceramic company into finger-width thick slices and roll the slices in wet towels. The bundles go into a plastic tote box where they will start to rehydrate.

After a few days in the box, I WEDGE <sup>20</sup> the clay thoroughly, and I will repeatedly do so every couple of days. The more it is wedged, the more pliable and uniform the clay body is going to get. After wedging, I make approximately 5lbs loaves, which will be wrapped in wet towels again and can stay in the box for several weeks. I check the clay between my fingers for moisture content every so often. If it feels too stiff, I saturate the towels with more water. If the clay feels mushy, I wring the towels out. The final consistency of the clay depends on the diameter of the nozzle and on the type of printer I intend to use that day. <sup>21</sup> For printers with especially small diameter tubing systems or nozzles, it is appropriate to experiment with adding 91% isopropyl alcohol during the last wedging. The expectation is that the alcohol evaporates fast, allowing the material to be thin enough to pass through the narrow path but to firm up swiftly during printing. In my experience, this is more wishful thinking than truth. The consistency of clay prepared with alcohol is generally more brittle and "short," more prone to failure than clay prepared solely with proper rehydration and lots of patient kneading.

When the consistency is right, de-aired clay is tightly packed into the printer's cartridge tube either by hand, by a traditional clay extruder or by a pug mill. <sup>22</sup> It is especially important to pay attention to this part of the process as not to trap any small or large air pockets in the tube with the clay. Trapped air bursting through the nozzle will be loud enough to make people drop what's in their hands, but it

<sup>17</sup> In the US, plastic clay is sold in 25lbs bags. For purchasing, find your closest regional ceramic supplier.

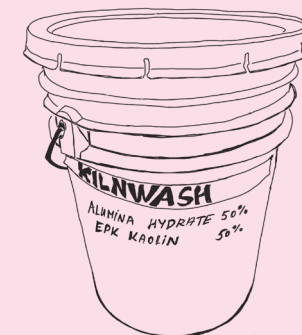
<sup>18</sup> An interesting example for various makers from around the world printing the same files with their local clays and printer settings is the *Stratigraphic Manufactory* project (2012) by the Antwerp-based Studio Unfold. [unfold.be/pages/stratigraphic-manufactory](http://unfold.be/pages/stratigraphic-manufactory)

<sup>19</sup> By covering shelves with kiln wash, using setters and saggars.

<sup>20</sup> Wedging is a process of kneading (similar to that of making pizza dough), which rolls up the clay into a tight spiral while squeezing out air bubbles, working in the sticky outside and breaking up hard clusters of dry materials.

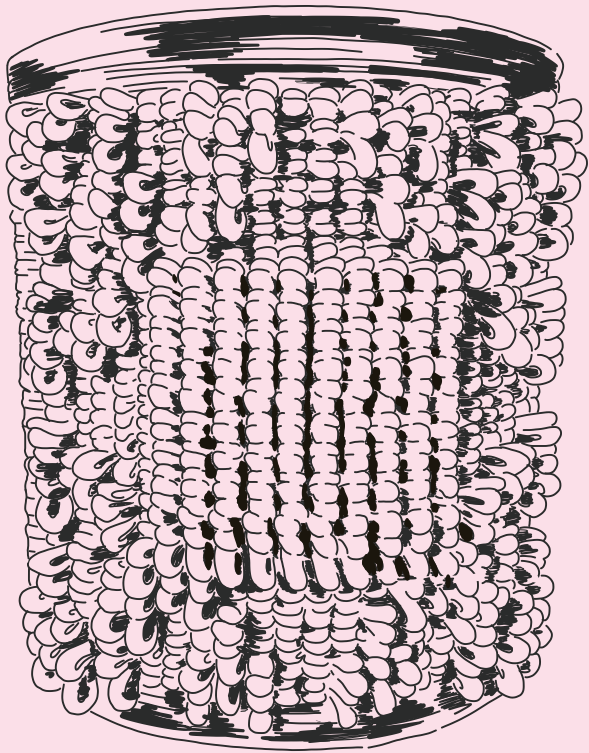
<sup>21</sup> At Slip Rabbit, we use two different printers: Our main workhorse printer is a Potterbot 7 extrusion printer made by 3D Potter. The Potterbot has a CARTESIAN system, with rigid rails for the XYZ axes, which make the platform move and the nozzle stay fixed. It is constructed with the clay cartridge placed above the nozzle, its content directly compressed down by the stepper motor. The result is a continuous extrusion and considerable limitations on retraction.

Our newer printer is a WASP 40100 for clay made by WASP, Italy. It is a DELTA printer with a fixed platform and a printhead that is being suspended from three independently moving arms. Deltas move extremely fast by default, which is not necessary an advantage in ceramic printing as the quality of the print tends to get less refined. As a result of higher speed, there is less time available for the clay coil to extrude and deposit at the precise location. The WASP works with an auger, which has the clay cartridge connected via a narrow hose system, necessitating the use of much softer clay.





can also jeopardize the structural integrity of a larger or trickier piece by shooting a bullet hole through it. Depending on the volume of the trapped air, there is also a duration without proper clay pressure following the blast. As the end result of the process speaks entirely through the language of clay in 3D printed ceramics, often it can be quite difficult to distinguish intentional and unintentional textures. The irregular blips from smaller air pops create an organic texture, which I enjoy a lot. They register the story of making the piece and add material quality to the otherwise uniformly striated walls. My most recent work, *Golden Means* is focused on exploring various ways of mark/texture making uniting various slips of data, code, CAD, machine and material into a unified surface.



<sup>22</sup> Both can be easily outfitted with a custom coupler that locks the tube in place. A pug mill is a power tool, able to efficiently reconstitute, mix and de-air large quantities of clay.

<sup>23</sup> This information contains the printer’s build volume (measurements on XYZ of the available work space), firmware configuration, Baud rate (speed of data), extrusion multiplier (flow rate or how much material is passing through the printhead), printing speed, retraction speed, and scripts. Once you have the printer profile right, you may never need to touch it, unless something is majorly off with your prints.

<sup>24</sup> “Exitus ācta probat.” The results justify the means.

**PRINTING** As part of the documentation of a commercially available 3D printer, a PRINTER PROFILE <sup>23</sup> appropriate to the specific machine is usually made available by the manufacturer. This profile is imported into the slicer and will act as a translator when creating the machine code. I tend to make some modifications to the basic printer profile in the slicer quite often, especially for the Delta printer. The adjustments I need to do respond to each specific printing situation: in addition to changing out the nozzle diameter, there may be significant challenges originating from the consistency of clay or the complexity and difficulty of the design. Each new print object requires the checking and changing of the actual PRINT SETTINGS. These include more local variables, such as layer height, infill, top and bottom solid layers, number of shells, and additions like a skirt or a raft. For the 3.5 mm nozzle on the Potterbot, I typically use anywhere between 1-1.2mm layer height, 4.1 extrusion multiplier, one shell, two or three layers of bottom and one skirt layer. These settings would print a fine cup, but major scale changes would require rethinking and altering these variables. There is no right or wrong here. <sup>24</sup> I take copious notes on each piece I make and save the proven profile under a new name in the slicer’s library of settings. <sup>25</sup> I’ve tried printing on various materials from paper to a thin sheet of high-density EVA foam, to plastic bats for pottery and salvaged squares of acrylic sheets, arriving at the 1/4” plasterboard <sup>26</sup> as the optimal base for the building print. When starting your print, be sure to set the printer’s Z height to the board on your platform, otherwise you may risk having the nozzle bump into the edge. <sup>27</sup> It’s worth experimenting with setting the Z height of the nozzle higher than logically required, especially for high pressure extrusions using a small nozzle diameter. The result is a lace-like textural pattern built of delicate clay coils falling and buckling onto themselves, like those in *We. The. People.* in my *Code Slip* series. I recommend slowing down the printing speed of the first layer to around 50%, which should give good traction to the base coil. In addition, setting up the print with at least one skirt layer will ensure sufficient flow by the time the printhead begins the design object. With a print that is too difficult to start, I sometimes turn to making the base from a clay slab. <sup>28</sup> This holds the base coil securely, but may leave a trace or be difficult to remove later. The rest of the printing process is a matter of experimentation with flow, speed, supports, <sup>29</sup> etc. My aim here is to provide general guidelines as it is rather difficult to provide specific suggestions to be reproduced in another studio, because each machine will take different settings, and each clay body and each project have a set of different needs. A lot can be gleaned by consulting general guides for slicing software and from making tests and takings detailed notes on them. In addition, during the time of wrapping up this book, Jonathan Keep published his accessible how-to guide for clay printing. <sup>30</sup>

<sup>25</sup> Once saved, each different profile can be called in from the library and used later. Having a library of past profiles provide consistency when working on a series throughout several months.

<sup>26</sup> Cut the boards to size, large enough to be clamped to the platform but small enough to fit a few of them on your dry racks. Tape the cut edges of the board with duct tape tightly.

<sup>27</sup> Or, as it happened during an exhausting afternoon recently, our Z height miscalculation resulted in the nozzle violently punching a hole into the middle of the board.

<sup>28</sup> I suggest using a slightly leather-hard slab, especially for porcelain. The moisture difference will result in different shrinkage later, ensuring that the actual print will separate cleanly from its base.

<sup>29</sup> While supports can be generated in the slicer, I stay away from them and generally try to solve every structural

<sup>30</sup> [wikifactory.com/@jonathankeep/clay-3d-printing](http://wikifactory.com/@jonathankeep/clay-3d-printing)



**DRYING** The golden rule of drying ceramic pieces is to take it slow, especially if the design has thicker and thinner parts in combination. Due to gravity driving moisture downward, the top of the piece, as well as any areas that stick out—ornamental loops and textures, handles, feet and loosely attached parts—will dry out much earlier than the rest of the piece does. This could separate the exposed part from the rest of the piece.

Clay shrinks as it dries. Because of that, it is important to remove any rigid support as soon as the walls themselves are firm enough to stand on their own. The time to do that is the LEATHER-HARD state. <sup>31</sup>

I strive to even out moisture levels throughout the piece during the drying process, for which I use various low-tech equipment <sup>32</sup> that either helps to draw out water or slows down the evaporation of it. In most cases, the best choice is to dry the piece upright <sup>33</sup> on its intended base since during drying considerable warping can also occur. I use a slice of craft paper under the drying piece; that way, the base of the piece can move as clay shrinks. While smaller pieces tend to pop off the plasterboard, I tend to be more proactive with larger forms or with those that have a complicated bottom. Turning these over and waiting a few hours for the board to detach cleanly usually takes care of things. In any case, don't pull, let time do the work for you. How do I know when a piece is dry? It should feel like a piece of chalk, no longer cool to touch.

Should you risk a piece by sticking it into the kiln still slightly damp and cranking up the heat to soak it on an almost-boiling temperature? Well, there are certainly times when there is no other choice but to take that risk. Because printed clay is layered and between the layers there is gen-

erally less adhesion than within a layer, the piece will be less likely to explode than to quietly and gently split. Tensions build up in the larger forms, wreaking havoc when least expected. I've lost many perfectly healthy-looking pieces to insidious splitting bottoms. Each piece has its particular set of issues that need a unique resolution, just to keep the process interesting.

<sup>31</sup> The leather-hard state is also the best time for altering and trimming clay or assembling objects from printed parts. Leather-hard clay still feels wet, but it no longer takes imprint from touching.

<sup>32</sup> These include contraptions such as a drying tent made of 2 mill plastic sheeting; large paper bags to slow down the drying; and small boards made of plasterboard (also called drywall or gips-carton around the world); and plaster bats and perforated tile setters to speed up the drying of the bases.

<sup>33</sup> Once it is leather-hard, I can lay the ceramic object on a soft piece of foam and work on the base or on hard-to-access regions. Leaving it to dry on the foam though would almost certainly lead to a wobbly bottom.

<sup>34</sup> If possible, pull with the paper, instead of touching the outside. This is another reason why drying ceramics on paper is a good idea. Another technique is to make a SHRINKING PLATE—a flat durable piece of clay made at the same time as the object—on which the piece sits while going through the drying and firing process. Move objects by grabbing the shrinking plate.

**FIRING** In the dry state, porcelain tends to be more fragile than other clay bodies. It needs more care when moving and setting down on the kiln shelf. To transfer pieces safely to a kiln shelf, I often build two stacks of perfectly equal heights next to one another on the table: one has a plasterboard with the piece and the other has a clean kiln shelf coated with kiln wash on top. Delicate constructions can be slowly and carefully slid over <sup>34</sup> from one flat surface to the next. Extremely delicate pieces will be moved onto a kiln shelf while still wet and left to dry. When loading the kiln, I make sure that each piece is fully on the shelf and all looks balanced. If there are tricky parts that may fall or drop during high-firing, I take measures to support these or clear space around them, giving them room to slump or fall by the heat work.

I fire all my pieces in a computer controlled electric kiln, which has its own dedicated area outside of the main work areas. <sup>35</sup> I don't recommend buying a kiln and setting up in your living or work space without ventilation. It's best for the pieces, for the kiln, and for everyone's health to work with a kiln that has proper ventilation to the outside. <sup>36</sup>

I fire pieces rather slowly and pack the kiln as tightly as possible to retain heat in the cooling cycle. In the first part of the firing, I go 65-90°F/hour. After QUARTZ INVERSION, <sup>37</sup> I increase the rate of heating to 110-125°F/hour. Color or glaze applications necessitate two firings, the first one, BISQUE, <sup>38</sup> goes to the neighborhood of 1800°F (980°C) and the final one, called a GLAZE FIRING or firing to maturation, goes to 2160°F (1182°C). <sup>39</sup>

I provide a few firing schedules that has worked well for me over the years. There are many community studios and ceramic supply stores which fire ceramics for individual

<sup>35</sup> Larger kilns may need a special type of outlet and a dedicated circuit. Checking the electrical requirements and consulting with an electrician before purchasing and installing a kiln is highly recommended. Make sure that the kiln's location is dry and is easy to access.

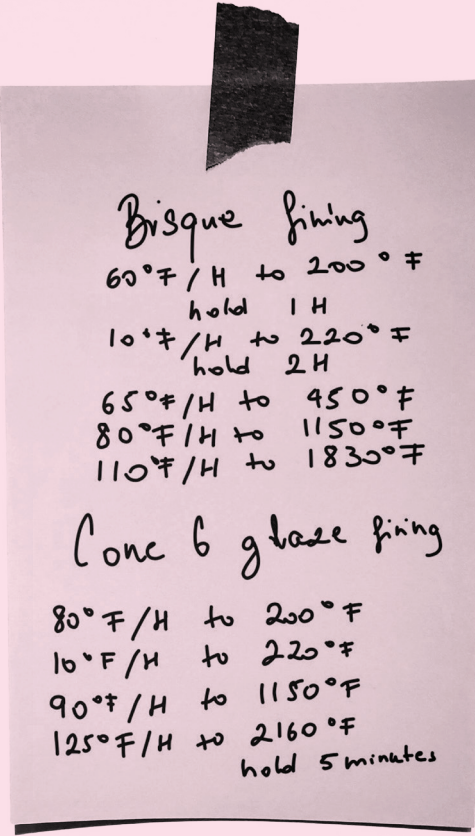
<sup>36</sup> I've seen many examples of that from home studios to community makerspaces; that's why I mention.

<sup>37</sup> At 1063°F (573°C) an abrupt change in volume occurs in quartz crystals as they go from stable alpha phase to the beta crystal phase in heating, and in reverse when cooling. To make sure that each part of the piece (thick/thin, bottom/top, etc.) is going through this transformation at the exact same time, take it slow between 950-1150°F (510-620°C).

<sup>38</sup> As the temperature rises towards bisque, chemically combined water, organic materials as well as compounds of calcium, magnesium and sulfur burn out.

<sup>39</sup> These temperatures are specific to the mid-range porcelain I use. Other types of clay may require adjustments to the glaze firing temperature.

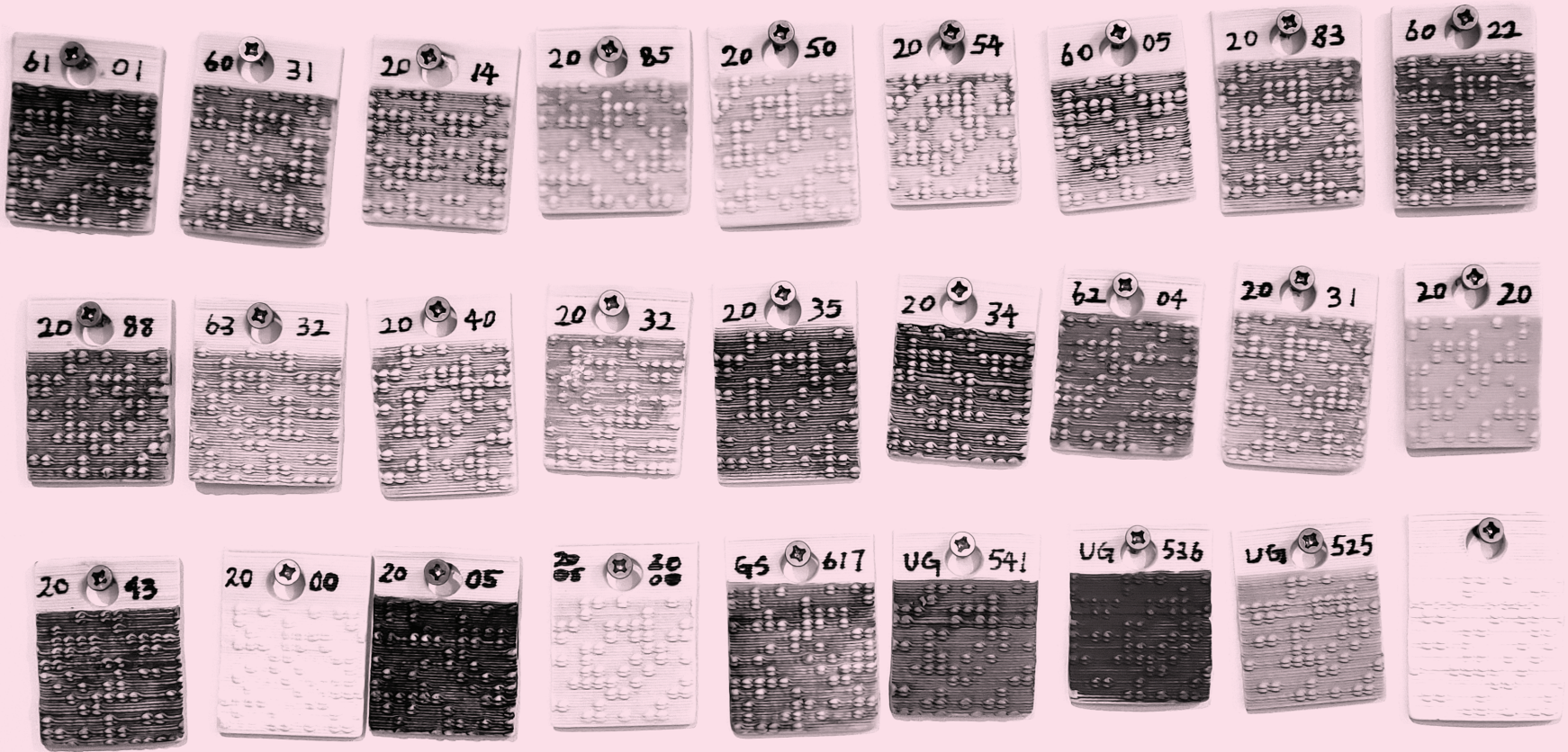
makers. This is practical for those with low volume production or who would not otherwise have access to a kiln. It's not a bad idea to become a member at one of those places and develop a good working relationship with them.



**GLAZING AND POST-FIRING** While it is easy enough to buy a jar of glaze at the ceramics supply store and brush it on a piece, glazing is an artform of its own. Proper preparation and application of glaze requires experience, a well-equipped designated studio space and some personal safety equipment. <sup>40</sup>

Most of my work is fired without glaze or uses only a selective application of it. I find the dry unglazed surfaces attractive because they don't conceal the subtle textural variations of the clay body. Glaze is like clothing: it can cover up and it can also steal the show. When I started printing, my desire was to create a glazing style that would highlight instead of concealing. I have developed a technique that uses a painterly application of pure ceramic pigments <sup>41</sup> on the bisque-fired ware and covers them with a thin layer of translucent glaze. I like the resulting watercolor-like effect that allows the pigment particles to be trapped in the small cracks and crags, creating vivid sparkles of color.

I spray <sup>42</sup> all my glazed pieces in thin layers with a transparent clear or a white glaze. Using a spray gun is the best method for controlling the thickness of glaze application and for creating a drip-free, smooth and even coat. The spray goes around the details of the texture, reaching spots that are visible but would otherwise be too difficult to cover thinly. There are plenty of other possibilities, from paints <sup>43</sup> to foils and dip-coat rubbers, to flocking and other mixed media for playing with surface quality and applying color to printed surfaces. Many of these would cover up the layered topographical appearance of a printed wall. The striation, which I have come to greatly appreciate, is a tell-tale sign of extrusion 3D printing. <sup>44</sup> Its predictable but slightly varying rhythm pleases my mind. I think that it also authenticates the work by revealing the process.



<sup>40</sup> Glaze materials consists of very fine silica powder and compounds of minerals and metals, many of which are highly toxic! Wear a properly fitted respirator and plastic gloves when handling them.

<sup>41</sup> There is a difference between glaze and pigment. Glaze is a glass forming mix of ceramic materials, high in limestone, feldspar (flux) and silica. Silica melts to become glass. Lime and feldspar both contribute to lowering the melting temperature of silica. Ceramic pigments are mineral or metal oxides or blends of these formulated by industry to be stable enough to result in an exact fired color.

Both pigments and glazes may interact with one another. The resulting color and glaze surface is dependent on firing temperature, kiln atmosphere (abundance or lack of oxygen) and many other factors. With glazing, always test extensively and be ready for surprises.

<sup>42</sup> Glaze materials consists of very fine silica powder and compounds of minerals and metals, many of which are highly toxic! Wear a properly fitted respirator and plastic gloves when handling them.

<sup>43</sup> Oil, acrylic, spray paint, car paint etc.

<sup>44</sup> Maybe technopotters will get over this physical feature someday soon enough. In the larger printing industry, the most recent methods are "high resolution," which strive to eliminate the striated look of FDM printing.

<sup>45</sup> [cdc.gov/niosh](https://cdc.gov/niosh)

<sup>46</sup> [ceramicartsnetwork.org/daily/ceramic-art-and-artists/ceramic-artists/essential-guidelines-for-a-safe-and-healthy-pottery-studio/](https://ceramicartsnetwork.org/daily/ceramic-art-and-artists/ceramic-artists/essential-guidelines-for-a-safe-and-healthy-pottery-studio/)

<sup>47</sup> [osha.gov/SLTC/respiratoryprotection/standards.html](https://osha.gov/SLTC/respiratoryprotection/standards.html)

**CERAMIC SAFETY** Clay is one of the most accessible materials, yet ceramics safety is a serious reality. Having proper ventilation in the studio in general, as well as locally in and around the necessary equipment, is crucial for maintaining a healthy and safe working environment. The National Institute for Occupational Safety and Health (NIOSH) <sup>45</sup> has established accessible recommendations for safety in the studio with regard to the use of ceramic materials and personal safety equipment.

Some of the most important ones: <sup>46</sup>

Don't eat, drink, or store food in work areas, and wash your hands thoroughly before eating.

Don't let clay fall on the ground, or if it does, pick it up while still wet.

Don't shake off towels, boards or hands with clay caked on them. In general, avoid activities that would make clay airborne.

Wet-wipe surfaces rather than sweeping or vacuuming. Use a properly fitted respirator with a particulate filter and refer to the OSHA respiratory protection standard. <sup>47</sup>

Eliminate lifting and carrying items weighing more than 50 pounds.

Use carts and proper ergonomics when transporting heavy materials.

If you perform repetitive activities, especially those involving sitting and hunching (wedging, constructing, finishing pieces or doing computer work), take a break often and stretch.