Making and Breaking Rules with Algorithmic Forms and Tactile Processes

A Technoceramist's Adventures with Mathematical Thinking

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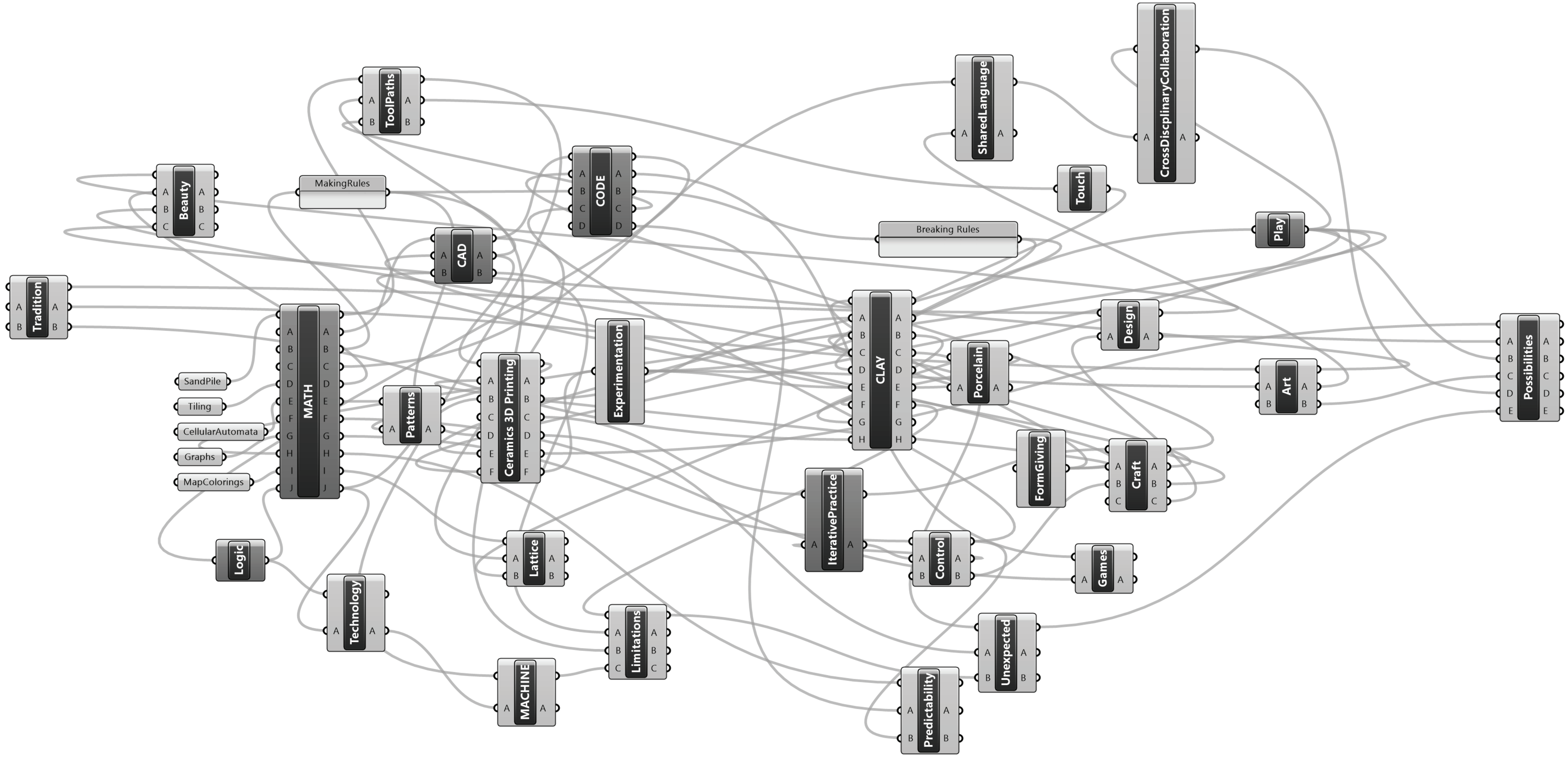
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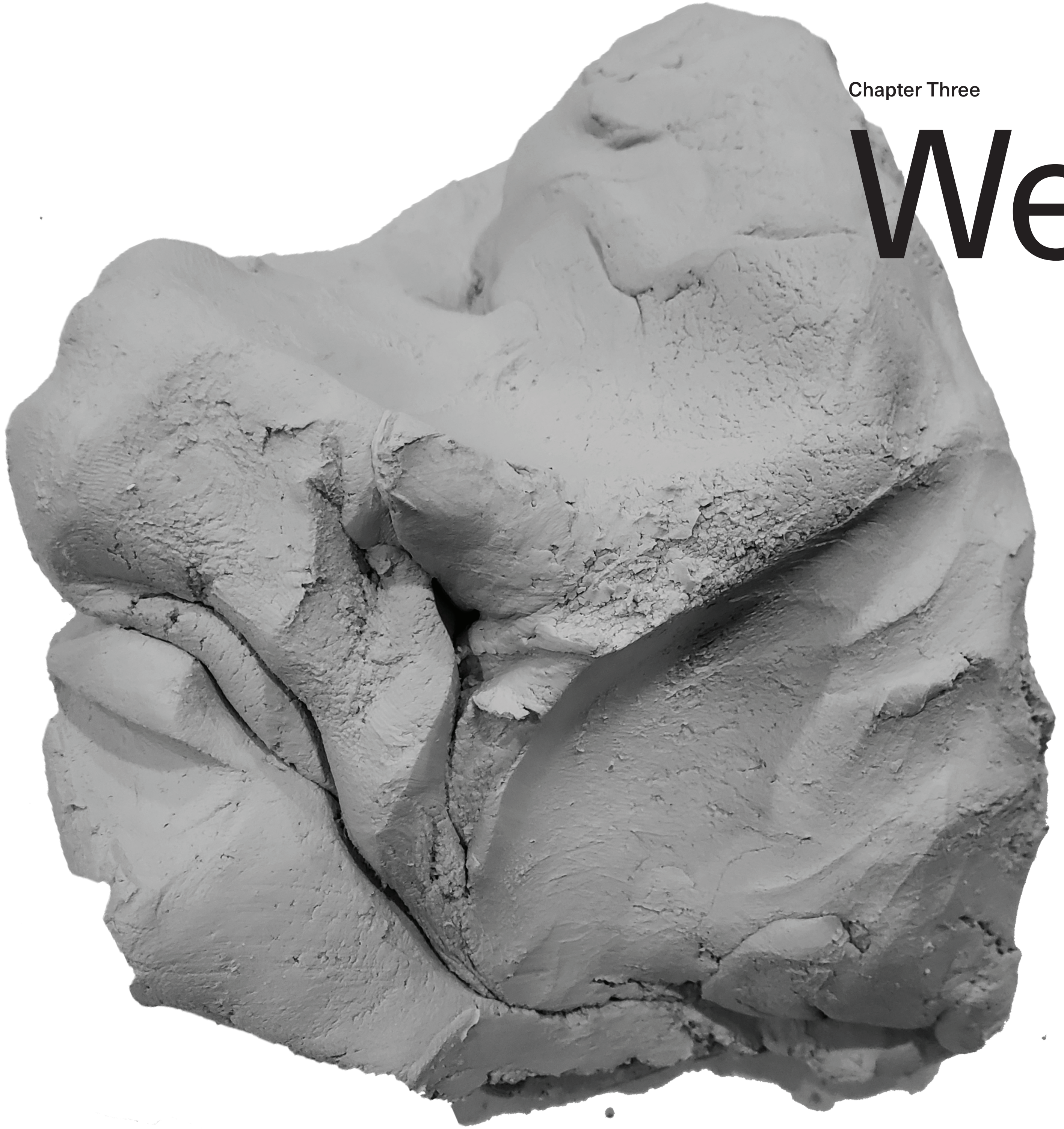
Wedging



Putting in the Elbow Grease

Wedging, in ceramics, is the process of kneading the clay into pliable matter, making it more uniform in consistency and thus more forgiving and easier to work with throughout the rest of the process. Wedging, which is quite humdrum and physical and seemingly having not much to do with the form-giving process, actually does something quite important: it makes the material come alive.

CLAIMING COMMON GROUND WITH DIFFERENT SETS OF VOCABULARY [01] In the fall of 2019, I attended the Illustrating Mathematics special semester at the Institute for Computational and Experimental Research in Mathematics (ICERM) at Brown University. The special semester was an opportunity for mathematicians interested in creating visual representations to share ideas among themselves and in a larger community of digital and visual artists. [02] At ICERM, I noticed a very interesting dilemma: mathematicians were wondering what an artist would get out of a math-art collaboration and, not surprisingly, artists were asking the reverse question. What does each discipline have to offer to the other and, most importantly, how do we attempt to converse with one another?

During my many interactions with mathematicians, I have noticed a language barrier. The language of math—being one that handles invisible abstract objects, spaces and processes— has to be extremely precise in its vocabulary definitions. These definitions can be quite opaque to an outsider. In fact, each math area is so specialized that, in order to introduce a research topic to their peers, a mathematician must start by defining the terms that will be used, even those ones that are universally accepted.

Perhaps the greatest difficulty Sara and I have encountered during our collaboration (besides coordinating the busy schedules of two academics) was a need to define and redefine everything, not only words but our art and math toolkits as well. For an artist, this highly technical vocabulary of math is confusing at best; it may seem impenetrable and full of traps. There is nothing more intimidating than trying to ask a question but not having the right words. It takes considerable effort and humility on both sides to strike up a meaningful dialogue. But just like when learning a new language, intentionality and practice matters, and a lot of ground can be covered by communicating through drawings, models, metaphors and even gestures.

Similarly, art also has its own language built on art history, aesthetics, philosophy and the making tradition [03] itself, which is not readily accessible outside of the specific area of practice. Without a doubt, we each had a great deal to learn. The participation of our students—both undergraduates and grads—was enormously helpful in this, as all ideas and terms were eventually vetted by the entire group, from PhD students in math to undergraduates from various majors.

All vocabulary used in the book is a result of deliberate compromises that ultimately allowed us to move forward together. While precise technicalities still matter a great deal within each of our professional areas, we had to find ways through which we could converse less restrictively with each other and with those who were not already in math or digital ceramics. For this reason, and to keep the content accessible, I continue to refer to the underlying mathematical models as GAMES.

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[01] In Chapter 2, I described that one of the initial challenges of our cross-disciplinary collaboration was a lack of shared language and how we solved this problem.

[02] icerm.brown.edu/programs/sp-f19/
This unique opportunity was organized by several mathematicians and made possible by ICERM's mission to support and "expand the use of computational and experimental methods in mathematics."

[03] Each type of making process having its own set of specialized vocabulary.

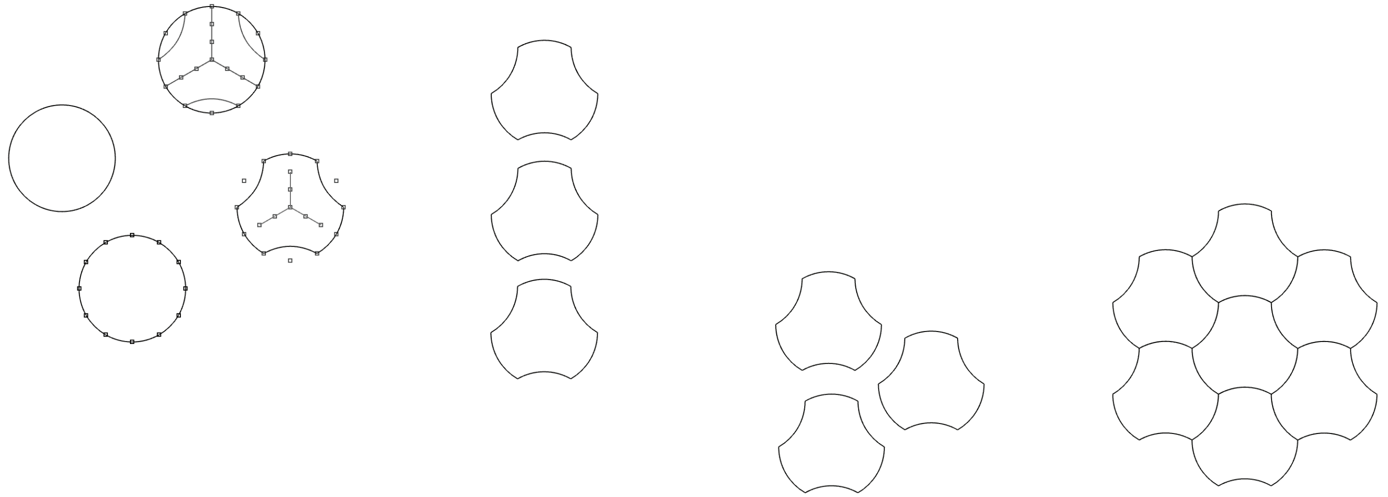
GAMES SHARE THE FOLLOWING BASIC COMPONENTS:

CELLS AND LATTICES

Imagine an environment [04] that is divided into small units, just like a Go game board. These units are called CELLS. They are structurally organized to form a LATTICE (also called a GRID). When built from all the same cells, the lattice is REGULAR.

STATES

Each cell can exist in a finite number of states, such as dead/alive; ON/OFF; or collect a specific value, which may be represented by a number or a color. These resulting states are always DISCRETE: only 0's and 1's in BINARY systems and written up as an INTEGER (a whole number) in non-binary systems.



04 Can be a 2D surface or a space of 3D or any higher dimensions.

05 Take this statement, for example: If the clay is too dry, then pieces won't stick together.

06 One unit or one row at a time. This is an important characteristic of the ELEMENTARY CELLULAR AUTOMATON.

07 Such as in an ABELIAN SANDPILE MODEL. Mathematicians call this characteristic COMMUTATIVE, meaning that the order in which the pile inside of each cell topples does not matter. Start anywhere and you still would get to the same outcome.

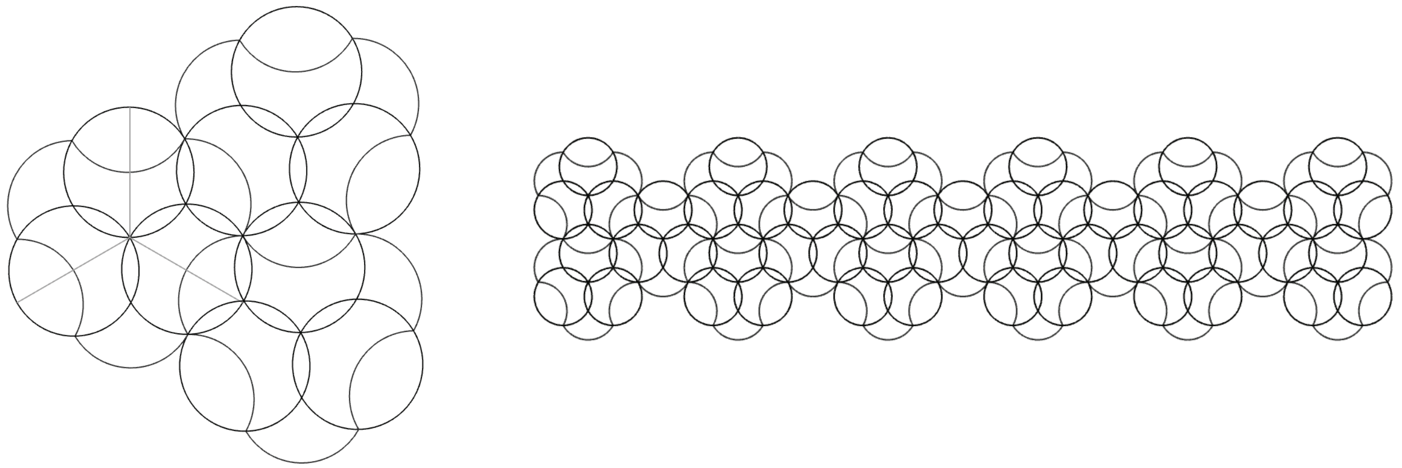
08 There are a wide range of possibilities: ripples, cascades, symmetries, transformations, etc. Abundant examples can be spotted on the beach sand in low tide, in animal skin patterns, and in plants such as ferns, pineapples and cacti, etc.

RULES

Rules are a set of instructions for IF-THEN [05] actions to be performed in the game. Any given sequence of these instructions is called an ALGORITHM. The sequence of instructions does not have to be logical; we could pick a random key to say what should happen next. There are certain flexibilities and restrictions when setting the rules of the game. Firstly, we need a rule that decides which cell locations are going to be checked and acted upon by the algorithms. Typically, rules scan the cell and selected near-neighbors. The change can happen in a LINEAR [06] fashion or it may play out everywhere on the game board simultaneously. [07] Secondly, rules are ITERATIVE. The whole point of the game is to run the rules repeatedly, until we run out of space or, in case of the sandpiles, until the system stabilizes and cannot be changed anymore.

PATTERNS AND MATRICES

Patterns are the outcome of the game. Patterns are the actual arrangement of cell (unit) states resulting from applying rule-algorithms. Each time the rule has run, a transformation happens and a new arrangement of states develops on our game board. There are plenty of patterns observable in nature and among things created by humans. Commonly, patterns are understood to have regularity, recurrence or self-similarity. [08] However, the term PATTERN refers to a human cognitive ability that recognizes certain regularities and relationships both locally (within a small area of neighboring cells) and globally (across the game board). Cognition organizes an array of cells in various states into meaningful motifs. Removing this subjectivity of human cognition, a given arrangement of units is called a MATRIX.



Rules and More Rules

GAMES WITH RULES When I first contacted Sara with my question about mathematical constructions based on simple repeating rules which may have the potential to build unpredictable complexities, she suggested that I look into a type of model called CELLULAR AUTOMATON (CA). Next time we got together in her office I was prepared with a thousand questions and had some plans.

Cellular automata are discrete game-like processes. They consist of cells that can only have discrete values, in other words, a finite number of states. Typically, CA are binary, but it is entirely possible to set up rules in ways which result in non-binary outcomes. The cells themselves may be organized in any number of dimensions: in 1D, they form a line (like beads on a string); in 2D, they live on a plane (like a tiled floor); in 3D, they occupy space (like a stack of boxes) and, in theory, they could expand beyond, into higher dimensions. [09] CA games do not require additional input after setting up a starting state [10] and repeating the rules. The matrix evolves on its own, the process of which can be recorded as snapshots in time, counting GENERATIONS. [11] One familiar example of a CA is Conway's Game of Life, [12] which is played on the plane and models the life-cycle of cells being born and dying over time according to how populated their neighborhoods have become. In the decades since Conway's discovery, there have been an abundance of applications of related numerical games in computer science, economics, political science and biology.

At Sara's suggestion, I started focusing on the elementary cellular automata, which—being set up as a single line—is possibly the simplest form of a CA. [13] This simplicity gave me an opportunity to develop and test methods for turning a binary numerical matrix into tactile matter, to show a timeline of changing cell states as a printed ceramic texture spread across a surface. Studying the elementary cellular automata in such detail also helped me to formulate further questions about complex systems based on simple rules.

Sara was kind enough to provide the basic code for the elementary CA, which I played with in the studio, changing and altering it according to my actual research questions and artistic ideas. The work with the CA was followed by a collaborative exploration of SANDPILE MODELS, which are played on a two-dimensional lattice but with an entirely different types of rules. Here we allow more possible states, which can be imagined as the number of sand grains (0, 1, 2, and on...) that are able to accumulate within each cell without the pile toppling over under its own weight. [14]

We tried playing these games by coloring in cells with markers and tossing pennies on makeshift game boards. However, repeating rules rigorously and precisely calculating nearly endless iterations would not have been possible without a digital infrastructure: coding and lots of computing power. Advancements in computing now permit running the full course when plotting out mega-matrices of CA games, at least in theory. In our actual practice, the more generations or more complexity we added, the more we felt the limitation of our computing strength. [15] Nevertheless, we were able to work with as many as a million cells for hundreds of thousands of iterations, resulting in unprecedented complexities.

We needed to tweak our own algorithms and approaches a number of times as a response to problems arising at every step of the computational process. Thus, the visual rhythm created with cellular automata or other game-like algorithmic systems is not merely an aesthetic experience.

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[09] Kind of difficult to imagine what that looks like! No wonder, our brains don't have a visual concept for higher dimensional spaces. Instead, follow the logic from 1D to 2D, and on, to 3D, 4D, ..., etc.

[10] INITIAL STATE

[11] GENERATIONS are determined by how many times the rules have been run.

[12] The Game of Life was popularized in the 1970's. See more in Gardner, Martin. *"Mathematical Games: The fantastic combinations of John Conway's new solitaire game "life."" Scientific American.* October, 1970. Vol. 223. Pg. 120-123.

[13] More mathematical details about this in Chapter 4: FORM GIVING – More on the Mathematical Concepts.

[14] These too will be explained in greater depth and detail in Chapter 4.

[15] Especially the sandpile models were breaking our equipment. Some of the plots ran overnight; many have never finished. I've since had a chance to discuss this with problem with Lionel Levin of Cornell University. Levin has done a lot of work with sandpiles and created both methods and code, which allow greater efficiency, such as a realtime visualization of the changes in the sandpile matrix.

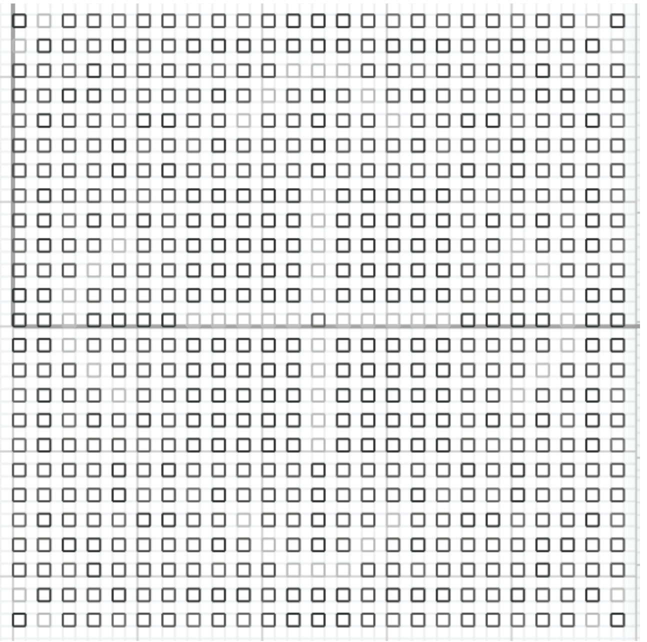
pi.math.cornell.edu/~levine/

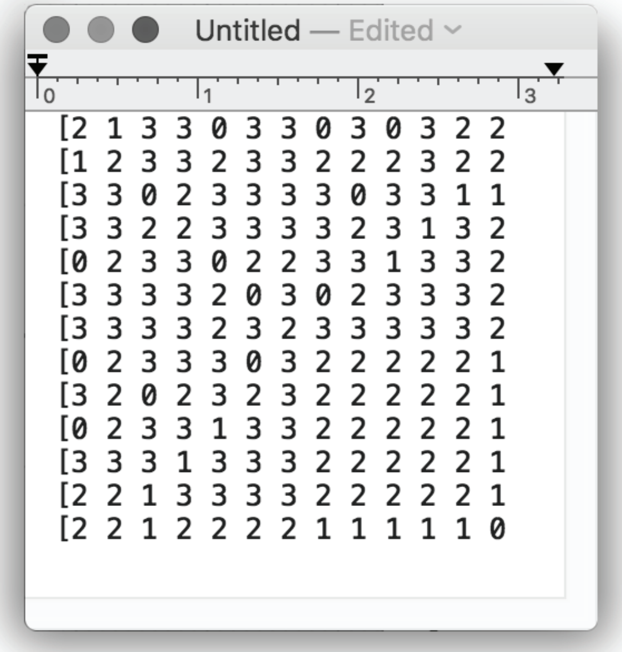
It is true that the resulting patterns are beautiful to look at, but, for me at least, they also became an archive of the pitfalls of algorithmic processes and of our predictive abilities when it comes to modeling complex systems and interactions.

The traditional depiction of cellular automata is a visual matrix. My plan was to give this model of system behavior a life as texture, as form, as a tactile material entity that has its own rules of formulation and its own existence. I was going to get this by 3D printing clay, which I hoped would be able to convey both the abstract algorithmic origins of the model and also the physical world it was called on to describe.

Ceramic printing has advanced in a few short years from the studio of a few early-adopter potters and makers to being the new best friend of the many design and architecture firms, which keep popping up all over my area for the making of one or another specific consumer product, typically, designer versions of common household items. Reflecting on this expansion of the field, I am now certain that my investigation of the connection between math and printing with clay was a valuable exploration, not for the tangible, but for the intangible results. Being computational in origin and digital in making, the objects that came out of this research may be reproduced with relative ease by others later, but working through these questions for the first time also allowed me to circumambulate larger ideas of making in the algorithmic age.

My initial attempts at mathematically inspired 3D clay printing treaded on unexplored ground and thus met with many new challenges: some in design; others in structural, coding or mathematical issues; and many were simply the usual birthing pains of the creative art process. Instead of running each type of pattern through the same workflow, which surely would have resulted in outcomes of close resemblance, I was striving—though not always succeeding at the first attempt—to create a new approach each and every time. The resolution of this, along with the excitement of the baby steps of actual math discoveries, which were shared amongst Sara, our WXML team and myself, has created a wonderfully rewarding experience and a constant flood of new ideas on which our explorations continued for many months.





MATH RULES THE DIGITAL WORLD Our workflow from the math to the object can be summarized by the following steps: After picking our game rules, we wrote them up in a mathematical program, CoCalc. [16] Upon running the program, we received a plot of a DISTRIBUTION MATRIX, black and white for an elementary CA or a multi-color map for sandpile models.

This matrix was then taken to a 3D modeling program, Rhinoceros, [17] and turned into geometries of cubes and cylinders. This process required careful calculations, which were reverse engineered from the relationship between printing layer height, nozzle size and cell size and desired scale of the finished object.

I was originally inspired by the relationship between mathematical thinking and our current digital-technological paradigm. In the process of working on these projects, I found that I had to learn about math even more through the actual process of making. This was not painful at all. In fact, it was easy to embrace and quite useful and exciting!

Undoubtedly, mathematics is both the supreme governing rule and the most critical engine of the digital world. This simple fact is easily forgotten in everyday life, as most of our daily experiences with technology are designed to give a low-barrier access to us, users, as well as to hide what's going on in the background. In most 3D printing projects, the user may not be aware that both mathematical thinking and actual math is part of their work from CAD to the code that communicates with the printer. [18] When a command does not work—for example, when two volumes cannot meld, a.k.a. BOOLEAN together—it is mathematics' way of saying: *This was a stupid question; try again, try better.*

[16] CoCalc (formerly, SageMath, is a web-based platform for computational math, founded by mathematician, William Stein.

[17] Rhinoceros (Rhino) is a popular modeling program used by architects and designers everywhere. More about it in Chapter 4: FORM GIVING – More on 3D Printing.

[18] Users of Rhino or any other 3D modeling program are familiar with these math terms: tangent, spline, Boolean, primitives, etc. Behind the rendering of geometry, algorithms run algebraic calculations with NURBS, mathematical representations of curves and surfaces. (More about these in Chapter 4.) Even the computer graphics preview (GPU) runs on math.

About Play

TRIAL AND ERROR Digital ceramics is grounded both in the world of math and in the world of matter described by physics. Each, but especially the latter in ceramic 3D printing, provides lots of opportunities for dealing with the unexpected and, consequently, for improvisation and for play. Forms constructed with algorithmic/parametric processes offer limitless variations. Every time a file is printed, it may come out slightly differently, especially if slicing or machine settings [19] are being changed. Clay, a very much-alive organic material, may have different properties [20] each time, resulting in outcomes that may be anticipated with practice but never guaranteed. Clay has a very strong physical nature that responds to gravity, time and many other factors that are often too numerous and unpredictable to account for. Touch it once and you will leave a unique and unrepeatable mark.

During our year of math and art collaboration, we have discussed, debated and tested various possibilities for simple game-like systems and often jumped around from one exciting variation to a more promising one within a particular type of game. Worthy as it is by itself, the process of making these patterns in clay was never meant to be a visualization exercise. [21] Instead of being concerned with visualizing the math involved, my aim was to find a new understanding of the freedom and determination inherent in algorithmic processes through clay.

Constantly, I was running into various obstacles due to limitations of one kind of another: computing power, software, machine, material or even my skillsets. In all maker practices, we speak of good craft, which usually refers to an experience-driven iterative procedure that keeps fine-tuning the process until the desired result is achieved. Repetitions build muscle memory and so does the accumulation of a variety of different types of experiences, both the desirable and the surprising outcomes. With the help of these, I can make more accurate predictions or initiate new paths of discovery. In this sense of learning by doing, digital making fits into the tradition of craft practice. [22]

Each step on the way, from coding to building a workflow of commands with the software, required numerous detours. I reworked the same object several times and still would come to find things of surprise. Even when I dialed in every parameter that I could control, each result was an object, consistent with the rest yet unique and unrepeatable.

This is a good place in my narrative for a brief detour from digital ceramics to textile arts made by individual makers throughout the past centuries in various cultures around the world: Algorithmic processes, symmetries, and transformations of patterns have always had a great importance in the creation of visual art and a special significance for our visual perception.

Many books have been written that analyze these patterns through the lens of mathematics, focusing on symmetries and transformations. [23] Art historians, artists, designers, and crafts persons have also drawn on these classifications or created alternative systems of understanding of existing pattern libraries based on making process/technology, regional historic and social context and the maker's individual narrative. From ceramics through textiles, every culture and every time period has produced a rich archive of pattern variations, many of which, we assume, have developed by individuals innovating a single small step at a time, both preserving a cultural tradition and,

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[19] pressure, speed, nozzle diameter, etc.

[20] Clay's make-up and consistency largely determines its behavior. Water content, types of clays present in the mix, as well as additives, impurities and atmospheric conditions, such as room temperature and humidity, also contribute to those physical changes that have an effect on the finished print.

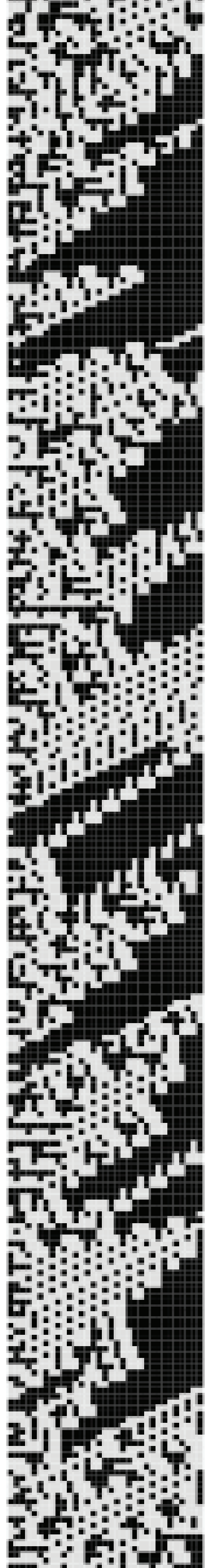
[21] Mathematical visualization is an area that makes abstract concepts imaginable through illustrations, diagrams or pictures. For many mathematical visualizations, images are often more useful than physical objects, as our minds are more attuned to make the leap from a 2D representation of a 3D space than from a 3D object to higher dimensional spaces.

[22] A similar argument is made in McCullough, Malcolm. *Abstracting Craft: The Practiced Digital Hand.* 1st MIT Press Paperback ed. Cambridge, Mass.: MIT Press, 1998.

[23] Washburn, Dorothy Koster., and Crowe, Donald W. *Symmetries of Culture: Theory and Practice of Plane Pattern Analysis.* Seattle: University of Washington Press, 1988.

at the same time, renewing it. Women were often in the forefront of this work, producing objects for gifts, commemorations, household utilitarian functions and, if they were affluent enough, sometimes just to kill time. In the case of basketry, knitting and weaving, a maker may be varying the UNDER/OVER sequence to create pattern variations, while in embroidery and quilting, play is based on alternating color sequences.

While having greatly benefited from the mathematical analyses of visual patterns, which look at designs in art to arrive at a classification of rules that create them, I decided to proceed in reverse. In my work with digital ceramics, I began with the math, asking what types of patterns might be created by formulating, navigating—and sometimes breaking—complex mathematical rules.



ROLE OF FAILURE Failing when building a large object from 1mm thick layers is inevitable. The wet form slumps and gets out of balance just enough for the next layer to miss alignment; cream cheese-soft clay collapses under its own weight; or a popping air bubble creates a void where clay was supposed to flow; etc. There are thousands of ways with ceramic 3D printing to not get what was just minutes ago within reach in the CAD program's digital preview. At other times, changes might happen in the kiln. The heat at vitrification temperatures pushes tiny inconsistencies even further and creates unrepeatable surprises. [24]
Potters refer to the "memory" of clay, the material's structural intelligence (or shall we say stubbornness?) by which it remembers prior forms it has taken. Each clay body has a "personality," describing tactile and workable properties, which can only be understood by developing a close relationship with the material through interaction.

It is exactly these—clay's memory, personality and directness—that make ceramic printing so exciting. And exactly this unstable ground is where the opportunity to make mistakes, to fail splendidly and intelligently, arises.
Failure is a frame of mind. I trust failure to be the precursor to fresher, better ideas and more elegant solutions.

If clay has a language, code also has its own language complete with syntax and logic. I was curious if what I knew about working with clay was also true for working with code. Causing the code to fail with intention, I decided, was the best way to find out. I embarked on an exploration into wreaking havoc on the self-organizing nature of the game by inputting binary patterns derived from various other textbased systems and by devising, what we called, mathematical "viruses." [25]

Viruses are simple but extraneous mathematical rules, which when introduced to the rulebased self-replicating system of the CA, would create unpredictable variations, many of them becoming manifest only after numerous iterations.

I also transcribed text into a linear string of ON and OFF cells by using various methods [26] and used it as the first line of the elementary CA. Interestingly, both this and the automata infected with a viral-rule would strive toward some kind of equilibrium, hinting at the difficulty in creating true randomness by algorithmic means.
The viral patterns [27] were ultimately of less visual interest than patterns created by strictly adhering to the logical rules. At other times, we would find inexplicable blips, which were consistent enough for us to interpret as part of the pattern but which, without exception, turned out to be coding errors.

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[24] These ranged from deformations to color changes, to sagging or slumped walls; and, in extreme situations, to cracks.

[25] Did this with the help of Daria Micovic, who was a senior in the math department and a Slip Rabbit intern at that time. She has worked with me on several coding projects, including this one, which played with the original elementary CA source code written by Sara Billey.

[26] One of these methods was to convert text into dots and dashes of Morse code, which I liked a lot for its reference to the history of telecommunication. We also created our own logic for various other types of transcription systems, as well briefly experimenting with using Braille.

[27] When the virus rule first expressed itself, it was definitely noticeable as a SINGULARITY (a mathematical term for something unusual compared to its surroundings). The more generations it went through, the less distinct its effects on the pattern became.

Breaking the Rules with Clay

Creating a clay object with a rigorous algorithmic design requires careful planning and tweaking. [28] Assuming that all the calculations were right, we would finally have a file ready for the printer. [29] Many aspects of how the math is encountered in physical form is ultimately decided by the numerous choices a craftsperson makes throughout the workflow, as well as by their individual vision for a desirable outcome. These choices are often too subtle to have an immediate visible effect. Rather, the sum of these choices will create a unique combination, which ultimately defines the shape of the resulting object.

When I started 3D printing with porcelain, the general consensus among ceramists as well as among tech experts predicted that this material—generally too fussy and difficult to work with—was not suitable for this process. I was warned that the rather gentle pressure of the extrusion would not produce sufficient adhesion in the walls, and the form (being extremely soft) would not be able to support itself. I was reminded that porcelain would continue to move, warp, shrink and crack uncontrollably in the drying process, especially given the added water content that makes it pliant enough for the machine to extrude. In short, that I would not get too far with it.

My earliest experiments, which started with building textures from sequenced loops, proved otherwise. The first trials were forms made of single stacks of loops put on humble cylinders. I experimented by slicing the form thicker and thinner, [30] increasing extrusion, switching nozzle diameters, putting the loops closer together and farther apart. Gradually, I stated building increasingly complex designs with these loops, then with other sorts of textural elements, playing now freely with the way they stacked, intersected or combined to form larger clusters. Through these experiments, I was able to create ways by which extruded porcelain walls can be made strong enough to stand. Depending on my design, I could also make them very thin and translucent. I also figured out solutions for supporting a variety of rather tricky forms, not by applying the presets of the printer, [31] but by foam, clay, wads of paper and other makeshift temporary structures, which are means familiar to ceramists.

Experimentation is a necessity. What will not work may be anticipated, but only repeated test prints will give me a confident understanding of where the form is the weakest, where it might fail, and how to prevent that. As each new form is a new challenge, figuring out as I go and learning through near-failures, are some of the most exciting aspects of ceramic printing.

Clay challenges all logical and predictable outcomes. Its own materiality is made even richer by a long ceramics history that is connected to the mundane, bodily and the abject. [32] The ceramic process leads to tactile and tangible objects with a spatial presence, which relates our abstract starting ideas about rules and systems back to the body and the human experience of touch.

Throughout this work, I have been most interested in striking a balance between reason (the logic of the math) and clay's natural tendencies. I paid attention to all those places along the process where logic can trip and chance takes over. Watching each piece form on the printer, each little coil that adds texture to the main form rising out of the extruder unit is a result of a long process. It is also a magical experience. I don't know until the very last pass is made on the form what the final outcome will be like.

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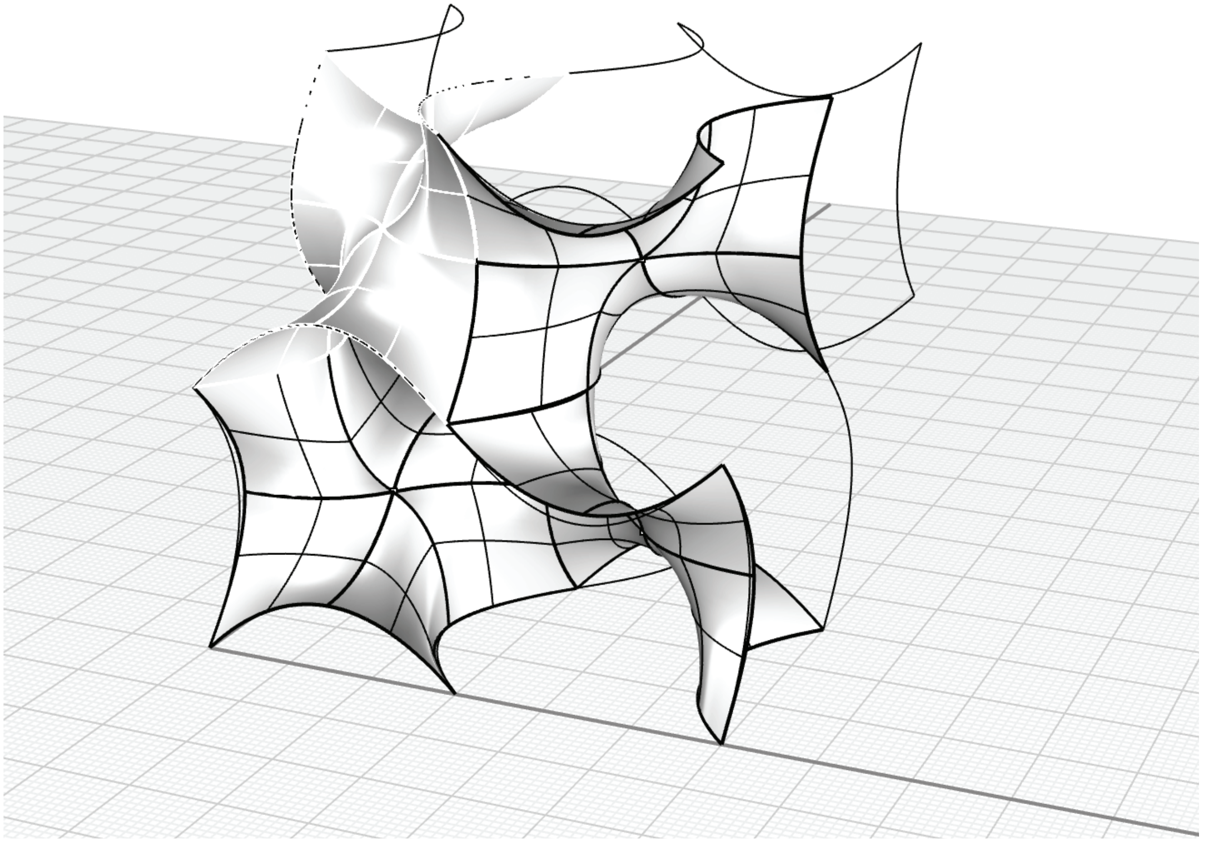
[28] One of the most important issues I repeatedly encounter while printing is scale-related: Increasing or decreasing the size of the finished object changes the scale of the extruded texture. In order for the patterns to translate crisply to the desired scale of the finished object, a considerable amount of reverse-engineering is necessary, which involves testing various nozzle diameters, layer heights and other print parameters.

[29] The print file itself consists of a list of commands combined with rigorously mapped spatial (XYZ) coordinates as if a strict road itinerary has been given. This does not only list the landmarks that need to be touched but also the distances between them, along with allowed speeds, acceleration rates and durations of rest stops. All of these are expressed as a list of numerical values that are bracketed by a simple vocabulary of letters and numbers specific to 3D printing technology, called a GCODE.

[30] This is described by layer height and determines how many layers are needed to build a particular detail, such as a loop. For example, a detail of 5mm height would have 4 layers of 1.25mm layer height, which is pretty typical for a 3.5mm nozzle or 5 layers at 1mm layer height (I most often use this for the 2mm nozzle).

[31] Every slicer program offers options for internal and external supports, which I almost never use. External supports leave a mark that interrupts the surface. Internal supports could close off spaces to airflow, putting the piece in danger of exploding in the kiln.

[32] Think about ceramics items used for nourishing (storing, cooking and food service) and caring for the body (hygiene, nursing and medicine, funerary objects). More about both porcelain and bone china in Chapter 4.



The finished piece has many stories, meaning accumulating layer upon layer. Thus, the origin story of these pieces reveals the process of their making, in addition to the mathematical ideas they represent. My job is to make choices in a way that explores and exposes not only WHAT they are but also HOW and WHY they have come to be.

Ultimately it is up to the viewer's interpretation to give life and context to these objects and, through them, to mathematical ideas.

Several of my previous collaborations with mathematicians and designers resulted in sculptural forms that would not have been possible without the use of 3D printing technology.

In 2016, I approached mathematician Henry Segerman about making, in bone china, one of his interesting prototypes for visualizing a 4-dimensional form. I sectioned the complex tetrahedron-like shape into simple parts in Rhino and prototyped those on a layer deposition printer. [33] I made molds from the prototyped parts and cast the molds with liquid bone china slip. Ultimately, the parts were assembled in the kiln and fired together. Much to my amusement, the nearly perfect form slumped and contorted, marvelously softening the rigid geometry of the model. [34] Similarly, I made a connection with mathematician Ken Brakke, the creator of Surface Evolver. [35] Ken helped me to explore the mathematical logic of a gyroid, [36] which turned out to be a rather impossible object to build by purely analogue means in clay. It has taken me many years to make the first one in porcelain, the break-through ultimately brought on by a ceramic 3D printer. [37]

Last but not least, even elementary mathematical ideas can bring interesting results when used as hacks [38] in the process of 3D printing. In the summer of 2018, I collaborated with IxDesigner, Audrey Desjardins, on a series of drinking vessels called ListeningCups. For these, we used ambient sounds, which we had gathered from a variety of urban environments. For our project, I devised a way for the 3D printer to use sound data in creating textures, not by moving but by stopping. Pauses of various lengths [39] created an extrusion in place, correlating sound volume changes with bumps of various sizes, thus encapsulating the audible information into tactile material. With Audrey, we contemplated the process of such transcription from the perspectives of both data stories and data tactility. [40]

Inspired by these results, I continued developing methods based on hacking the machine itself and putting technology in the service of the material. These new projects used math, more specifically trigonometry. [41] With some coding, which recalculates sine and cosine of the original spatial coordinates, the sound data sends the printhead to one of four randomly assigned new directions, creating a unique alternative path each and every time. The resulting lines weave in and out of the surface of the vessel, each sound environment making its unpredictable footprint through rather rational means in clay.

[33] All this work was done during an artist residency at Sundaymorning@ekwc, widely known by its former name European Ceramic Workcenter (Europees Keramisch Werkcentrum or EKWC)

[34] This piece, entitled *Perfect Imperfect* has become part of many of my installations, from *Axiomatic* to *Parlor Games: Scientia*.

[35] This is a computer program for modeling and visualizing hypothetical soap film surfaces, so called MINIMAL SURFACE models.

[36] A gyroid is an infinitely connected triply PERIODIC minimal surface discovered by Alan Schoen in 1970. Periodic means that the object consists of units that repeat without change.

[37] My version of the gyroid is called *Mystery. Solved. Mystery* in reference to the back and forth email conversations with Ken while trying to figure out the geometry of this object.

[38] By hacks, I mean editing, changing or simply tweaking the machine code.

[39] which corresponded to the changing loudness of sound pattern from each environment. We could have used any other aspect of the sound file: frequency, wavelength, amplitude, etc...

[40] See a detailed description of this project and our definitions for the terms data tactility and data stories, in *ListeningCups: A Case of Data Tactility and Data Stories.* (co-authored with Audrey Desjardins) ACM Proceedings, Designing Interactive Systems (DIS) 2019.

[41] This project is called *Pathfinder*. The pathfinder code, which was written with the help of Daria, also found its way to several recent projects of mine.