Making and Breaking Rules with Algorithmic Forms and Tactile Processes

A Technoceramist's Adventures with Mathematical Thinking

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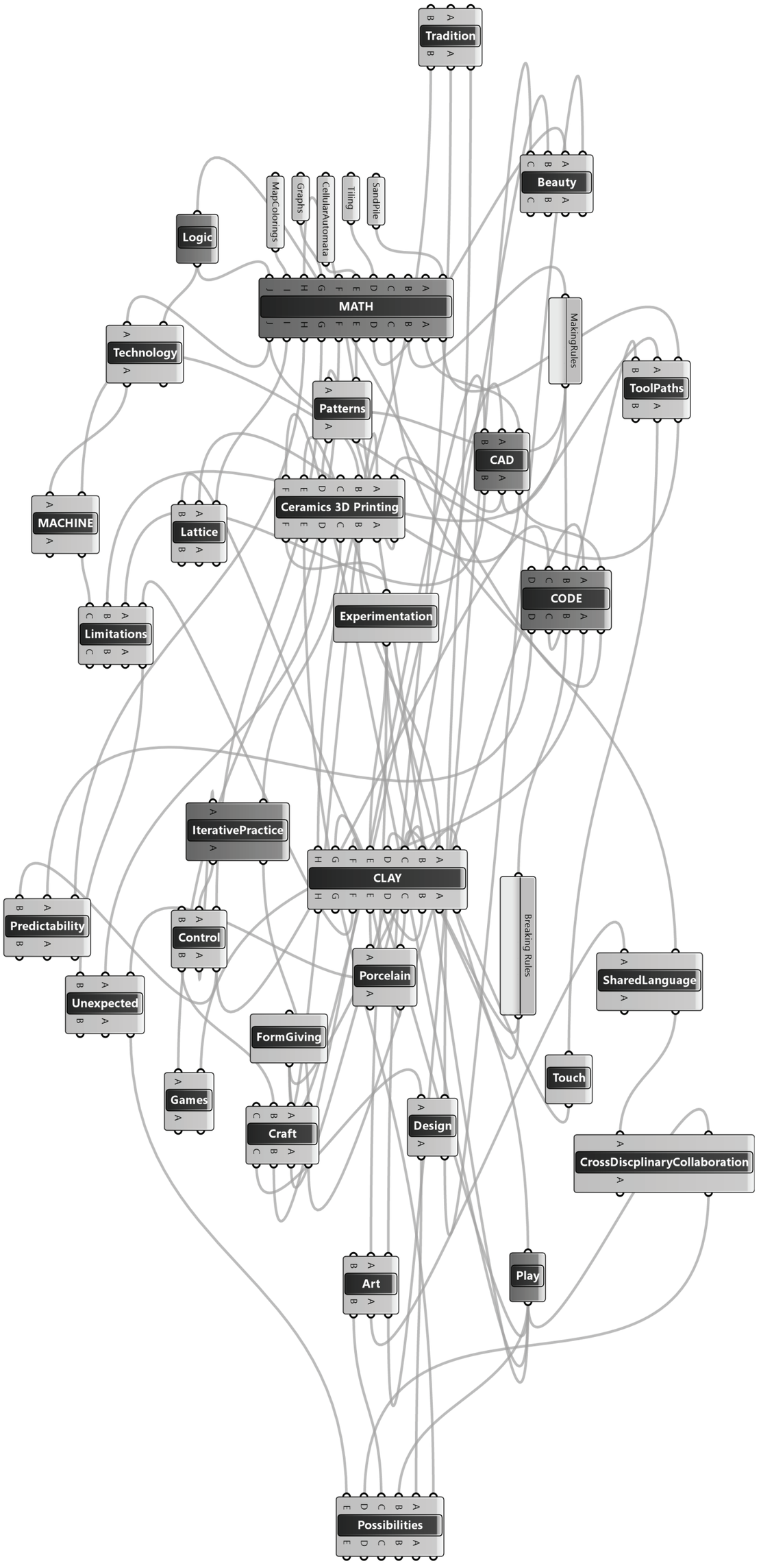
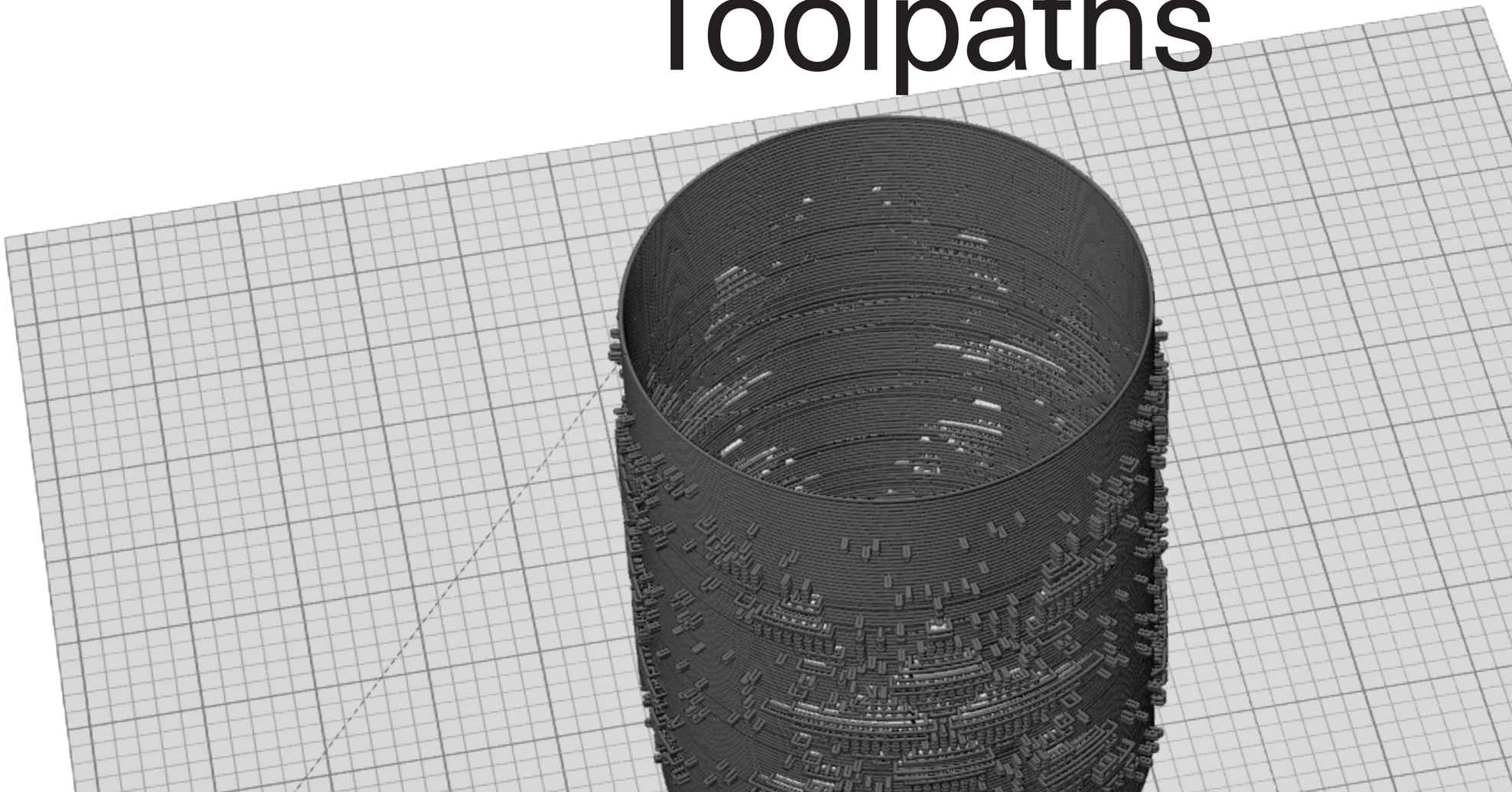
Contents


Tradition
Beauty
MapColorings
Graphs
CellularAutomata
Tiling
SandPile
Logic
MATH
Technology
MakingRules
ToolPaths
Patterns
CAD
Ceramics 3D Printing
MACHINE
Lattice
CODE
Limitations
Experimentation
IterativePractice
CLAY
Predictability
Control
Breaking Rules
Porcelain
SharedLanguage
Unexpected
FormGiving
Touch
Games
Craft
Design
CrossDiscplinaryCollaboration
Art
Play
Possibilities

Chapter Two

Toolpaths



Math ∩ Art. Say What?

MATH AND ART HAVE A LONG HISTORY TOGETHER

◊1 All cultures have left physical artifacts, along with written, drawn or oral histories that demonstrate some form of mathematical thinking manifesting in an astonishing repertoire of patterns found on functional, decorative and ceremonial objects. Everywhere we look we see evidence of mathematical thought, with which generations of artists have created rules and systems, representing ideas relevant for their communities. Mathematical rules are responsible for varying, transforming and repeating individual components of design ◊2 until they form larger complex systems of aesthetic significance.

Math has a reputation of being difficult and dry, but it can also be playful, accessible and quite beautiful. Art may be treated with no expectation for logic or practicality, but it has repeatedly demonstrated that it can be both useful to science and non-conforming at the same time. Separate as the two disciplines often seem in the contemporary compartmentalized world of education, there are various communities of artists, craftspeople, designers, mathematicians and programmers out there who take special interest in creating visual or physical manifestations of mathematical ideas in the form of images, animations, objects and VR/AR spaces. To these creative practitioners, the use of math is essential for the creation of something of an aesthetic value.

Each software platform—from photo manipulation to 3D modeling and virtual reality—that has been developed to support contemporary art and design practices attributes its existence to cutting edge research mathematics. Academia and industry often work in tandem on the theoretical development and testing of these technologies for possible applications that range from pragmatic uses to artistic whimsies.

Tools, processes, objects and sites, through which more and more people may become makers themselves, are critical to our shared understanding of how to navigate within the playfield of technological possibilities and digital futures. Mathematical thinking is not a requirement for feeling comfortable with these tools, but using digital tools and processes also could lead to building more precise cognitive habits and more awareness to how we actually think and solve novel problems.

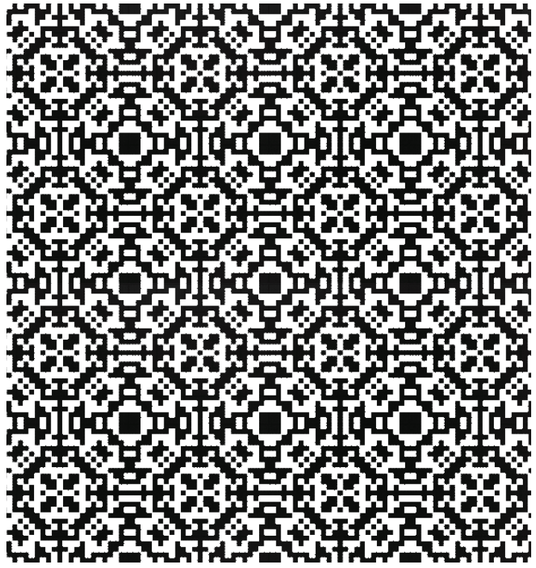
◊1 The mathematical symbol ∩ means the intersection of two sets.

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

RULES AND SYSTEMS IN ART While the creation of art is not expected to be logical, many artists and designers start out with a set of simple rules and limitations, only to find more freedom for improvisation and more creativity through constraints. In fact, all creative process begins by establishing boundaries and rules, which later are used as a point of reference: mostly respected or perhaps transgressed by intention. Many in the contemporary art world, such as the conceptual artist Sol LeWitt, [03] have been rule-makers. But it is enough to see the prolific work of generations of weavers, basket makers, beaders and potters to recognize this same human instinct for organizing: Small motifs and textures are combined endlessly into complex and varied, yet still logical, variations.
In *Critical Space* [04] contemporary artist Andrea Zittel lays out a list of things she knows for sure. Rule #10 on her list goes like this: *What makes us feel liberated is not total freedom, but rather living in a set of limitations that we have created and prescribed for ourselves.* Rule #11 states: *Things that we think are liberating can ultimately become restrictive, and things that we initially think are controlling can sometimes give us a sense of comfort and security.*

Algorithmic thinking, while not necessarily logical, is anchored down by the security of rules. Many forms of textile and fiber arts require a form of algorithmic thinking, which often ends up being responsible for ultimately creating the content in the work. [05] Knit, purr, purr, knit, . . . creates a rhythm and a textural pattern. Similarly to knitting, working with a ceramic extrusion printer builds up a form layer by layer. This requires the designer to anticipate the how the outcome of each line will affect the next and, as a consequence, affects all the later ones.

Of course, the reason why art appeals to us is often found in the breaking of the rules. However, disorder only makes sense in the context of order. The human mind [06] is wired to be attuned to both order [07] as well as to some form of irregularity created by a singular peculiar occurrence, which breaks the predictable rhythm.



[03] LeWitt explicitly created work by combining simple units of lines, colors or shapes in a rational manner and playing out all possible variations.

[04] Zittel, Andrea, Morsiani, Paola, Smith, Trevor, Contemporary Arts Museum, and Albright-Knox Art Gallery. *Andrea Zittel : Critical Space.* Munich: Prestel, 2005.

[05] This form of art is often referred to as PROCESS ART.

[06] It is safe to say that my interest in math has originated from an interest in how the mind works when making and breaking rules.

[07] This is most often in the form of repetition or some form of symmetry.

[08] When we first met more than a quarter century ago, Sándor wooed me with vivid and intriguing explanations about how to contemplate the existence of higher dimensions. Ever since, I can always rely on him for explaining obscure terminology or plugging in the sieve-holes in my understanding of math concepts, and for pointing out the necessary connections when I'm failing without them.

MY CONNECTION TO MATH At school, I never excelled in math. But I readily picked up on patterns and logical connections between things and was able to apply these from one example to the next quite easily. My formal math education ended at the pre-calculus level sometime in high school. Math probably would not be as much part of my life now had I not found a life partner in an amazing and generous research mathematician, Sándor Kovács. From our dates early on, to dinner table conversations to this day, he has continued to open up the world of math to my eyes and color it vividly with his own passion for the subject. [08]

In the past five or six years, I have been also reaching out to various mathematicians: sometimes to colleagues, friends or friends of friends; other times to willing strangers whom I contact cold via email and whom graciously lend me a bit of their time and attention. Sometimes I solicit photos of their workspaces like I did for *Parlor Games: Parallax*. [09] Other times, like during the making of *Axiomatic*, [10] I have general questions about math or the process of making math. Yet other times, I want to learn about a particular area of research, usually within the expertise of the researcher. [11]

During all these years, on and off between other artistic projects, I've been returning with regularity to the intersections of visual art and mathematical thinking. As an artist, I develop a grasp of things by constantly circling them, with the hope of getting closer and closer to some kind of understanding, even though I often find that comprehension itself is often malleable. My projects, even the non-mathematical ones, consider the process of knowledge-making, while trying to zoom in on where and how learning and knowing develop during the process of interaction between mind and the body.

In 2018, I was honored to co-receive the Bergstrom Art and Science Award with Sara Billey, which facilitated our year-long interaction focused on a type of mathematical algorithm that creates a self-organized behavior similar to grains of sand rolling off a large pile. Through these sandpile models, as they are called, I was able to get a rare insight into the creative process of doing research mathematics and understand more about algorithmic systems, while realizing some of the underlying math as textures created in 3D printed porcelain.

Around this collaboration a much wider theme, a more-encompassing potential has emerged for me: Going from my initial somewhat philosophical question about the scientific nature of order and chaos, I dove into combinatorics [12] and then further into math, observing an immensely rigorous and objective process of knowledge making. As much as I enjoyed the process of math-making, I also constantly found myself distracted by interesting paths that kept emerging on the side. Many of these became the topic of new work, provided additional layers of meaning to ongoing research or would become a source of a new project somewhat later. [13] Math, coding, digital form giving and parametric design build on one another. Each of these are by themselves deep and rewarding areas to explore with 3D printed ceramics. But the joy of being an artist is a penalty-free transgression of boundaries, be those of methods, disciplines or ideas. Our year of research had, most importantly, allowed me to contemplate how the deterministic nature of algorithmic, rule-based process may be disrupted by errors, mistakes, intentional

[09] *Parlor Games: Parallax* was a participatory installation at the Kittredge Gallery, University of Puget Sound in 2015. It explored themes of knowledge, discovery and chance by drawing inspiration from philosophy, theater, circus sideshows, parlor tricks, science labs and cabinets of curiosities. Many of the pieces in the show were inspired by objects people surround themselves with while at work.

[10] *Axiomatic* was a year-long collaborative research project with Jayadev Athreya, supported by a Simpson Center for the Humanities Collaboration Studio Grant. Through interviews with mathematicians, Axiomatic explored parallels of creativity in the arts and in math. As a result of this collaboration, I started creating math-art pieces in ceramics.

[11] Mathematicians have always been generous with explaining what they do and sharing digital models or code like those I used for making for *Perfect Imperfect* (courtesy of Henry Segerman) or in *Mystery. Solved. Mystery.* (courtesy of Ken Brakke).

[12] Sara's research area, dealing with enumerating possible solutions to game-like systems.

“viruses” or the uncontrollable nature of the physical world.

My questions about art and sculpture have not changed much since my early days in art making. They are only being re-contextualized in the technological paradigm of the present: What can be done with digital tools in the context of touch, space and the haptic sense? How does clay, when expressed through the digital process, help not only to explore this new kind of making but also to embody a different yet familiar tactile and sensory experience of the world?

13 Along those side paths, I was able to spend time on a comparative study of patterning traditions in grid-based textile techniques, such as Nordic and Eastern-European weaving, embroidery and knitting; to get not only some experience with coding but also contemplate the advantages, biases and fallacies of it; and to briefly revisit my neuroscientist past with questions like how our minds are programmed to think in terms of patterns, efficient shortcuts and other time-saving algorithms.

The Technological Paradigm

BRAVE NEW WORLD: TECHNOLOGY IN PRACTICE

The contemporary paradigm of the everyday world oscillates between a relentless technological idealism and a matching skepticism, going as far as depicting various digital doomsday scenarios. Traditionalists decry the good old days of analogue; while technophiles consider computational forces as a panacea for ills plaguing productivity, efficiency or an assertion of control.
I prefer to not subscribe to either of the extreme ideologies. Rather, I view technology as a tool with potential and significance but one that needs to be both examined and utilized critically. The pace by which our technological world is advancing and changing our daily digital environments, habits, tools and workflows creates all kinds of effects, which ripple through the practice of visual arts but also of mathematics. Keeping pace with the technological world is difficult for many reasons. [14] Withdrawing from the digital in favor of the analogue, however, is more of a romantic than a viable option.

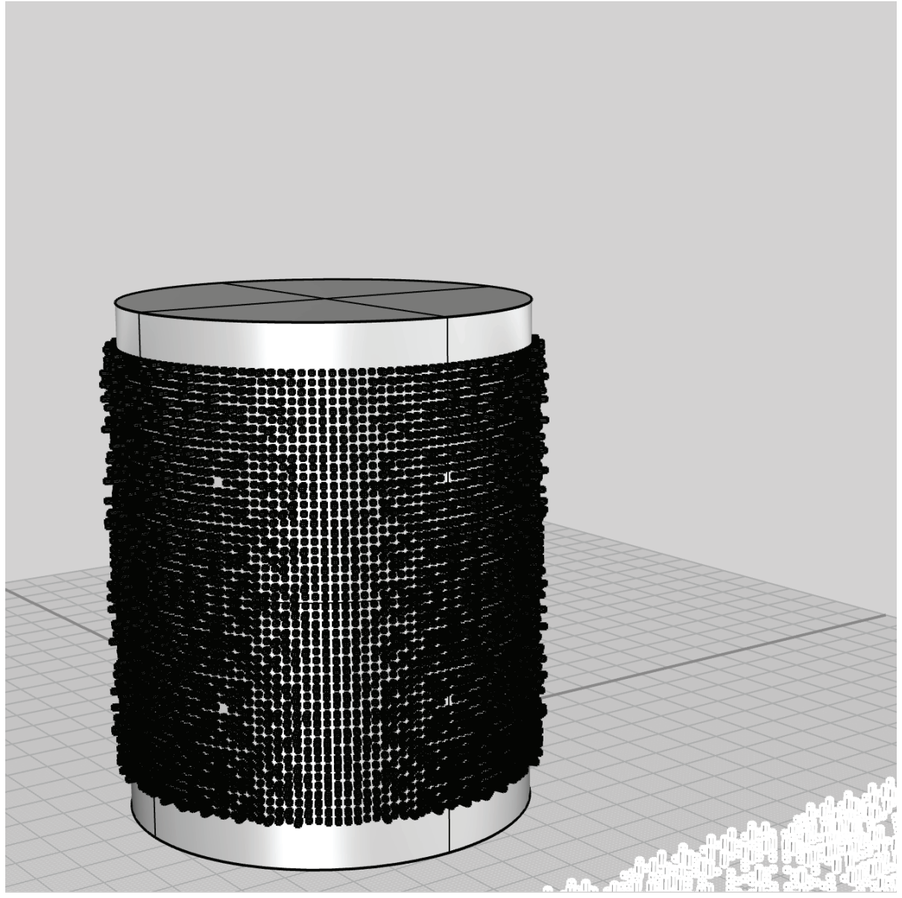
In the commitment necessary, I see my own daily encounters with technology in the studio similar to exercising choreographed routines of hands and analogue tools. The haptic practice of a craftsperson consists of a tremendous amount of repetition dotted with an occasional innovation, such as when honing a new move. [15] Working with digital tools, however, I also spend a large chunk of my time on actually learning new software or hardware and innovating by making new paths from one to the other: testing, hacking, changing, fine-tuning and constantly re-evaluating. Using a digital workflow, there are many ways to get to one thing. In this sense, digital ceramics projects have a significant research and development aspect. [16]

Digitally-aided is often synonymous with production on a massive scale. However, most of the projects described in this volume exist only as unique one-of-a-kind objects. Repetition only serves the process in perfecting the desired outcome, which can only happen through testing, testing, testing and copiously recording every minutia detail of the process.

[14] The most significant of these are related to access: economic, generational, geographical and educational.

[15] For example, a potter would perform a repertoire of touch over and over until clay gains a satisfactory form using the same set of moves and tools.

[16] Having to do with functionality, aesthetic effects or even just achieving some kind of a result. This R&D is similar to introducing a new product design in industry.



TECHNOLOGY, MATHEMATICS AND THE HUMAN Since mathematics does not describe the real world but looks for abstract relationships, it is part of everything we know and use in daily life. Mathematical games and patterns have been used for modeling and predicting outcomes in many areas of scientific research from physics, biology, medicine and pharmacology to population and traffic studies, fluid and gas dynamics, and artificial intelligence. [17] Mathematical modeling and visualization are dependent on computing. With the help of digital tools, mathematicians are able to get a glimpse of entities that defy the confines of our space-time dimensions. Similarly, mathematical functions are the engine of all design, meshing and parametric software packages used in designing three-dimensional objects on the computer. While an average user does not need to be well-versed in these, there is a definite advantage to considering from the math perspective what the software can or cannot do.

Repeatedly applying a set of rules that move figures on an ever-changing game board; associating one endless list of data with another; regularly transforming millions of points; figuring out a valid path from one coordinate point to the next with a certainty of a fraction of a millimeter, until the totality of it describes an object—these are aspects of computing and math I need every day in my making process of digital ceramics. Very little, if any, of this would be possible without digital tools. I have to admit that my human cognitive capacities are no match to what these tools can compute.

However, computation-based tools tend to become obsolete over time. A multitude of programming languages and even types of hardware/machinery have already gone out of use, making their programs and operations unsupported, thus no longer workable. The computational expenses of many digital workflows in 3D practice are just too much for computers older than a few years to handle. Thus, both the mathematician and the digital artist find themselves in constant need of innovation and investment, theorizing, building and testing out new workflows and tools that uniquely address their way of working or a certain desired outcome. Building cross-disciplinary collaborations and fostering communities where interactions between physical and digital makers can happen informs our shared learning with technology and our expectations toward it.

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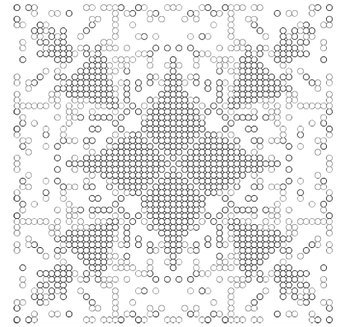
17 Schiff, Joel L. *Cellular Automata: A Discrete View of the World.* Hoboken, N.J.: Wiley-Interscience, 2008.

Mathematical Thinking is Universal

ON MATHEMATICAL THINKING Through my schooling in Hungary, I was lucky enough to get a reliable and lasting foundation in basic geometry and algebra, which was contextualized for us within a well-documented but completely Eurocentric intellectual tradition. [18] Western mathematics is based on a specific language and a representation system complete with its own proprietary methodologies and tools, which mathematicians use to advance knowledge in the field. The following quandary may be familiar to you from school: In order to be understood and to be able to solve problems that arise within math, one needs a fluency with its language and methods. Chances are, you either liked math and were good at it, or you got (self)labeled as having no math skills and avoided it at all costs. Thinking within the confines of a certain methodology, this all or nothing attitude made sense then.
It used to make sense to me too.

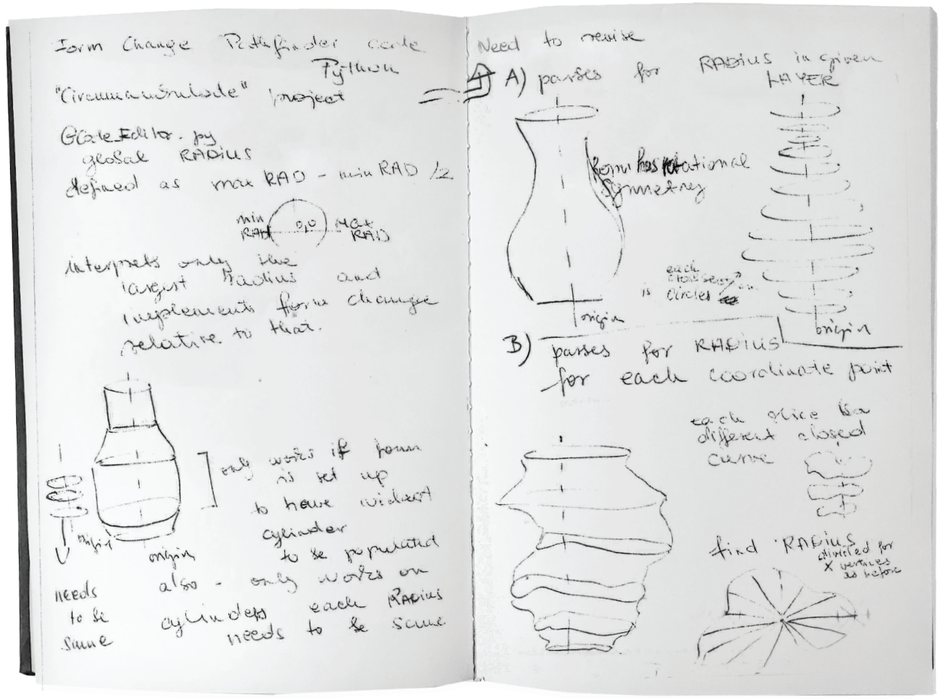
Only very recently, though, I have started considering a broader picture of mathematical ideas, some of which may even fall outside the Eurocentric tradition of the academic discipline of mathematics. While spending time in Brazil, I was introduced to ethnomathematics, a study of mathematical thinking and mathematical ideas in the social context of a given culture. The thinking processes studied by ethnomathematics [19] may seem a little out-of-the-box, but they are unquestionably useful within the specific context they belong. By themselves, these thinking processes create systems of language, logic, representation and methodology, which make sense and work efficiently in the given cultural fabric.

Being a visual artist and an outsider to math, the idea of an inclusive view of math appeals to me. In general, I find it more natural to think in terms of connections and not in terms of boundaries. As a result, when talking about my projects or process, I will be using the term MATHEMATICAL THINKING and reserving the word “mathematics” to refer to established areas of study.



[18] This version of mathematical history acknowledged very little of the interactions that happened amongst cultures. Instead, it created a trajectory from the Greeks, through the Renaissance, to modernity and all the way into the present; spanning bridges between math and all forms of making practices from the arts, to architecture, engineering, as well as to physics, linguistics and philosophy.

[19] Ascher, Marcia. *Ethnomathematics: A Multicultural View of Mathematical Ideas.* New York: Chapman & Hall, 1991.



PROBLEM SOLVING / PROBLEM FINDING In math, coding, design and in art making, how to build the path to the solution of a complex new problem is never obvious at start. It takes lots of trials, errors and revisions to get to the most simple, effective and most economical solution. This solution is often referred to as BEAUTIFUL by mathematicians. In pursuit of an artwork, economy of a solution may not be of concern. Instead, the most expressive end result may be the one that resonates with us, or the most unusual solution is the one that befuddles and intrigues with even more questions.

Similarly, in 3D printing, one can arrive at the final form through parallel paths. Because the process takes many pieces of software and equipment, figuring out what to do can often be a zig-zag path across multiple platforms and processes, and one with lots of U-turns. During the making of these projects, solving the math was only a starting place. There were many other questions to figure out related to the making, but these questions themselves were often unclear until I was able to get near enough to ask them with clarity and specificity. When making anything in art, each process step may require a unique solution, one that I may have never done or, never done in this same form. [20] This is always true in 3D printing with clay. In addition to thinking forward, I have to also think backwards in a step-by-step fashion and to know the conditions and limitations each stage imposes as well as how to answer those. [21]

The entire extent of this process is not obvious at the beginning; thus, I always find myself doing many trials and backtracks. The benefit of taking such a winding route when problemsolving is the many unexpected side-paths and surprises that I generate and get to study along the way. Being able to spot where an opportunity might arise (and change course) is a freedom uniquely belonging to art.

Many volumes have been written explaining the root of creative thinking in art and science. [22] For me, creativity simply comes down to this:

When observing how things work, finding opportunity in the unexpected or in the most mundane—even in blips and flaws.

Making it simple or if I can't, putting it together from the simplest steps.

Asking the "what if" [23] question when spotting potential.

Knowing when and how to revise a question. This is often no more than an intuition and not a logical calculation.

Listening to my intuition. Being able to do so is a matter of trust, but also a skill that is developed through practice. [24]

[20] This distinction between applying a well-honed set of actions toward an already defined solution or problem-solving through one unique step after the other and using the outcome of each step to determine the process is what differentiates CRAFT from art.

[21] In order to have my object come out the right way, I have to think about what kinds of structural issues the form might pose: how it sits on the printing plate, how it is sliced; anticipating how each layer's path will support or hinder the design.

[22] A few excellent sources that look at this question from a cross-disciplinary perspective:

Sawyer, R. Keith. *Explaining Creativity the Science of Human Innovation.* 2nd ed. New York: Oxford University Press, 2012.

Jacob, Mary Jane, and Baas, Jacquelynn. *Learning Mind: Experience into Art.* Chicago, IL: Berkeley, CA: School of the Art Institute of Chicago; University of California Press, 2009.

Lakoff, George., and Núñez, Rafael E. *Where Mathematics Comes from: How the Embodied Mind Brings Mathematics into Being.* 1st ed. New York, NY: Basic Books, 2000.

[23] As in "What if we create this system?" "Where do we start?" "What are the parts?" "What is the relationship among the parts?" "How does the system change over time?" "How could we impose our will on the behavior of such a system?" "How are we going to break it?" "When will it break?" "What will that look like?"

[24] Trust emerges from making mistakes and finding a way to solve them through fixes, patches, work-arounds or complete overhauls.

Artists and Mathematicians Working Together

LOOKING FOR A COMMON GROUND In early 2017, I had approached Sara with my inquiry about mathematical rules that have the potential to build complex and sometimes unpredictable systems. What may seem to be an interesting question for a (somewhat geeky) coffee date, is not without challenges when it grows into a work collaboration. Our first hurdle was language. Needless to say, we had none in common at the beginning. Each of our disciplines has its own specific vocabulary and interpretation; the essence of communication within a professional peer group is mediated through this language. Outside of the professional group, each term needs a lot of explanation, as it tends to carry both historical and contextual subtleties.
As we went on, we needed to define—and often redefine—our shared semantics. We bridged the gap with a conditional vocabulary, which was a result of compromise: neither rigorous enough for a mathematician nor quite descriptive enough for an artist. But it moved us along, and that was important. While our work was visual in a large part, a shared language helped to explain what was done, what needed to be done and where to go next.

Our second big challenge was to not simply illustrate existing math but to think and make collaboratively in a way that generated new ways of thinking about the subject of our inquiry. Getting into the math too deeply is not without risks for an artist. Throughout the process, I was simultaneously worried about my lack of understanding of the in-depth mathematical research and about losing sight of my initial research question on how algorithmic systems create complexity. I repeatedly got sucked into endless hours of pondering, problem solving and problem finding about some of the math we were discussing.

You see, mathematical thinking is quite satisfying and addictive.

My interest in rule-based systems came from a place that was not mathematical in the beginning; rather, it was about how our human brain thinks and makes sense of things through logic and cognitive patterns. In the process of our collaboration, I was able to get a glimpse of how math is being made. I found that mathematical thinking as a mental exercise is rather beautiful, slick and effortless when practiced with rigor.
I definitely wanted to keep in mind why I was working with math and kept asking myself “What, if anything from our findings, is vital and meaningful to me?” “Where are the connections between these ideas and those real-life experiences that other people care about?” “How do I explain this work to a general audience in a way that does not submit non-experts to too much tedious technicalities?” “At the same time, how may the resulting work help to spur a love of math and mathematical thinking?”

The third issue was solely technical, based in the studio and a fairly novel challenge. I set out to devise a physical processes for making numerical data tactile using clay. I had to do this in a way that made sense not only for using a 3D printer but also created a meaningful result in the context of ceramics as an art form. 25
Exciting as the math process is, art is first and foremost about conveying an idea through making: an aesthetic expression paired with a meaningful experimental or craft process. The development of the artwork, I found in comparison to doing math, moves along in a completely different time-dimension. 26

25 Even when I got to hone in on the digital workflow, the material itself frequently ended up being an even more challenging aspect. I use porcelain, one of the most technical materials in sculpture. Myriad issues make the process rather unpredictable, mostly due to the inherent material qualities of clay. In ceramics, nothing is ever taken for granted until it comes out of the kiln.

26 Ample time was necessary for developing workflows, arriving at novel solutions, which took both trial-and-error tests as well as endless repetitions to refine. The production of ceramics itself is very time dependent: drying, firing, glazing, refiring require the artist to submit to the process of time and matter. Even when I got to hone in on the digital workflow, the material itself frequently ended up being an even more challenging aspect.
In addition, it took me a while to reflect on what came out of these tests and to acquire and polish the language that allows me to share this work with others.

Technology and the Craft of Ceramics

In the emerging area of ceramic 3D printing, tools, processes and outcomes are being developed at this current moment, resulting in a continuously changing field of equipment, software and paradigms. It is exhilarating to be at the forefront of such innovation where individual experiments, even the “failed” ones, can easily take hold and become trends. Contemporary ceramics comes in regional flavors that are beholden to traditions. Digital ceramics, on the other hand, has been developing as a global and universal expression. Besides reflecting on its own origin story in technology, digital ceramics also has the responsibility to consider its own relation to the rest of the clay tradition.

3D printing is a form of ADDITIVE [27] manufacturing, which gained popularity in the beginning of the 21st century. One of the most important reasons behind the vigorous spread of this technology is its deep roots in co-development through sharing and collaboration. [28] The RepRap spirit of open-source is still very much part of how the small but devoted community of global multidisciplinary makers develop new tools, pragmatic and conceptual foundations and visual aesthetic through shared iteration and innovation, while putting the results back into the digital commons.

The ceramic 3D printers used by artists these days are not entirely novel tools among additive sculptural processes. This type of printer is essentially a soft paste extruder, albeit a very smart and precise one. They are a modified version of the commonly available 3D printers, which use various types of plastics. [29]
In ceramics, extrusion tools have been used from studio pottery to industrial mass production of tiles, bricks, and pipes. These tools are based on holding a certain volume of soft clay paste under pressure and squeezing it through an opening with a desired diameter and shape. So, in the sense of the physical process of manipulating clay, the extruder 3D printer is not novel tool.

What is novel about it is in the idea of breaking down—or, rather, building up—a form based on spatial coordinates. This gives the process an unprecedented granularity, [30] accessibility and transparency. Following the prescribed path of the digital design, the ceramic 3D printer extrudes a thin coil of soft porcelain and creates the object layer by layer, line by line. The form it makes is still dependent on the materialness of clay and would not exist and often cannot stand without the human hand.

This material quality of clay is unlike any other material in the repertoire of techno-objects. [31] Clay has physicality, a strong presence, which the digital potter is able to exploit even more: Building the final design from organized rows of increasing heights, this modern tool connects her to the ceramic tradition of coil building [32] and wheel throwing. Both techniques build on repetition that allows the maker to predict and control the outcome with a good degree of certainty or refine this process when needed. [33]

Working with ceramics is time-sensitive and material-sensitive, which, combined with a craftsperson’s touch, the nature of the specific tools used, and clay’s own ability to morph throughout the process, results in a certain level of unpredictability and adds a degree of variability to the finished object. In addition, the digitally aided workflow creates limitless entry points for creating and hacking a design, be those on the level of the design software, code, machine properties and settings or focused on the ceramic materials themselves.

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27 Building by adding material, as opposed to SUBTRACTIVE, such as carving, that takes away material.

28 A project, started by Adrian Bowyer in 2005 at the University of Bath, called RepRap (replicating rapid prototyping) was the original impetus of this rapid growth. The RepRap initiative has developed versions of accessible low-cost 3D printers that can print most of its own components. They can be built quite easily, as well as modified for various printing needs, such as using paste materials. Users contribute to the development of the project by continuously tweaking and updating it, keeping each new version open and public.

29 PLA and ABS are the most common types of plastics used for printing. More about these in CHAPTER 4. In these printers, the extruder part contains a heating unit, which (similarly to an ordinary glue-gun) melts and thus dispenses the plastic filament.

30 detail and potential to manipulate

31 such as digital embroidery, computer knitting, CNC carving, etc.

32 Coiling is probably the most ancient technique for building with clay. It refers to creating long thin rolls of clay and placing one on top of another, gradually pushing, squeezing and shaping them into a growing wall.

33 This leads us back again to the notion of craft. Digital ceramics is a form of practice where the craft process is paired with inviting and exploiting the unexpected and unrepeatable, looking for chance to introduce alternate possibilities.