Making and Breaking Rules with Algorithmic Forms and Tactile Processes

A Technoceramist’s Adventures with Mathematical Thinking

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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 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.

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, 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.
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, 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. 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.


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. Regular pentagons though are entirely different. We would not be able to tile a plane in our ordinary Euclidean geometry with them. But certain types of irregular convex pentagons and also a wide range of random shapes can fit together to make irregular tiling.

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. 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.

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.

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.

Note that a hexagon is made of gluing six copies of equilateral triangles together.

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 (like a soccer ball) or a hyperbolic plane such as surfaces similar to corrals or cutely leaves of a lettuce. More about these in Taimina, Daina. Crocheting Adventures with Hyperbolic Planes. Wellesley, MA: A.K. Peters, 2006.

The work of M. C. Escher provides great examples for artistic versions of these irregular tiling. See more in the well-maintained archives of the M. C. Escher Foundation at mcescher.com.

It is also quite possible to create a tessellation that does not show 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.


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As introduced earlier, the cellular automaton (CA) 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 by updating rules, which specify conditions for when and how the state of the cells might change. The rules take into consideration the ON 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 might change, the rules take into consideration. When the rules are applied, a given array of cells advances to the next state, which can be seen as generative process. The process of self-reproductive logical systems and, with the theory of the cellular automaton, emerged in the mid-1960's from contributions to cybernetics made by Alan Turing, Stanislaw Ulam and John von Neumann. Interestingly, many of, 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 Game of Life, referred to as 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.

There are only three simple rules, taking into considering 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 many but also in what location we would find surviving generations.

The cellular automaton has the advantage of being more amply by some form of base 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 cellular 3D printing is an example of Cellular Automata for its basic construction being a linear grid. Cells are "scanned" by the rules in triplets, the process generating a nearly endless combination of patterns, showing not only in how many but also in what location we would find surviving generations.

Following Wolfram's designation, ON cells are marked with a black color, while OFF cells are with white. Producing thousands of generations from a single string, he was able to observe four distinct classes 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 for some peoples' tastes, but there certainly raise interesting questions later replaced emergence with a more expanded notion of "self-transcending constructions." A self-transcending construction is a fulfilling description especially for 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.

## Rules

### Rule 1: Cell dead becomes alive when exactly three of its neighbors are ON.

### Rule 2: Cell alive stays alive if exactly three of its neighbors are ON.

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


Wolfram's designation, ON cells are marked with a black color, while OFF cells are with white. There are four types of resulting states:

1. **1. Uniform states:** states that are repetitive and remain unchanged for all time. These states are often called "snowflakes" or "grids." Some are periodic, repeating every few generations, while others are aperiodic, never repeating.

2. **2. Random states:** states where no particular pattern is established. These states are often chaotic and unpredictable. They may exhibit long-term behavior that is difficult to predict or control.

3. **3. Stable states:** states that neither random nor periodic. These states are called "stabilizers" or "snowflakes." They are often very simple and repetitive, but they are also very difficult to predict.

4. **4. Oscillating states:** states that show regular oscillations between two or more states. These states are often called "oscillators" or "oscillating systems." They may exhibit long-term behavior that is difficult to predict or control.
Here again, Slip Rabbit intern, Daria Micovic, was tremendously helpful.

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


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 two elements to form a third element 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 remains 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).
One of the most visually interesting areas of mathematical research is sandpiles. 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 topple and the distribution of the chips change 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, using reflection to complete an infinite loop of firings. Sometimes, the game results in an infinite loop of firings. This kaleidoscopic beauty seems both perfectly logical for the destruction? Sure, there was a proverbial straw, an ultimate shove... But rather than blaming that the collapse, I had to reconcile the complex physical phenomenon, in particular the water, the shape of the heap, imperceptible imbalances of the form and the universe of grains that make up the material. On a microscopic level, it would be impossible to see actual collapse. Sara’s artwork was a critical moment: Where was the exact spot on the form whose weakness is responsible for the destruction?

An interesting mathematical aspect of sandpiles is called an Abelian sandpile group. 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. These are configurations that will occur infinitely often 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 makes no difference. 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 avalanche sizes in the sandpile, the patterns and patterns-families that appear, the density of sand in the pile, and so much more. This kaleidoscopic beauty seems both perfectly logical and also 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.

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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 “pinning” the right edge of the board to the left. We placed the sink hole onto a single cell in the center while “pinning” the right edge of the board to the left, 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 changes 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 and 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, using reflection to complete the pattern.

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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, 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, as well as challenging forms may require a certain 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 on 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 has 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 the resulting object needs to be sintered.

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. 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 BI-printed object still needs to go through a sintering process in order to become VITREOUS.

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.

More on 3D Printing

Sintering is a process of fusing powder into a solid object. It has to do with the sintering or sintering and bonding of powder particles. 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. Imagine sintering a line by arranging a set of fishing poles that have a rope tethered to them. You can only move the rods, which in turn affect the sintered shape of the line but you cannot directly manipulate the powder deposited in the line. You can only move the rods, which in turn affect the overall shape of the line but you cannot directly manipulate the powder deposited in the line.
In addition, NURBS are based on computation, resulting in a form, which, while it seems rendered on a screen, may not be of a VALID object. 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. Several commercial software packages are the ones most commonly used—stores settings containing instructions specific to the type of machine and material used. The process of slicing converts the model into a series of toolpaths on which the machine layers and builds in layers. Stepping for precisely setting the extruder multiplier or the tool speed can make or break an object, but these slicer parameters are also great fun to experiment with in ceramic printing.

11. Grasshopper is associated with a quad polygon mesh, which responds to shaping by selecting the desired edges and warping the overall shape by pushing/pulling them.
13. Rhinoceros is the currently offered AutoCAD, 3DS MAX, Revit, Maya, Fusion 360 and other valuable programs aimed at the board for various 3D modeling needs in architecture, engineering, animation and games industries. A beginner user would probably most likely encounter Fusion 360, a wonderfully intuitive modeling and 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.
14. Software based on PARAMETRIC DESIGN allows retroactive manipulation. Most of the Autodesk products have some parametric features. Solidworks, 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 omnipresent parametric modeling program is Grasshopper 3D, a visual scripting environment embedded into the 3D modeling software 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 unleashed by architect and designer Grasshop- per 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.
15. The final design state of a printable object looks like a mesh, a closely structual 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. T splines don’t reach the accuracy of B splines and may not produce the desired smoothness. 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.
16. A vector that is perpendicular to each triangular surface is described by the surface normal of the triangulated surface tiled with triangular tiles. The location and orientation of the tiles is described by the surface normal and vertices of the triangles using a three-dimensional Cartesian coordinate system.
17. SLICING programs are applications that work with STL files, translating these files into the language of FDM printers, called GCODE. The slicer software—Cura and Simplify 3D are the ones most commonly used—stores settings containing instructions specific to the type of machine and material used. The process of slicing converts the model into a series of toolpaths on which the machine moves and builds in layers. Tricks for finessing slicer settings across the board are part of the art of 3D printing. Changing the layer height or the number of passes the printer makes around the perimeter or varying the extrusion multiplier or the tool speed can make or break an object, but these slicer parameters are also great fun to experiment with in ceramic printing.
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 at select coordinates and design a Python code, called the Pathfinder, which serves to reroute the printer to one of four possible destinations around the original coordinate point.

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 serves 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.
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 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 paste ceramic materials and to publicize their research methodology. 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 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.
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 or through an auger system—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.

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.

Direct extrusion is similar to how a syringe works.

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.

This fingerprint is evident in traces of pressure changes, air bubbles, interruptions from startings and end 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

Clay and porcelain have a long and fascinating history. Clay was used by early civilizations for making pottery, while porcelain became a symbol of wealth and status in China. The process of making porcelain is complex and requires skill and patience. It involves mixing various ingredients, such as kaolin, feldspars, and silica, and shaping the clay into the desired form. Porcelain is known for its high degree of whiteness and translucency, which is achieved through careful control of the firing process. The firing temperature for porcelain can range from 1210°C to 1320°C, depending on the desired properties.

The making of porcelain involves several steps, including preparation of the clay, shaping, and glazing. The glaze is applied to the surface of the porcelain after it has been fired, giving it a shiny, smooth finish. Porcelain has been used for various purposes, from fine tableware to artistic sculptures. Its durability and beauty have made it a popular choice for centuries.

The history of porcelain is filled with intrigue and mystery. It has been linked to alchemy and secret formulas, with stories of artists and potters working tirelessly to create the perfect porcelain. The porcelain made during the Song Dynasty is considered some of the finest ever produced, and it continues to inspire artists and collectors today.
Porcelain in the Industry and in the Studio

Industry has developed many processes and methods specifically addressing the challenges of working with various types of porcelains. Factories and manufacturers in any part of the world I have visited, from rural Wisconsin (Kohler Co.) to Arita, Japan to Stoke-on-Trent 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.

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.

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 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 is necessary for turning the dried clay object into a vitreous ceramic piece or into brittle, but structurally sound, bisque ware.

There are tools, such as jigs and molds as well as techniques, such as those for drying, assembling and firing.

Some 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.

One of the most interesting of these concept experiments is Fossilized by the London-based group Amalgamma. www.amalgamma.org/

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

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 2150-2600°F or 1180-1426°C; high-firing clays mature at 2600°F or 1426°C.

The three main areas are: For clay, we have designated areas for the printers, a work bench for clay preparation, a large table for printing and hand-building. The above area includes spaces for glaze preparation, drying, and post-printing work in the kilns, vents and racks for kiln furniture. We have storage areas for green, bisque and finished work everywhere else.

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.
In the US, plastic clay is sold in 25lbs bags. For purposes of kiln wash, using setters and setters and breaking up hard clusters of dry materials. By covering shelves with kiln wash, using setters and setting the clay thoroughly, for further experimentation.

WEDGING
Wedge 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 form of patient kneading. If it feels mushy, I wring the towels out. If the clay is too stiff, I saturate the towels with more water. If the clay is too soft, I dry the towels at the kiln. 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 temperature 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. Only 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 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 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 to experiment with the material itself.

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, we WEDGE 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 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. 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 is still possible to extrude the plastic clay 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.
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 and molding material quality to the otherwise uniformly striated walls. My most recent work, Golden Means, is focused on exploring various ways of mark/texture making through various slips of data, code, CAD, machine and material into a unified surface.

PREVIEW As part of the documentation of a commercially available 3D printer, a PRINTER PROFILE is 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 or 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.

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. 

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 a thin sheet of high-density EVA foam, 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. 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 violently punching a hole into the middle of the board. 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, 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 taking 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.
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, it is slow, especially if the design has thicker and thinner parts in combination. Because of that, it is important to remove any rigid support as soon as possible. The leather-hard state is the best time for altering 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 possible. The leather-hard state is the best time for altering the piece does. This could separate the exposed part from the rest of the piece. The leather-hard state is also the best time for altering the piece does. This could separate the exposed part from the rest of the piece. This could separate the exposed part from the rest of the piece. It should feel like a almost-boiling temperature? Well, there are certainly times when there is no other choice but to take that risk. Because of that, I use a slice of craft paper after drying the 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. 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 of that, I use a slice of craft paper after drying the 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.

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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. 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 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 crevices, creating vivid sparkles of color. I spray all my glazed pieces in thin layers with a transparent clear or 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 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: its predictable but slightly varying rhythm pleases my mind. I think that it also authenticates the work by revealing the process.

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) 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:

- 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.
- 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.
- Glass 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.

TERMINOLOGY

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