Hold Up:
Machine Delay in Architectural Design

by

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ABSTRACT

This thesis introduces an architectural design approach that is founded on working with digital fabrication machines, materials, and time: Machine Delay Fabrication (MDFab). MDFab is characterized by the materialization and manipulation of the time taken by digital fabrication machines to do work. MDFab contrasts with other approaches to digital fabrication that architectural design has appropriated from adjacent fields (for example, human-computer interaction and automated manufacturing). In particular, MDFab is a response to “real-time” digital fabrication techniques, which use embedded sensing to immediately interact with the designer, material, and/or environment. Real-time techniques have negatively distanced architectural designers from material, temporal, and instrumental understanding. Further, the current dependence on real-time points to a future of anti-anticipation: a time in which architectural designers—and human beings, in general—will not have to anticipate what happens next. MDFab is an alternative to this future: it offers a way to interact with digital fabrication machines that enables architectural designers to advance the material thinking, improvisation, and speculation that are—and should always be—fundamental to the architectural design process.

The first part of the paper is concerned with the historical, theoretical, and practical contextualization of MDFab. MDFab is situated within work in both the arts and sciences that has explored the productive potential of delay. These experiments in delay set up critiques of three contemporary architectural design approaches to digital fabrication. These critiques are supplemented by an examination of digital fabrication projects that have opened alternative contexts for architectural design research. The first part concludes with a discussion of the science and practice of curing in concrete fabrication. The second part of this paper is dedicated to the introduction of Machine Delay Fabrication. The foundational concept of MDFab, machine delay, is introduced. The conceptual design implications of MDFab are discussed. The method of 3D printing concrete that was invented to explore MDFab is presented through a detailed account of its design. The findings of the concrete 3D printing exploration are used to speculate on the aesthetic, constructive, and ethical possibilities of MDFab in architectural design. Finally, the work is recontextualized in terms of the not-so-distant future that awaits architectural design practice.

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A Note to the Reader

Though this work will mostly be presented in what I hope to be a logical—and somewhat chronological—order, there will be moments in which I will deliberately visit things from the future or revisit things from the past. Hold tight; the (deferred) end will arrive.
Prologue: The Promise of Creating Grain

My thesis work began, in earnest, in December 2016, when I wrote a paper called “What Can Ragnar Kjartansson Teach Digital Fabrication (or, The Promise of Creating Grain).” In that piece of writing, I used the work of Icelandic performance artist Ragnar Kjartansson to describe what I felt was missing—and what could be gained—from our interactions with digital fabrication machines. I tried to write in, or on, a kind of mechanical loop: cycling back and forth between my memories of Kjartansson’s repetitive performances and my present disillusionment with the use of machines in contemporary architectural design practice and education. I tried to point to what could be gleaned from the poignancy of Kjartansson’s physical embodiment of the machine—I don’t think I had the words then that I have today.

After writing that paper, I resolved to find out exactly what I meant by “The Promise of Creating Grain.” I initiated research into developing a new way for architects to design with digital fabrication machines, specifically 3D printers: I wrote software; reconfigured digital-to-physical workflows; designed machine parts; and speculated on new forms of architectural design. I broke the machine (open) and made it fail, a lot. Upon reflection, my research process was unmistakably architectural, it had: conceptual development (the “Grain” paper and initial, small-scale 3D printing studies); design development (the creation of “the machine” and scaling of the experimentation); and construction documentation (the speculative blueprint that I layout in this paper). I hope that other young architectural designers will be inspired to embark upon similar explorations in search of their own Grains.

Now, without further delay, I’ll tell you what I found.
Part I
1. The Productive Delay

We begin our discussion by looking at historical projects in the arts and sciences that have explored the productive potential of delay. In addition to demonstrating that creative explorations into delay are nothing new, these projects provide a conceptual foundation for understanding how digital fabrication has brought about the prospect of a new kind of productive delay in architectural design.

MINIMAL MUSIC

As Slow as Possible / John Cage

Musical compositions require rests. A rest can produce: the tension between two notes; the end between one passage and the beginning of the next; or, depending on its duration, the background upon which sound is scattered. John Cage’s “As Slow as Possible” (2001-ongoing) began with a rest that lasted for seventeen months.1 Once it is completed, Cage’s piece will be the longest concert in the world, taking place over six-hundred and thirty-nine years. Note changes will occur several years apart so that most of the piece is filled only with the resonance of notes that were played in the distant past. The near silence of “As Slow as Possible”—which results from the extremely delayed end of each note—produces a sonorous context in which other events take place: the organ is tuned, repaired, and maintained; sermons are held in the church where the organ is housed; celebrations are organized when a note is changed.2 The piece is sustained by the rest. As

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1 Fritch, John and Jeffery Byrd. “Aural Argument: Cage’s ‘As Slow As Possible’.” Reasoned Argument and Social Change, Edited by Robert C. Rowland, Washington, National Communication Association, 2011, 529-536, 532.
2 Wakin, Daniel J. “John Cage’s Long Music Composition in Germany Changes a Note.” New York Times, May 6, 2006, http://www.nytimes.com/2006/05/06/arts/music/06chor.html. Accessed February 25, 2018.
one journalist noted, “the performance is so slow that the organ it is being played on was not even complete before the music began.” In other words, the performance establishes, exceeds, and precedes the machine.

**Tape Loops / Karlheinz Stockhausen**

A very different example of productive delay in music can be found in the experimental composition of Karlheinz Stockhausen (1928-2007). Stockhausen is considered a pioneer of electronic music primarily for his introduction of tape loops (physical loops of magnetic recording tape that cause sounds to repeat) into the compositional process. Stockhausen’s fellow composer Jonathan Harvey describes Stockhausen’s set-up thus:

> The soloist plays via a microphone into a tape recorder which records him. The sound travels along a tape loop (adjustable) which gives a delay before being played back over stereo loudspeakers. This same sound on its way to the loudspeakers is in addition diverted back on to the (stereo) recording head, which for some of the time will therefore be recording both the live soloist and his time-delayed recording.

The delay, that is, is turned into the primary element of composition. In a typical arrangement, Stockhausen determines the delay between the recording and playback of the sound, while three “players” collaborate on how the soloist is recorded as well as what part of the recording is played back: in turn, the soloist is asked to anticipate, remember, or respond to the feedback of the tape loop. The specific way in which the music is delayed determines how the musician improvises upon the composition and, ultimately, how the improvisation becomes the piece itself. In Stockhausen’s composition, we can see how delay produces material—including, in a sense, the one doing the delaying.

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3 Judkis, Maura. "World’s longest concert will last 639 years." *Washington Post*, November 11, 2011, https://www.washingtonpost.com/blogs/arts-post/post/worlds-longest-concert-will-last-639-years/2011/11/21/glQAWrdXiN_blog.html?utm_term=.600888ea9660. Accessed February 25, 2018.
4 Harvey, Jonathan. *The Music of Stockhausen*. Berkeley and Los Angeles, University of California Press, 1975, 97.
5 Harvey, 98.
Delay in Glass / Marcel Duchamp

Marcel Duchamp’s “The Bride Stripped Bare by Her Bachelors, Even” (1915-1923) is popularly known as “The Large Glass.” However, it has another title, which only exists in Duchamp’s scribbled formulation of the work: “Delay in Glass” (“Retard en Verre”).

Duchamp’s piece consists of an intricate material collage that depicts a mystical scene of automaton-like suitors chasing after a “half-robot,” “half four-dimensional” bride. Between “the bachelor machine” and “the bride machine” are several panes of glass—this is ostensibly what keeps the bachelors from reaching the bride. Glass is also used to sandwich the entire assemblage, which causes it to appear to be more of a window than a sculpture.6

What is a delay in glass? There are at least two possible readings of Duchamp’s lesser-known subtitle. First, we can understand that the scene is suspended: the gravity-defying bride permanently floats above the bachelors in another part of the glass sandwich—the dramatic conclusion of the chase has been indefinitely deferred. Here, we can see Duchamp’s efforts to cut and spatialize time; that is, to create “an instantaneous state of rest.” In Duchamp’s view, this jolting-to-a-rest produces a metaphorical electricity that surges through the piece. He calls this charge, which ran between the Bachelors and their would-be Bride, “clockwork movement.”8 The delay is what keeps the piece ticking, its internal motor.

Another reading of the subtitle is that Duchamp is working in, or with, the medium of delay. He chooses “delay in glass” as a painter would choose “oil on canvas.” However, there would be a crucial difference in this analogy: delay is a property that is inherent to glass, whereas oil paint is not inherent to a canvas. As glass refracts light, it slows that light down—the light is delayed; oil paint is applied to a canvas. In this sense, since “The Bride Stripped Bare by Her Bachelors, Even” exists between panes of glass, we could say that it is the very delay in glass, i.e., its refractive properties, that makes the work visible.

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6 Dalrymple Henderson, Linda. *Duchamp: In Context*. Princeton University Press, 2005, 89-90.
7 Henderson, 200.
8 Henderson, 91.
Drip Painting / Jackson Pollock

Jackson Pollock (1912-1956) also works with the delays caused by inherent material properties. But Pollock’s style is more overt than Duchamp’s. Pollock is famous for innovating “drip painting,” in which he lays canvas on the ground and uses different techniques to cover it with paint from above. Pollock draws in the air and lets gravity do the painting. By physically distancing himself from the canvas, Pollock is able to simultaneously witness the paint as it falls and decide where to next move his body. Art historian Claude Cernuschi argues that the delay in movement between artist and paint—the paint always one step behind the artist—also gives Pollock a fuller understanding of the fluidity of the material. While the paintings might look frantic and arbitrary, the delays embedded in the painting process are part of a method that is carefully devised.

In Pollock’s case, the material delay works on multiple levels. First, the viscosity of paint causes the painter’s encounters with the canvas to occur at different rates, which ultimately causes different painted forms to appear. For example, if the artist is moving quickly while dripping viscous paints from greater heights, the delay between artist and paint is longer and sparser lines land on the canvas. Second, as previously mentioned, the delay allows for a critical distance in which the artist can observe the material fluidity and refine it to better suit his expression. Stockhausen’s delays facilitate improvisation between multiple collaborators; Duchamp’s delays allow the material to improvise on itself; Pollock’s delays enable the painter to improvise with himself.

Performance Loops / Ragnar Kjartansson

Like his predecessors, Duchamp and Pollock, the Icelandic performance artist Ragnar Kjartansson (b. 1976) innovates old artistic techniques to push disciplinary boundaries. In particular, Kjartansson translates the musical technique of looping—which Stockhausen discovered in(or, invented with) tape recorders—into physical performance. Kjartansson’s work typically consists of performers, himself included, repeating the same theatrical or musical act for hours without stopping: the performer, that is, becomes the mechanical loop. In these repetitions, Kjartansson creates a space of “ceaseless, repetitive

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9 Schjeldahl, Peter. “The Dripping Point.” The New Yorker. December 21-28, 2015, 18.
10 Cernuschi, Claude and Andrzej Herczynski. “The Subversion of Gravity in Jackson Pollock’s Abstractions.” Art Bulletin, vol. 90, no. 4, 616-639, 2008, 622.
unfolding that materializes the passage of time and fills its passing with layers of performance.”¹¹ There is not one end in Kjartansson’s performances, but several. Similar to Cage’s work, the end—the real end—is perpetually delayed. Unlike Cage, however, Kjartansson’s delay is not caused by drawing the end out but by re-presenting it over and over again. The architectural design methodology that I propose in this thesis depends on lessons learned from Kjartansson’s looping.

ARCHITECTURAL DESIGN

Architectural designs cannot possibly materialize as instantaneously as the bits and products that now circulate through social networks and global markets—their materialization takes time. Most architects have responded to this new fact by frantically attempting to enable architecture to catch up with virtual and late capitalist realities; others, though, have begun to show the benefits of further delaying the materialization of architectural design as a response to our current historical moment.

Bruder Klaus Chapel / Peter Zumthor

The Bruder Klaus Chapel by Swiss architect Peter Zumthor (b. 1943) was completed in 2007. The interior and exterior of the structure are built using two very slow means of fabrication that combine to produce a space that is unparalleled in its materiality. The concrete that comprises the envelope of the Chapel was poured at a rate of 50cm per day for 24 days that were spread out over the course of nearly a year. The delay between pours creates horizontal seams, which are evocative of rammed earth construction.¹² Zumthor calls the technique “rammed concrete.” The effect of the rammed concrete is a building that resonates within the natural landscape in which it sits: the building does not merely sit on a hill, as many other buildings do, but rather becomes a material transposition of the hill’s underlying geological stratification. The interior of the Chapel is constructed using a different delayed fabrication process. The formwork for the rammed concrete exterior was a conical arrangement of felled trees. When the final layer of concrete was put in place, the

¹¹ Schoen, Christian, ed. The End: Ragnar Kjartansson. Ostfildern, Germany, Hatje Cantz Verlag, 2008, 17.
¹² Postell, Jim and Nancy Gesimond. Materiality and Interior Construction. Hoboken, John Wiley and Sons, 2011, 229.
trees were set ablaze and left to smolder for three weeks—or, until they had turned to ash. The charred imprint of the absent forest is permanently cast into the concrete walls.\[13\]

The building appears as though it is simultaneously being layered upon and crumbled from within. Like Duchamp’s Glass, it is stuck in an ambiguous moment of becoming.

**3D Printed Steel Bridge / MX3D and Joris Laarman Lab**

We can find another, more recent example of productive architectural delay in a very different kind of architectural practice. Since 2015, a robotic additive manufacturing startup, MX3D, and Joris Laarman Lab have collaborated to 3D print a steel bridge. The project, which was very recently completed, had considerable technical challenges. Unlike 3D printed plastic, which is the most commonly used material for 3D printing, 3D printed steel cannot be continually piled upon itself: when steel is reheated before it is allowed to fully harden, it loses strength. As a result, a cooling period has to be granted for each bit of steel that is printed. Initially, this cooling period caused significant delays in the bridge’s fabrication process. But the MX3D the team have come up with a more efficient way of depositing the steel that leverages the necessary delay. Instead of printing each layer all at once, the printer divides the layers into segments: while one segment is cooling, the printer moves onto the next segment, which is located in another location so that the just-printed steel is not reheated too soon. The non-linear path of the machine shortens the overall cooling process and allows the printer to continue onto the next layer more quickly.\[14\] The embrace of the necessary delay as a *productive* delay—rather than as an obstacle—actually optimizes printer speed rather than slowing it down.\[15\]

**THE SCIENCE OF MEASUREMENT**

I will now turn back to the 19\textsuperscript{th} century to discuss technological innovations that addressed the collapse of time and space in an increasingly connected world.

\[13\] Postell, 229.

\[14\] Kuang, Cliff. “How Machine Learning Will Unlock the Future of 3D Printing.” *Fast Company Design*, September 19, 2017, https://www.fastcodesign.com/90143244/how-machine-learning-will-unlock-the-future-of-3d-printing. Accessed February 23, 2018.

\[15\] This fabrication method bears similarities to the novel concrete 3D printing method that I will introduce later on, particularly with regards to its use of non-linear tool path planning. I would consider this project to be another instance of Machine Delay Fabrication.
Standardized Time

When public clocks were first introduced to Paris in the latter part of the 19th century, each clock told a slightly different time. The pneumatic impulse that caused them to tick originated at the central clock, which was located at the center of the city; the impulse took different times to reach the clocks depending on their respective distances from the city center. As railroad transportation became more common, public clocks became more ubiquitous and the tiny delays between them increasingly became more problematic for commuters that wished to make it to their trains on time. In 1880, city officials came up with a plan to compensate for the minute temporal discrepancies: they would delay the transmission of the impulse to each clock by an amount of time that was proportional to the clock’s distance from the central signal. The central impulse, now, was sent to the clocks at the outer-most parts of the city before it was sent to those that were more centrally located. This innovation, or embrace, of delay produced standardized time in Paris.

The American Method of Longitudinal Measurement

The 19th century also saw the beginning of the scale of globalized trade as we know it today. Despite the higher frequency and greater lengths of naval travel, cargo ships had no way to precisely determine their longitudinal position. Latitude could be determined by gauging the altitude of the sun, but longitude had no accurate reference point. The lack of a longitudinal measurement system was a particularly large obstacle for transatlantic trade between Europe and the United States. Ships simply had no way to track their position across the Atlantic Ocean and could not monitor the durations of their trips.

In 1849, the astronomer William Cranch Bond devised the “American Method” of keeping time to solve this problem. In the American Method, one person tapped on the key of a telegraph at every second. Each tap transmitted electrical current to other telegraphs on the same network. These distant telegraphs noted the receipt of this broadcast by drawing a tick mark on a drum of rotating paper that cycled through the telegraph receiver’s

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16 Galison, Peter. *Einstein’s Clocks and Poincare’s Maps: Empires of Time*. New York, W.W. Norton and Co., 2004, 94.
17 Andrewes, William J.H. “A Chronicle of Timekeeping.” *Scientific American*, February 1, 2006. https://www.scientificamerican.com/article/a-chronicle-of-timekeeping-2006-02/, Accessed February 26, 2018.
18 Galison, 102.
19 “American Method in Astronomical Observation.” *The National Museum of American History*, http://americanhistory.si.edu/collections/search/object/nmah_852072. Accessed April 13, 2018.
printing device. A local clock set to the same time as the distant clock simultaneously triggered tick marks on the same paper at the same pre-established intervals. The distance between the mark made by the local clock and the mark made by the distant clock was dependent upon the time it took for the distant signal to arrive, which was dependent upon how far away it was located. By measuring the space between the marks, naval travelers could precisely tell what time it was. More importantly, since the earth rotates on its axis every twenty-four hours, they could establish a precise measurement of longitude (fifteen degrees of longitude equals one hour).  

Both of the above scientific inventions—standardized time and longitudinal measurement—utilized the concept of delay and the concept of simultaneity. While my research acknowledges the irrevocable intertwining of delay and simultaneity, it also proposes that a discussion about temporality in architectural design is more productive when it is contextualized in terms of delay.

In addition to providing historical and theoretical context, all of the above examples reveal an essential characteristic of delay: it is found in all temporal things. Stockhausen found delay in the tape recorder; Pollock found delay in thick paint; Zumthor found delay in earthen processes; Bond found delay in electronic impulses. Delay is always already present in time. In this thesis, the organizing question is not whether delay exists, but rather: When does it exist? How much of the delay is there? And: What do we do, as architectural designers, when delay occurs? The brief history of productive delay outlined above offered some possible ways of addressing these questions. In the next chapter, I provide a survey of contemporary architectural design approaches to digital fabrication in order to demonstrate how—if at all—we are trying to answer these questions in our own field today.

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20 Galison, 103-104. “American Method in Astronomical Observation.” The National Museum of American History, http://americanhistory.si.edu/collections/search/object/nmah_852072. Accessed April 13, 2018.
2. Contemporary Architectural Design Approaches to Digital Fabrication

Digital fabrication is a general term that is used to describe a variety of additive and subtractive manufacturing techniques that are implemented through a combination of CAD (computer-aided design) and CAM (computer-aided manufacturing) software. In this chapter, I will critique the interests and objectives of what I consider to be three distinct approaches to digital fabrication research and practice in architectural design: 3D printing; optimization; real-time. In particular, I will show how these approaches conflict with the kind of working-with machines and materials that I described in the previous chapter.

3D PRINTING

The advent of 3D printing has encouraged an approach to digital fabrication that is, in general, anti-making and anti-materiality. In the typical architectural designer-3D printer relationship, we delegate the task of making—and all of the thinking that necessarily goes with it—to the machine: an apparatus that is literally outside of ourselves. We are fundamentally disembodied from the making of our designs. This disconnect is exacerbated by the fact that 3D printers are usually located in spaces that are physically separate from the designers that use them. We are not even there to witness our designs materialize.

One consequence of this disembodiment is that no knowledge about the machine is gained. For example, when the designer returns to the machine to find that her print has failed, she likely will not know why. Rather than trying to understand why the print failed (or to find creative opportunity in the failure), most designers, particularly architecture students, will try another machine or another fabrication process. The quickness with which designers give up on 3D printers points to the disposability of the 3D printer in the design process. We only recognize our
dependence on the 3D printer when the machine breaks down and fabrication by another means would take too much time—only then, that is, do we sit with our machines.

On an ontological level, the ability to make without being present for the act of making affords the pseudo-virtue of “multi-tasking,” or the ability to fill the passing of time with more things. By distributing our “self,” in the Cartesian sense, across several places at once we dematerialize our extension into the physical world. We spread ourselves thin. The consequence of this spreading-thin, I want to argue, is that we become out of touch with our own materiality (Fig. 1).

Fig. 1. Designer as slicer: the materiality of the printed thing is a result of my inability to precisely trace my own lines.

In addition to disconnecting us from ourselves, 3D printers also put us out of touch with the materiality of things. “Black box” 3D printers—so called because of their hermetic enclosures—prevent us from understanding formative material processes by encapsulating material formation within the machine (Fig. 2). Desktop plastic printers, for example, must all at once: move filament to the extruder head, instantaneously heat it, push it through the nozzle, cool it; in the more expensive models, the printer heats the filament again to make sure that it doesn’t cool too quickly once it touches the print bed. Within this carefully choreographed, micro-assembly line, there is a great deal that designers could learn about the materials they are printing with (e.g., how they can be formed). And yet, this knowledge is often hidden behind proprietary plastic armor. If we compare our current
3D printing systems to Pollock’s dripping technique, we can clearly see how our material understanding is being limited.

![Image of a 3D printer interface with a notification]

**Fig. 2.** A mysterious message pops up on the interface of a “black box” 3D printer—“the sensor has detected a malfunction.”

Architectural designers often use 3D printers out of convenience. As a result, our interactions with 3D printers are almost literally thoughtless: we default to the machine settings (settings that are optimal for the printer, but not necessarily for the design); press “start”; and walk away. If the print is successful, we return to find our design idea solidified in plastic: unworkable and inadvertently finished. The smoothness of the printer’s plastic output homogenizes our design thinking, but our brief interaction with the machine does not allow us to see this.²¹

In a typical 3D printing workflow, the designer creates a 3D model and then passes it through “slicing” software, which sections the model into a series of thin horizontal layers—the thinness of the layers is dictated by the print resolution the designer wants to achieve. Each layer is subsequently divided into X-Y-Z coordinates, formatted into G-Code (the standard machine programming language), and input to the machine. The layers are then printed in order, starting with the bottom layer first. Such a workflow is designed to ensure the most predictable result: layers are

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²¹ The unworkability of 3D prints has contributed to the decline of sketch models. Instead of cardboard, hot glue guns, and scissors, architectural design students now use plastic and 3D printers. 3D printers simply do not encourage students to conceptualize their projects through material experimentation. If not the materials at our fingertips, what then informs our architectural design concepts today? A discussion for another time, perhaps.
precisely laid on top of one another for hours, sometimes days, on end. However, this material predictability comes at the expense of design flexibility: the slice does not change during, or as a result of, the printing process. It is as permanent and predictable as a saw cut.

Fig. 3. On the left: a typical failure caused by not instructing the printer to provide supports; on the right: a study in which I speculated on how that failure could be instrumentalized and integrated into a 3D print.

If we look more closely at the uniquely direct representation-to-materialization workflow of the 3D printer, we can find the opportunities to experiment with the materiality and instrumentality that are central to the conceptualization of architectural design (Fig. 3).

Architectural designers can reject the predetermination of the slice. 3D models do not have to be discretized into strata and materials do not have to be layered—in fact, most materials, like the steel in the aforementioned 3D printed bridge project, do not want to be layered at all. We can leave room for the material—and not the machine—to interpolate between points (Fig. 4). Kai Franz has demonstrated such techniques with his “Plopper” system. In Plopper, liquid binding agent is messily drizzled on piles of sand from varying heights. The results are unpredictable undulating composite meshes that resemble scribbles that have been extracted from crumpled pieces of paper.22

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22 Franz, Kai. “Dual-Axis Precision Deposition System(Plopper).” Kai Franz, http://www.kaifranz.de/Plopper.html. Accessed April 22, 2018.
Researchers at the Bartlett School of Architecture’s Design Computation Lab and MIT’s Digital Structures Group have invented ways to print without any kind of layering by manipulating the material state changes that are, as previously mentioned, typically encapsulated within the machine. In these techniques, the plastic filament is heated and cooled at precise rates to enable extrusion in midair. More recently, MIT’s Self-Assembly Lab has developed a rapid liquid printing process in which material cures as it is being suspended in a gel solution—there is no print bed to layer upon. In contrast to the rigidity of the typical 3D printing workflow, these projects work with material properties to offer architectural designers other, more imaginative ways that their designs might materialize through the machine. More importantly, this kind of speculative research shows us that how we design is influenced by how we make and what tools we use.

Similar threads of research have been conducted in the programming of 3D printers, specifically the creation of novel G-Code software. In “Monolithic Representations” by W. Andrew Atwood, software glitches are observed and instrumentalized into a novel 3D printing interface. The
designer can interject different textures into conventional 3D prints by instructing the printer to “pause,” “loop,” or “gap.” I will discuss Atwood’s research in more detail in the next chapter.

Recent advances in full-scale 3D printing, specifically in concrete, have narrowed the gap between how we design and how we build. Yet concrete 3D printers still form material in the same way as their desktop-sized counterparts: through digital slicing and physical layering. As a result, 3D printed concrete buildings look like scaled up versions of printed architectural models. There is nothing gained in the material translation other than scale. Of even greater significance for the linkage between architectural design and construction is that the printing process is not yet embraced as a constraint in the design process: 3D printed concrete buildings look like fossilized versions of existent architectural styles.

Fig. 5. An early study in 3D printed cement demonstrated some characteristics of the method that I introduce in this thesis.

The unique expression of the concrete 3D printer, as both a tool for design, fabrication, and education has not yet been realized. There are, however, some obvious opportunities for investigation. 3D printing concrete negates the formwork that is used in conventional concrete construction techniques—designers and builders can literally see forms as they materialize (Fig. 5). This potential for learning from, or working with, the material as it is being printed has seldom been

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25 Atwood, W. Andrew. “Monolithic Representations.” Matter: Material Processes in Architectural Production, Edited by Gail Peter Borden and Michael Meredith, Routledge, 2012, 205-212, 209.
explored. Instead, research in concrete 3D printing, like that which is carried out at the Technische Universiteit Eindhoven or at Contour Crafting, is mainly focused on how to engineer both the material and the machine to produce the most controlled or largest possible outcome—the objectives are optimization and buildability rather than architectural design.26

Some exceptions to technically-focused 3D printed concrete research include the design research of Rael San Fratello, Amalgamma, and Bekkering Adams, in which new methods of materializing concrete have been explored through experimentation with 3D printing workflows.27 The unique aesthetics and fabrication methods that were unveiled in this research prove that 3D printed concrete can be used to rethink architectural form-making processes.

OPTIMIZATION

Optimization in digital fabrication is an exploitation of digital tolerances that results in an excess of precision. The digital fabrication machine can achieve the resolution equivalent to pixels on a computer screen; however, the materials we fabricate with cannot achieve this same precision. Still, we expect digital objects to seamlessly flow into physical things and, in most contemporary architectural practice and education, we spend significantly more time optimizing our digital models rather than their physical representations. We design for the digital model rather than potential of its physical being; for the precision of the machine rather than the messiness of our design thinking.

We can see the lack of concern for materiality in how much time architectural designers dedicate to optimizing digital representations (e.g., renderings): we create virtual soundstages; texture digital surfaces with images of materials found online; and zoom to 400% on Photoshop to eliminate any trace of digital imperfection. We spend more time searching for the perfect texture map in Google Images than we do handing the material itself. In turn, the role of the digital fabrication machine has become the physical reproduction of the digital image (Fig. 6). But images do not scale up to the material world or into the reality of materializing architectural design.

26 Bos, Freek et. al. “Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing,” Virtual and Physical Prototyping, vol. 11, no. 3, 2016, 209-225.; Khoshnevis, Behrokh. “Automated construction by contour crafting—related robotics and information technologies.” Automation in Construction, no. 13, 2004, 5-19.
27 Augur, Hannah. “Fossilized” 3D Printed Concrete Structures by Amalgamma.” ALL3DP, January 24, 2016. https://all3dp.com/fossilized-3d-printed-concrete-structures-amalgamma/. Accessed April 22, 2018.; Rael, Ronald and Virginia San Fratello. “Material Design and Analysis for 3D-Printed Fiber-Reinforced Cement Polymer Building Components.” Ambiente 11 Proceedings. Edited by Hallnas, Lars, et. al. Sweden, CTF The Swedish School of Textiles, 2011, 136-141.; Teague, Lauren. “3D print is making an impression on concrete.” FRAME, January 31, 2017, https://www.frameweb.com/news/3d-printing-is-making-an-impression-on-concrete. Accessed April 30, 2018.
Some architectural practitioners, such as Marc Fornes / Theverymany and Aranda Lasch, take the exploitation of digital precision even further by leveraging the low tolerances of digital fabrication machines to implement complex computational forms. However, these forms are optimized according to geometric parameters rather than material constraints. The material, along with the digital fabrication machine, is an afterthought, a means to a predetermined end. Projects that rely on optimized computational geometries are often discretized into hundreds, if not thousands, of several small parts because their architectural designers use pixels as a metaphor for materials. Optimization is not as effective for the architectural designer that must negotiate parameters (e.g., social, political, economic) beyond those of her own creation.

In structural optimization workflows, engineers put whole buildings through comprehensive digital analyses (e.g., the finite element method) to find ideal or, at the very least, safe solutions. The results of structural analyses are output with several decimal places, even though their built interpretation—i.e., the construction—will likely be carried out on “muddy sites by workers wearing thick gloves.”

The discrepancy between the digital world of simulated forces and the real world of construction shows the excessive precision of optimized structural models. Structural simulations are, at best, approximations of actual, material constraints. Further, the real world of construction

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28 Hughes, Francesca. *The Architecture of Error: Matter, Measure, and the Misadventures of Precision*. The MIT Press, 2014, 5.

29 Hughes, 128.
includes other constraints that impact material assemblies: coordination between various tradespeople and manufacturers; unpredictable site conditions; the competing interests of multiples stakeholders and regulating agencies—its complexity defies simulation.

Digital fabrication can work towards achieving impossible structural tolerances, but optimization itself is asymptotic. We might take the well-known example of Gramazio Kohler’s brick-stacking robots, which embody the supposed virtue of “robotic precision.” Even in the precarious stacks of bricks certain material allowances had to be made—the research team actually uses adhesive to hold the bricks together.³⁰

There will always be a disparity between the precision of the robot and the imprecision of the brick it places. We need to recognize that understanding the brick necessarily precedes understanding the robot that places it.

Any simulation or optimization of material performance through parametric modeling—be it for geometric, structural, or robotic purposes—must be coupled with a fundamental understanding of how the material works. Otherwise, the designer does not know what to input to the parameters or, in some cases, what parameters to create. We should use digital fabrication to build the material intuition that is necessary to make optimization useful rather than convince ourselves that optimization is an end in itself (Fig. 7). The architectural preoccupation with optimization has to do in part with a fixation on the approaches of adjacent disciplines, such as product design or industrial manufacturing. In these related fields, digital fabrication occurs at small scales and/or in controlled environments. It is not coincidental that most of the completed work by computational designers, like Theverymany and Aranda Lasch, exists mostly in the form of pavilions or pieces of furniture.

The most risky place for design optimization is in architecture schools. Architectural design education has levels of indeterminacy that are necessary to prepare students for the uncertainty in architectural practice. New architecture students, whose design exercises are made deliberately vague and abstract, are most adversely affected by a premature introduction to optimization techniques. In focusing on optimization, these students inhibit other drivers in the design process—namely their own subjectivity—as well as the cultivation of improvisational design thinking. Alternatively,

³⁰ Bonwetsch, Tobias, et. al. “The Informed Wall: Applying Additive Digital Fabrication Techniques on Architecture.” ACADIA 06. Edited by Gregory A. Luhan, et. al., Louisville, Kentucky: University of Kentucky, Lexington, 2006, 489-495.
architecture schools can use digital fabrication to assist with “uncertainty training.”\(^3\) The digital fabrication machine, that is, can facilitate experimentation with aleatory material processes—indeterminacy can be studied rather than overcome.\(^3\)

![Fig. 7. I formed an arch by heating a piece of aluminum and drizzling plastic (with a 3D printer) from above. The conductive properties of the metal enabled the arch to form.](image)

**REAL-TIME**

Real-time digital fabrication represents architecture’s most significant attempt to overcome uncertainty and material disparities. Real-time researchers equip machines with various sensing mechanisms so that they can immediately respond to, or interact with, the material, the designer, and/or the environment. Digital input, via the sensors, and machine output are so tightly coupled that the process gives the impression of instantaneous interchange—everything appears (to a human) to occur in “real time.” However, what we perceive is only the appearance of simultaneous cause and effect. In fact, for real-time feedback loops to function efficiently (or at all) one thing must happen after another and delays—although imperceptible—must and do take place.

\(^3\) In his book, “The Nature and Art of Workmanship,” the industrial designer David Pye outlines two approaches to making: the workmanship of risk and the workmanship of certainty. He argues that if we encourage certainty over risk, we will eliminate craft, as well as all of the unexpected possibilities and pleasures that come with it.

\(^{32}\) Hughes, 247.
Most current research in digital fabrication unequivocally embraces the benefits of real-time techniques without interrogating either their disciplinary origins or implications. The concept of real-time has been borrowed by digital fabrication researchers from the related fields of computer science and human-computer interaction. In computing, real-time is useful due to the large amounts of information that must be cycled through a processor at any given moment. It is also necessary because of the high expectations—both in industry and in everyday life—of processing speed and system responses. (For instance, we don’t doubt for a second that the letter “a” will appear immediately after we strike its corresponding key on the keyboard.)

Architectural design, however, does not have the same “deadline” requirements as real-time data scheduling. In practice and education, the design process must make time and space for self-reflection and observation—we must stand back from our drawings to see how our lines read. Further, architectural design pedagogy teaches the importance of iteration by requiring students to alternate creation and critique until they have realized the fullest potential of their design concept. The cultivation of design concepts through iteration takes time.

At the scale of construction, time is even farther removed from the minutia of real-time computing. Due to unforeseen circumstances and tedious amounts of coordination between designers, engineers, and builders, building projects are rarely executed on schedule. Architectural designers usually account for construction delays even before the construction begins. Unexpected construction delays are often the result of decisions that were hastily made during the design process. There can be nothing fast about designing a building.

Real-time digital fabrication techniques are always delayed by the properties of the materials they operate on; machine impulses can move faster than materials can react. Therefore, the digital fabrication machine has to be tuned to the speed of the material process in order to carry out its function. When the machine is not tuned, material failures occur (Fig. 8). For an architectural designer, this tension between speed and materiality is significant because it means that employing real-time techniques is often, though not always, an attempt to control material rather than work with it. As a discipline that necessarily engages with issues of materiality and uncertainty, architecture...
must consider whether or not the appropriation of real-time is in fact useful for architectural design processes.\textsuperscript{35}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{On the left: the print speed was tuned to the material; on the right: the print speed was faster than the material could support itself.}
\end{figure}

Some uses of real-time in digital fabrication preclude designers from working with materials at all. In some cases, for instance, digital fabrication machines are programmed with information about material performance so that they can cycle through feedback loops until a certain goal is achieved. The act of relinquishing sensory perception to sensing devices is more dangerous for architectural design than other disciplines—though truly not beneficial for anyone—because thinking through materials is a skill that architects need to improvise in both design and construction. For example, when drainage issues cause mold and cracks to form on the brick façade of our newly designed computer science school, we need to understand why and what material system is required to fix the issue.\textsuperscript{36}

The encapsulation of material knowledge by real-time techniques is exemplified by the “anti-simulation” approach that was put forth by Roland Snooks. In anti-simulation, sensors receive and transmit information about material performance to modify pre-programmed tool paths in real-time:

\begin{quote}
\textsuperscript{35} I’m not necessarily advocating for a return to the intuitive methods of artists like Pollock or Stockhausen but rather for a way to combine the virtues of the digital fabrication machine, e.g., repetition, with that of the human designer, e.g., improvisation.
\end{quote}

\begin{quote}
\textsuperscript{36} See “MIT Sues Frank Gehry, Citing Flaws in Center He Designed” at www.nytimes.com/2007/11/07/us/07mit.html.
\end{quote}
“design takes place in and on the object rather than in anticipation of the object.” In other words, the machine fabricates according to changes sensed in actual material performance rather than according to a code that has been derived from digital material simulation; it can self-correct, absorb error, and respond to unpredictability. Snooks’ method moves past sheer optimization; however, it also deliberately leaves out the empirical observations of the designer—material intuition is gleaned by the machine. Real-time techniques sacrifice human learning for the sake of efficiency just as optimization techniques sacrifice subjectivity for the sake of precision.

Another representative real-time project is “Augmented Materiality” by Ryan Luke Johns. In Johns’ research, an augmented reality (AR) interface is introduced to allow the designer to control the robotic melting of a piece of a wax in real-time. The designer determines where the melting should occur and the software determines how to melt the material without compromising the overall structure of the form. The fabrication progress is relayed to the designer—in real-time—as the melting is carried out. The AR interface visually obscures the material so that what the designer is truly augmenting is an augmented image of wax rather than the wax itself. The interface conceals the material process as it is occurring.

My research is less interested in creating more “intelligent” digital fabrication machines, in the Negropontian sense, than it is in establishing the knowledge that architectural designers need to work with digital fabrication machines. I aim to break open feedback loops, dig into material processes, explore the necessary and productive delays in real time, and, in doing so, give the machine a different context to work in. Similar objectives have been investigated in recent digital fabrication projects that will be presented in the next chapter.

37 Snooks, Roland and Gwyllim Jahn. “Closeness: On the Relationship of Multi-agent Algorithms and Robotic Fabrication.” Robotic Fabrication in Architecture, Art, and Design 2016, Edited by Dagmar Reinhardt et. al., Springer, Heidelberg, 2016, 219-239.
38 Johns, Ryan Luke. “Augmented Materiality: Modelling with Material Indeterminacy” Fabricate 2014, Edited by Fabio Gramazio et. al. 216-223. Zurich, gta Verlag, 2014, 216-223.
39 The techniques demonstrated in both Johns’ and Snooks’ work project originated in theoretical work that was done almost fifty years prior. In his treatise, “The Architecture Machine” (1970), architect and MIT Media Lab Founder Nicholas Negroponte defines an “intelligent machine” as one that can “discern changes in meaning brought about by changes in context.” Negroponte later goes on to advocate for real-time graphic interfaces and embedded sensing so that the machine can “see, hear, and take walks in the garden.” Ironically, the subtitle of the book is “Toward a More Human Environment.”
3. Machine Misuse

Digital fabrication has reached a turning point in its relatively short history as a field of study: now, it can, and should, depart from its manufacturing origins and establish evaluative criteria beyond convenience, optimization, speed, and efficiency. This chapter discusses recent work that has explored digital fabrication machines in alternative aesthetic and constructive contexts. I call this work “machine misuse.” My research advances this new research direction by contextualizing digital fabrication machines in terms of their temporality. Before I give examples of machine misuse, I will situate it in the philosophy and history of breaking machines.

FINDING USE IN BROKENNESS

The ontological question of usefulness became more urgent as a result of the utilitarianism of the Industrial Revolution. Such urgency is reflected in the work of the twentieth-century German philosopher Martin Heidegger, who lays out his concept of “handiness” (Zuhandenheit) in his now famous example of the hammer:

… the less we just stare at the thing called hammer, the more we take hold of it and use it, the more original our relation to it becomes and the more undisguisedly it is encountered as what it is, as a useful thing. The act of hammering itself discovers the specific ‘handiness’ of the hammer.40

40 Heidegger, Martin. Being and Time. Translated by Joan Staumbaugh, Albany, State University of New York Press, 1996, 69.
When the hammer is broken, Heidegger goes on to write, it does not lose its handiness. Instead, it becomes “present-at-hand” and we, in turn, are compelled to focus our attention on the thing itself—on both its material properties and on its physical potential. The concept of being present-at-hand points to a distinction between brokenness and failure central to my architectural research: the broken thing approaches failure but has not yet failed. All hope is not lost in brokenness. On the contrary, the broken thing contains the possibility of recovering its being. To be clear, Heidegger does not address the possibility of fixing brokenness; however, for my research, repairing the tool—as well as our relationship to it—is part of the reflection that architectural designers need.

The contemporary Italian philosopher Giorgio Agamben also speaks about being present through brokenness but in terms of “the work of art.” In fact, Agamben comes very close to naming delay as both the essence and gift of the work of art: “... in the work of art, the continuum of linear time is broken, and man recovers, between past and future, his present space.” Agamben argues that the work of art breaks time by having its own rhythm, and, further, that its rhythm creates the perception that we are “held, arrested before something, but this being arrested is also a being-outside, an ek-stasis in a more original dimension.” Herein lies a key difference between Heidegger and Agamben. In Heidegger, brokenness comes about through holding the hammer in your hand—i.e., through use or misuse; in Agamben, brokenness arises by being “held” by the work of art. Heidegger's brokenness is active(you can do the breaking), whereas Agamben’s brokenness is passive(you are broken).

The kind of digital fabrication research that I call “machine misuse,” which is concerned with the direct manipulation of machines, operates within a more Heideggerian framework of brokenness. In this work, researchers: devise a novel methodology to appropriate, or “take hold of,” digital fabrication machines; break them; investigate their brokenness; then reinvent their use. The difference between machine misuse and Agamben's brokenness is that in machine misuse brokenness is of the researcher's making. However, machine misuse also adopts aspects of

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41 Heidegger, 72.
42 I came across machine delay by inducing temporary states of brokenness (which will be described in Chapter Five) that revealed the working of the machine. Machine delay, in other words, pointed to and grounded the integrity of the machine. To reiterate from the conclusion of the first chapter: delay is found in all temporal things.
43 Agamben, Giorgio. The Man Without Content. Translated by Georgia Albert, Stanford University Press, 1999, 101-102.
44 Agamben, 99.
Agamben’s brokenness by arguing that, in some instances, you hold up the machine in order to be held—or show how you’re already held up—by it.

**HISTORICAL EXAMPLES OF MACHINE MISUSE**

Much like historical explorations into productive delay, investigations into brokenness through the misuse of machines are also nothing new. Here, I will discuss two examples of such work from the visual arts and design.

**Glitch Art / Nam June Paik**

In the visual arts, experimentation with brokenness was initiated by mid-20th century media artists such as Nam June Paik. Paik literally and figuratively deconstructs the emergent technologies of his time (for example, CD players, color TV, and audio samplers) to uncover the artistic possibilities that arose as each machine is forced to the brink of failure. In Heideggerian terms, his work deliberately positions new technologies in a state of present-at-handedness so that we, along with the artist himself, can witness the aesthetics—both visual and cultural—of their functionality. In one series, Paik creates environments that are augmented by glowing assemblages of broken television sets. Paik manipulates the circuitry behind each television so that it displays only one, distorted image rather than the assortment of wholesome programming that is a staple of American households at the time.

**Design Hacking / Andrew Witt**

Designer, theorist, and historian Andrew Witt, argues that the practice of altering machines to achieve “specifically aesthetic ends” is not new to design, either. Witt points to experiments with drawing machines that were directed at expanding the “range of visual geometry,” which non-architects began carrying out as early as the 19th century. For example, William F. Rigge, an astronomer and reverend, spent more than a decade devising an elaborate machine of different-sized gears in order to draw new kinds of combinatorial curves (the machine was completed in

45 Brooks, Andrew. “Glitch/Failure: Constructing a Queer Politics of Listening.” *Leonardo Music Journal*, no. 25, 2015, 37-40, 37.
46 Weaver, Alison. “Nam June Paik: The Photograph as Active Circuit.” *Afterimage*, vol. 42, no. 3, 2016, 16-21, 16.
47 Witt, Andrew. “Design Hacking: The Machinery of Visual Combinatorics.” *Log*, no. 23, 2011, 17-26, 17.
48 Witt (2011), 18.
Witt draws parallels between historical pursuits of what he calls “instrumental knowledge” and the contemporary conviction that innovating digital fabrication machines is a valid approach to “spatial invention.” “Design hacking,” as Witt names the contemporary analog, has precedent in the lineage of experimental machine-making practices. However, Witt also acknowledges that the emergence of new technologies, e.g. parametric design and robotic fabrication, has fundamentally changed the trajectory of this kind of design experimentation. It is this new trajectory that I would now like to examine.

**CATEGORIES OF MACHINE MISUSE**

I am going to organize the following contemporary examples into four categories:

- **Digital Materiality**
  projects that are concerned with augmenting the physical presence of the machine;

- **Material Computation**
  projects that combine the intelligence of materials with the intelligence of machines;

- **Computational Manipulation**
  projects that reconfigure and/or reinvent software parameters;

- **Machine Reconfiguration**
  projects that focus on building their own machines or machine parts.

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49 Witt, Andrew. “A Machine Epistemology in Architecture: Encapsulated Knowledge and the Instrumentation of Design.” *Candide Journal for Architectural Knowledge*, no. 3, 2010, 37-88, 37.

50 Witt (2011), 17.
DIGITAL MATERIALITY

Morphogenesis / Betti Marenko

The contemporary Italian theorist Betti Marenko encourages designers to work in a morphogenetic model of matter in order to access “ways of understanding the material processes by which objects come into being.”\(^5^1\) In Marenko’s model, material processes include everything from manufacturing assembly lines to electronic circuits. Marenko contends that a morphogenetic approach can grant designers deeper knowledge of the materiality(e.g., silicone chips, copper wiring, ceramic components, etc.) of the digital machine and, further, that designers need this knowledge in order to design to for the material intelligence of the “technodigital object.”\(^5^2\)

Props / Francois Roche

The work of experimental architect Francois Roche is in the spirit of Marenko’s morphogenetic thinking. In his studio, New Territories, Roche creates architectural narratives that portray uncanny human-machine relationships, disrupt ordinary perceptions, and project dystopian futures. In New Territories’ fantastical fictions, the machine often has a material embodiment and a twisted psychological outlook. Such strange unfolding is exemplified by his project, “Props.”

In Props, pre-programmed robotic deposition is disturbed by the robot’s reaction, via sensors, to the materialization of its own mechanics: the sound of its kinematic movement; the air from its pistons; or the clicks from its switches. Material is frenetically and randomly spewed rather than carefully and precisely placed. The materiality that results from the chaotic deposition process is an expression of the robot’s inner workings or, as Marenko might say, the robot trying to understand its own coming-into-being.

MATERIAL COMPUTATION

Remote Material Deposition / Gramazio Kohler

Fabio Gramazio and Matthias Kohler are popularly known for their work in the robotic stacking of bricks. In that body of research, the team demonstrates the complex arrangements and low tolerances that can be achieved when a robot is transformed into a mason. In a lesser known

\(^{51}\) Marenko, Betti. “Digital Materiality, Morphogenesis and the Intelligence of the Technodigital Object.” *Dekonze and Design.* Edited by Betti Marenko and Jamie Brassett, Edinburgh, Edinburgh University Press, 2015, 107-138, 137.

\(^{52}\) Marenko, 111.
project called “Remote Material Deposition” (RMD) the researchers demonstrate a more extreme interaction between robot and material performance. In RMD, the robot is not delicately stacking bricks into precarious configurations, but instead throwing large clay pellets into a sinuous low wall. The strength and precision of the robot facilitates the experiment, but it is truly the sticky and soft properties of the clay that enable the unexpected material result.

Can’t Help Myself / Sun Yuan and Peng Yu

A far less constructive, though equally provocative, example comes from the world of performance art. In 2016, the Guggenheim Museum in New York City showed its first piece of robotic art, entitled “Can’t Help Myself.” The piece, which was conceived by the Chinese artistic duo Sun Yuan and Peng Yu, consists of a large robotic arm that has been condemned to contain its own continuous leaking of a thick red liquid with an extra-large metal squeegee. The task is futile; the robot can never quite sop up all of the fluid and each scrape of the squeegee invariably leaves red streaks behind. The result is a constantly evolving robotic painting that is part-Jackson Pollock and part-Francois Roche.

PARAMETRIC MANIPULATION

Scripted Movment Drawing Series I / Andrew Kudless

In Scripted Movement Drawing Series I, Andrew Kudless explores various robotic drawing techniques, but the ones I am most interested in here concern the manipulation of typical software inputs (e.g., layer height, speed, pressure) to achieve a range of visual effects. For example, Kudless equips a robotic arm with a felt-tipped pen and programs it to draw a grid of over one thousand of the same circle. However, he manipulates the code so that each is drawn with a different amount of pressure—some circles appear faint and others bold. Kudless’ drawings are visual fields that bleed in and out of focus.

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53 Doerfler, Katherine et. al. “Remote Material Deposition: Exploration of Reciprocal Digital and Material Computational Capacities” What’s the Matter – Materiality and Materialism at the Age of Computation, Edited by Maria Voyatzaki, ENHSA, 2014.

54 Kudless, Andrew. “Matsys, Scripted Movement Drawings Series 1.” http://matsysdesign.com/2014/07/13/scripted-movement-drawings-series-1/. Accessed February 26, 2018.
Monolithic Representations / W. Andrew Atwood

W. Andrew Atwood conducts research that is similar to Kudless’. Atwood writes his own G-Code software that enables him to interject material anomalies into standard plastic 3D prints. Atwood names his new printing operations “Gap,” “Loop,” and “Pause.” In Pause, the designer stops the extruder movement, but not the extrusion, for a certain amount of time before continuing its programmed routine. The dwelling of the active extruder results in a bump whose size is proportional to the duration of the dwell. The Pause technique is similar to some components of the new 3D printing technique that I will introduce later.

MACHINE RECONFIGURATION

Making Machines that Make / The Maker Movement and Nadya Peek

The Maker Movement has emerged out of the nascent do-it-yourself culture that was brought on by contemporary social media (e.g., YouTube). The Movement is characterized by the use of open source design and prototyping software, the sharing of design knowledge through online platforms, and the standardization of digital design information. Nadya Peek, a recent PhD graduate from the Center for Bits and Atoms at MIT’s Media Lab, epitomizes the ethic of the Maker Movement and takes it even further by developing ways for makers to make their own machines for making. Peek’s dissertation, entitled "Making Machines that Make: Object Oriented Hardware Meets Object-Oriented Software," is aimed at making “the making of tools accessible at a personal level.” Peek’s DIY CNC kits empower users to make whatever machine they can imagine. In recent workshops, students have used the kit to make machines for laser shows, painting, pizza-cutting, Zen gardening, and playing chess.

SCUMAK (Auto Sculpture Maker) / Roxy Paine

The American sculptor Roxy Paine engages less in the reconfiguration of machine parts than in the recontextualization of machines processes. Paine designs and fabricates bespoke machine parts to juxtapose natural and industrial processes. In his SCUMAK (Auto Sculpture Maker) series, Paine creates a microcosmic assembly line, which consists of a large-scale plastic extruder that drips

55 Anderson, Chris. *Makers: The New Industrial Revolution*. New York, Crown Business, 2014, 21.
56 Peek, Nadya. *Making Machines That Make: Object Oriented Hardware Meets Object-Oriented Software*. Dissertation, MIT, 2016, 16.
gobs of material onto a conveyor belt. \textsuperscript{57} The layered heaps of plastic look like lava that has been displaced from the side of a volcano. SCUMAK appropriates the imagery and physicality of industrialization, as well as the materiality of large-scale natural phenomena, to contextualize a machine that does nothing of any use.

I will now pause the discussion on digital fabrication to focus on one, unique instance of productive delay in material processes: curing time.

\textsuperscript{57} Volk, Gregory. “Roxy Paine: Reaching for the Sublime.” \textit{Art in America}, October 2010, 136-142.
4. Curing Time

The purpose of this chapter is to show that materials, like machines, take time to do their work and, further, that this curing time is a necessary and productive delay. At the end of the chapter, I will pivot to look at the work of two artists that have explored material possibilities inherent to processes of forming concrete.

THE CURING PROCESS

The process of curing concrete illustrates the intrinsic entwining of temporality and materiality in the production of architecture. Broadly speaking, curing is the chemical process whereby certain materials harden. In concrete, curing is brought about by cement hydration, which is the reaction between water and cement that causes the binding of particles in a concrete mix. The role of concrete fabricators in the curing process is to control “the rate and extent of moisture loss from concrete during cement hydration.” In other words, we cure concrete until we get the material performance we want.
In construction, concrete is typically left to cure for the duration that is necessary to ensure that it meets specific structural performance criteria, such as strength or durability—longer curing times increase the probability of producing concrete that performs at a more structural level. In fact, even though concrete can be ready for use, i.e. load-bearing, after only a few weeks, curing that continues on a molecular level can increase its strength over several years. If insufficient curing time or unconducive curing conditions are provided, material failures such as cracking, erosion, shrinkage, or creep may occur quicker than expected and worsen until they become hazardous. To be clear, cracking and shrinkage, which some architectural practitioners may regard as imperfections, always occur—it is just a matter of when they occur and to what extent. In either the strengthening or weakening of concrete, most permanent effects are delayed.

The curing of concrete is affected as much by the contents of the mixture as it is by environmental conditions. For example, the primary consideration in curing time is controlled dehydration, which is affected both by the water content of the mixture and the humidity of the immediate context. There are a number of techniques used to reconcile the internal and external moisture levels, including: the use of set and/or surface retarders; misting the concrete with water at regular intervals; and keeping the form wrapped in a vapor barrier (Fig. 9). Unmanaged moisture

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61 Benboudjema, Farid. “Delayed Effects – Creep and Shrinkage.” *Mechanical Behavior of Concrete.* Edited by Jean-Michel Torrenti et. al., Hoboken, NJ, Wiley and Sons, 2010, 339-401, 347.
62 Taylor, 2.
loss can bring about rapid shrinkage, which can lead to fissures that increase the likelihood of a complete material breakdown.

Atmospheric temperature is also an important consideration in the curing process. Colder temperatures will result in decelerated evaporation and a slower curing process, whereas warmer temperatures will have the opposite effect. Volatile or extreme temperatures conditions can cause differences between the internal and surface temperatures of the concrete that also lead to dangerous amounts of cracking.\textsuperscript{63}

The interior of concrete continues to cure long after the exterior has finished curing, but the material becomes inaccessible to probing after it reaches a certain hardness. Therefore, there is no precise measurement of how much concrete has cured over long durations of time. There are, however, a variety of methods that are used for approximating the rate of dehydration: using a rebound hammer to test hardness; testing water absorption of the surface; or sending ultrasonic pulses through the material—the time the pulse takes to travel through the material is proportional to its water content.\textsuperscript{64} Different measurement methods—and the varying precisions that each can obtain—have led regulating agencies to have different standards for minimum curing times. For example, the American Concrete Institute stipulates that the minimum curing time is seven days given proper conditions, whereas the Unified Facilities Guide Specification stipulates that the required curing time is wholly dependent on the components of the concrete mix.\textsuperscript{65}

The combination of imprecise science, unclear regulations, and significant costs—both in time and money—has deterred builders from embracing the process of curing as a necessary and productive part of the construction process.\textsuperscript{66} Contractors simply do not want to spend prolonged amounts of time on cultivating the performance of their concrete structures, especially if the difference in results will be imperceptible to their clients. Instead, they build to the specifications of their contract documents and, like the 19\textsuperscript{th} century Parisian city officials mentioned in the first chapter, standardize time for the sake of efficiency and convenience. In direct contrast, my research operates with the conviction that purposeful engagement with the temporality of concrete will open up new material performances and new ways to build.

\textsuperscript{63} Taylor, 2.
\textsuperscript{64} Taylor, 135-137.
\textsuperscript{65} Taylor, 139-140.
\textsuperscript{66} Taylor, 115.
COLD JOINTS

A cold joint is defined as “a visible joint in concrete that occurs when concrete has been laid at different times.” Cold joints are inextricably tied to the fact that every batch of concrete has its own curing time, which is initiated in a different moment than the curing time of the concrete that it is placed in. Cold joints are common in building construction and are typically innocuous unless there has been an unusually long duration between batches. Such a prolonged delay could result in a cold joint that significantly weakens the structure.

In the history of concrete construction, cold joints have been given little attention, and for good reason: concrete is typically poured into a formwork all-at-once, with little delay. However, the advent of 3D printed concrete has changed the assumptions of the typical construction process. Unlike conventional concrete production, 3D printed concrete is formed through several small depositions (i.e. layers), which happen one after another. Between each deposition, there is a delay, and in each delay, there is the formation of a cold joint. Therefore, there are at least as many cold joints—and delays—as there are layers of material. I will revisit the materialization of delay through cold joints when I introduce my research method (Fig. 10).

![Poured](image1.jpg) ![Printed](image2.jpg) ![Dripped](image3.jpg)

Fig. 10. The 3D printing method that I will introduce later further breaks down the concrete fabrication process.

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67 Gorse, Christopher, et. al. Oxford Dictionary for Construction, Surveying, and Civil Engineering. Oxford University Press, 2012, 83.

68 Delays between layers also exist in small-scale 3D printing but their material consequences are normally imperceptible due to the size of the physical outputs.
ARTISTIC EXPERIMENTATION WITH CONCRETE

The artists Michelle Fornabai (b. 1967) and Anish Kapoor (b. 1954) have produced work inspired by the formative processes of concrete. A comparison of their concrete works will further illuminate the discrepancies between building materials and building practice, as well as suggest the new forms of architectural design that can emerge if we search for inspiration in concrete itself.

Concrete Poetry / Michelle Fornabai

Michelle Fornabai has an ongoing series, entitled “Concrete Poetry: 10 Conceptual Acts of Architecture in Concrete,” in which she contextualizes concrete fabrication techniques in performance art and installation. For example, in “act 3”, which is subtitled “To a Water Lily,” Fornabai performs the “slump test” (a standard test for characterizing the properties of a concrete mix onsite) in several white troughs that are arrayed in a grid. In each trough, the slumped material is suspended in a shallow pond of water, like a water lily. Fornabai subsequently uses a concrete vibrator to settle the material in each trough to different frequencies (e.g., F# or Bb). The unpredictable slump of each mound is a result of the interaction between the components in the mix and the vibrations of the musical note. Fornabai reinvents conventional concrete construction technique as pieces of art to point to the gap between the permanence of construction and the temporariness of material testing (the slumped pile is disposed of after the test is conducted), as well as to reveal the futility of architecture’s attempt to standardize materials that, by necessity, defy form.

Architects continue to resort to the slump test to maintain the appearance of material understanding. However, the slump test does not incorporate temporality beyond the duration of the slump and therefore only gives partial knowledge of the material’s performance. By omitting time from our understanding of concrete—and materiality, in general—we are stifling our knowledge of the material. The disciplinary side effects of the slump test are similar to those of real-time digital fabrication: both techniques collapse long-durational material processes into destructively brief moments.

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69 Fornabai, Michelle. “The Art of the Slump.” ARPA 4, May 3, 2016, http://www.arpajournal.net/theartoftheslump/. Accessed February 28, 2018.

70 Fornabai
Concrete Room / Anish Kapoor

At the other end of the technological spectrum, the artist Anish Kapoor experiments with a version of 3D printed concrete in order to produce objects of an architectural scale. In his fabrication setup, a three-axis locomotion system is equipped with a cement gun in order to extrude concrete at varying points from high above the print bed.\footnote{Boehner, Patrick. “Anish Kapoor – 3D Printing in Cement.” 
Magpie Aesthetic, August 27, 2010, http://anishkapoor.com/621/cement-room. Accessed April 26, 2018.} The natural flow of the material dictates “the loose, stacked spirals of the sculptures.”\footnote{Valentine, Victoria L. “Anish Kapoor Stages a Mesmerizing Forest of Concrete.” Arts Observer, May 24, 2012, http://www.artsobserver.com/2012/05/24/anish-kapoor-has-staged-a-mesmerizing-forest-of-concrete-at-gladstone-gallery/. Accessed April 26, 2018.} The process is similar to the deposition of Roxy Paine’s SCUMAK, which was described in the Machine Reconfiguration section of the third chapter. Kapoor and Paine initiate new methods of forming material through repetitive, mechanistic deposition.\footnote{73 However, neither artist develops their method into a methodology.}

Like Fornabai’s series, Kapoor’s work also appropriates a concrete technology for art. However, unlike Fornabai, Kapoor’s experimentation is devoid of context—just because it is of an architectural scale does not make it architectural. When Kapoor’s concrete sculptures were presented in the Gladstone Gallery in New York City, the title of the exhibition was “Concrete Room,” as in: a room filled with concrete objects, not a room made from concrete itself. The irony of the title reveals the extent to which Kapoor considers his work a contribution to the discipline of architectural design.

While it is true that the material is the primary driver of Kapoor’s work, there is no intentionality behind the haphazardly stacked forms—the material merely fell as it pleased. Kapoor’s passive approach to making is just as detrimental to material thinking as the slump test dependency of current construction practice. The same could be said about Paine’s machine: both projects approach architectural-scale fabrication without architectural rigor. Architectural designers can learn more about material research from Fornabai’s concrete slumps than Kapoor’s concrete piles or Paine’s molten mounds.
The distinction between architectural design research and artistic experimentation is important because some of the material experiments in my research resemble the formal gyration of Kapoor’s objects (Fig. 11). However, what I am most interested in is developing a comprehensive, mutualistic process between the architectural designer, the machine, and the material. The process comes before the product. My research does not approach 3D-printed concrete as the sloppy dripping of material—or the controlled layering of slices—but as the careful leaving-behind of drops. In my work, I let the material cure.
Part II
5. The Concept of Machine Delay

I will now introduce my concept of machine delay by defining its terms and examining its philosophical underpinnings. I will also offer a basis for the necessity of this concept today.

THE DEFINITION OF MACHINE

In the history of machine production and machine use, the definition of “machine” has necessarily changed along with its physical referent. I should, thus, clarify the use of the word “machine” in the context of my research. To do so, I will reflect on a few historical precedents, in chronological order.

In a seminal text in the field of mechanical engineering, “The Kinematics of Machinery: Outlines of a Theory of Machines” (1876), the engineer Franz Reuleaux gives a very specific definition of machine: “A machine is a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinant motions.”74 In Reuleaux’s view, the machine is a decidedly physical thing; it has “bodies” and “motions.” However, what is most important to me about Reuleaux’s definition is that a machine “can be compelled to do work.” I will revisit the topic of “work” or, more specifically, what it means to make something do work later in the discussion.

After the first World War established new, farther-reaching mechanical and chemical military technologies, the definition of machine moved beyond a purely physical description to include the space and systems in which the machine takes place. In “Technics and Civilization” (1934), the

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74 Reuleaux, Franz. The Kinematics of Machinery: Outlines of a Theory of Machines. Translated by Alex B. W. Kennedy, London, Macmillan and Co., 1876, 35.
philosopher and historian Lewis Mumford defines the machine as being both a physical thing, e.g. “the printing press or the power loom,” and the intangible implications of “the entire technological complex.” Mumford defines the former as the machine and the latter as “the machine.” In Mumford’s work, “the machine” includes social, cultural, and economic values, as well as the knowledge and skills that machines give their users. Here, the definition of machine is already becoming ambiguous: it is both larger than its constituent physical parts and a part of the human context that uses it.

In their work “Anti-Oedipus: Capitalism and Schizophrenia”, which was originally published in 1972—almost 100 years after “The Kinematics of Machinery”—the philosophers Gilles Deleuze and Felix Guattari define a machine as a “system of interruptions or breaks.” Here, the definition of machine is even further abstracted from the image of a physical thing; it is merely something that always disrupts the “continual material flow” of reality. In Deleuze and Guattari’s philosophy, the machine has no physical center. Instead, it is distributed through the reality in which it is situated—it adapts whatever structure the “material flow” gives it.

We need to see the dematerialization in these historical definitions of machine—from Reuleaux’s “body” to Mumford’s “complex” to Deleuze and Guattari’s “system.” One objective of my research is to re-materialize the machine through a new designer-machine symbiosis. Therefore, I will adopt a definition that mixes the material and abstract qualities of my historical precedents. I define a machine as **a system that does work**.

Unlike my historical precedents, which are descriptions of how machines work, my definition aims to articulate how I think the machine should be used. In architectural design, we need to assert definitions that we can simultaneously work on and through, as well as engage with the philosophy of our language—the work that we define for ourselves is fundamental to what our design process becomes.

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75 Mumford, Lewis. *Technics and Civilization*. New York, Harcourt, 1934, 12.
76 Deleuze, Gilles and Felix Guattari. *Anti-Oedipus: Capitalism and Schizophrenia*. Translated by Robert Hurley, et. al. Minneapolis, University of Minnesota Press, 1983, 36.
This definition suggests that the machine is actually a kind of delay.
77 Deleuze, 36.
THE DEFINITION OF DELAY

Delay is a necessary and productive component of time. I will briefly delve into the concept of time put forth by the French philosopher Henri Bergson (1859-1941) to come up with my working definition of delay.

In Bergson’s philosophy, cause and effect are never actually perceived at the same time, but we look back on them—in the next moment—as if they were simultaneous.\(^78\) Time flow, thus, consists of the contraction of the past into the present and the expansion of the past into the future.\(^79\) According to Bergson, we only perceive different layers of the past. Time is actually “the piling up of the past upon the past.”\(^80\) (I’d argue we could replace the word “time” with “3D printing” and still have a true statement.) This “piling up” is what Bergson calls “duration”\(^{durée}.\) The 3D printing method I will introduce later literally materializes Bergsonian piles.\(^81\)

Movement through the contracted levels of the past, or “states” as Bergson calls them, is differentiated by the perceiver.\(^82\) In Bergson’s view, the individual has “the capacity to change rhythms of expectations in time” or “control intervals” through their perception of different qualitative states.\(^83\) In other words, time is a subjective thing: we can will the slowing of time; we can insert delays. We could also insert simultaneities or “real-time-ness” — what is important is that a choice exists.\(^84\)

Drawing upon the Bergsonian concept of duration, I define delay as both an in-between time (noun) and the in-betweening of time (verb). Bergson shows us that what we call “time” is a piling-up of pasts; I am materializing the piles in order to show us—and hold us in—the delays that bind those pasts (Fig. 12).

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78 Bergson, Henri. Time and Free Will: An Essay on the Immediate Data of Consciousness. Translated by F.L. Pogson. Mineola, NY, Dover Publications, Inc., 2001, 5; Lampert, Jay. Simultaneity and Delay: A Dialectical Theory of Staggered Time. London, Continuum International Publishing Group, 2012, 11.;

This thinking recalls the real-time approach to digital fabrication that was described in Chapter Two, therefore we could also call it “machine simultaneity fabrication.”

79 Bergson(2001), 35.

80 Bergson, Henri. Creative Evolution. Translated by Arthur Mitchell. Mineola, NY, Dover Publications, Inc., 1998, 5.

81 My method is distinctly different from the computational design work mentioned on page 33, which uses pixels as a metaphor for materials. I am not using metaphor, I am literally materializing time.

82 Bergson(2001), 66.

83 Lampert, 131.

84 However, for the sake of architectural design, this research chooses delay.
THE DEFINITION OF MACHINE DELAY

In the first chapter, I described the Duchampian “foundness” of delay. Now, using our definition of “machine” and “delay,” I will define “machine delay” as the time between machine latency and machine work. It is found in all machines. If we do not grant machines this time, they will not work as expected. It is, thus, also a necessary and productive delay.

I will now describe my discovery—or, invention—of machine delay in order to demonstrate its productiveness. At the outset of my thesis work, I researched how desktop 3D printers could be reconfigured and reprogrammed to augment the design process—the assumption was that 3D printers were something we design for, but not with.85 In one particular experiment, I programmed the 3D printer to alternate extrusion and retraction at extremely quick intervals—invariably, it could not keep up. Instead, it hiccupped through the printing process and left holes where we would normally expect material to be (Fig. 13). The oscillation between being at work and being broken suggested that the 3D printer required a certain amount of time to be functional. If the machine was

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85 See the description of digital models and digital representation on page 32 for more clarification on this assumption.
tuned to work more quickly than it could, it would break down, or come close to it. This was my first experience of machine delay. What was most significant to me—an architectural designer—about this encounter was not just finding machine delay, but the possibility of a time—between failure and functionality—that could produce new materiality and new interactions between the designer and the machine.

Fig. 13. The product of my first encounter with machine delay.

Framing the machine in terms of its delay is inherently critical of our expectations of machine work: we expect the machine to function, not to be delayed! Our expectation of digital machines is even greater: we expect them to function fast. But we don’t recognize the contradiction in these expectations: there is delay in machine functionality; machines take time to work. To reiterate from the end of the first chapter, my objective is not to negate the importance of
simultaneity, i.e. the perception of a machine that operates without delay, but to explore what happens when we choose to perceive the machine delay instead.

The time taken by a machine to do its work is also the time that we are required to wait for the machine to do its work. For as long as there have been machines, there have been people waiting for them. It is important to recognize that when we make machines do work, we make ourselves wait for them—in other words, we will our own delays, just as Bergson suggested. The concept of machine delay opens the possibility of seeing this waiting as being delayed with the machine.

**THE AGE OF ANTI-ANTICIPATION**

Digital machines have created porous boundaries between architectural design and the world it inhabits—the same work and delays occupy both realms. As a result, the waiting-for that defines my design research in digital fabrication can also teach us about ontological structures. In our contemporary technological moment, this waiting-for—as opposed to -with—machines has, in my opinion, taken disappointing forms, we: leave the machine to do something elsewhere; get angry; or, most often, engage with another machine, e.g., an iPhone or computer, thus compounding the machine delay—we wait while we wait. Our inability to wait for machines demonstrates the popular perception of machine delay as a hindrance; an in-between time that immediately needs to be filled. My research aims for a different kind of human-machine—specifically, architectural designer-machine—relationship. I propose that we should not only embrace machine delay but see it as a way to fill time. Or, to put it in Bergsonian terms: we can use machine delay to set the rhythm of our duration.

As machines—in all forms—have become more integrated and integral in everyday life, our inability to tolerate waiting for them has become greater. Such intolerance is reflected in the advent of “machine learning,” which aims to give every machine the ability to learn its users’ tastes, tendencies, needs, and, even, movements well enough to anticipate to their choices before they make them. Machine learning marks the beginning of “the age of anti-anticipation”: a time in which we...

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86 There are different definitions of “machine learning” depending on whom you ask. On its website, the software corporation Nvidia says that machine learning is “the practice of using algorithms to parse data, learn from it, and then make a determination or prediction about something in the world.” In a website on artificial intelligence called TechEmergence, Dr. Danko Nikolic, a scientist at the Max-Planck Institute for Brain Research, defines machine learning as “the science of getting computers to act without explicitly being programmed.” The latter definition is more in line with the future without human anticipation that I aim to counteract.
will no longer have to anticipate what will happen next (Fig. 14). The irony of this imminent—if not already present—moment is that it will actually result in more waiting: self-driving cars will turn driving into waiting to arrive; autonomous drones will turn shopping into waiting for deliveries; “smart” apartments will turn going to sleep into waiting for your bedroom to reconfigure itself. Our future will consist of more waiting. We need the concept of machine delay in order to wait better.

Machine delay is a comprehensive term that can be applied to new—and future—delays as well as to previously established types of delay, such as propagation delay (electronics and physics) and tape delay (acoustics). However, as our interactions, including our waiting-for, with machines of all kinds—both in architectural design and everyday life—become more routine, it is imperative that we develop a generalized theory of machine delay. We need machine delay and “machine delay,” in the Mumfordian sense. The latter introduces the possibility of finding—and embracing—delay in all machines and human-machine interactions.

Fig. 14. A mobile speed bump that I made to disrupt the age of anti-anticipation.87

87 For a video of the mobile speed bump in action, please visit: https://www.youtube.com/watch?v=Itw7agbbfRE
6. Machine Delay Fabrication

*Machine Delay Fabrication (MDFab)* is an approach to architectural design that is characterized by the materialization and manipulation of the time taken by digital fabrication machines to do work.\(^{88}\) Here, the “time taken” can be understood as the time between digital input and material output.

There are three types of machine delay that pertain to Machine Delay Fabrication, and each one corresponds to a different timescale:

- **Integral-Machine Delay**: the machine is delayed by its own work, e.g. clock speed or its processing of information;

- **Interactive-Machine Delay**: the machine is delayed by the designer’s work, e.g. programmed delays or the time between instructions;

- **Material-Machine Delay**: the machine is delayed by the time taken by materials to do their work, e.g. flowing, curing, heating, or cooling;

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\(^{88}\) The root of the word “manipulate” is the Latin word “manipulus,” which means handful, or literally, to fill one’s hand. In the beginning of the 19th century, it also started to be used to describe the “skillful handling of objects.” In more recent history, it has taken on negative associations that are more abstract than a physical hand. Here, I use “manipulation” in a manner that is closer to its original definition.
In MDFab, the digital fabrication machine is not compelled to do work (as was the case in Reuleaux’s definition of “machine”), but instead compelled to hold up. There are several ways hold the machine up:

- Make the machine pause briefly, or for an extended amount of time
- Make the machine dwell (in a single state)
- Make the machine wait for something to happen
- Make the machine slow down, but not stop
- Make the machine break without failing
- Make the material output drag behind the digital input
- Interrupt the machine
- Distance the machine from its inputs and/or outputs

Each of the actions listed above has distinct material consequences that depend on the digital fabrication machine that enacts them and the material that machine is working on. For example, making a CNC router dwell during a milling operation will result in melting or charring of the stock material, whereas making a desktop plastic 3D printer dwell during its extrusion will result in a build-up of the filament. MDFab is a generalized approach that can be used by designers to initiate new relationships between varieties of machines and materials.

THE ARCHITECTURAL DESIGN POSSIBILITIES OF MDFab

The question that architectural designers need to ask is: what can happen in a digital fabrication machine delay? We can begin to answer this question by speculating on the aesthetic,
constructive, and ethical possibilities of Machine Delay Fabrication in architectural design. I will outline these possibilities here and develop them in greater detail in the final chapter.

![Fig. 15. Cement performs like filament if the machine prints so slowly that the material cures while it is being printed.](image)

**State Change**

As we discussed in Chapter Four, Curing Time, materials assume different properties as they go through state changes. In several types of digital fabrication (e.g., 3D printing, vacuum forming, or laser sintering) materials need to change states in order for the machines to do their work. In other words, the machine is delayed by the necessity of the state change. The state change is often sequenced to minimize this delay. However, if we prolong the (already existent) delay between the machine’s work and the material’s state change, we can reveal in-between states—of both the machine and the material—to design and fabricate in. We can also discover how the material and machine perform when they are between their normally-perceived performances (Fig. 15).

**Improvisation**

Machine Delay Fabrication can create a space for improvisation. In a Pollock-like process, we can observe the performance of our machines and influence what happens next. For example, we can deliberately pause the digital fabrication machine to change the course of its routine or insert

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89 This is what the MX3D team did in their 3D printed steel bridge, see page 23.
a new constraint. Our designs can emerge from an improvisation upon the performance of the machine’s fabrication. The improvisation of MDFab can also be a collaboration in the style of Stockhausen: others can enter into the machine delay to affect the outcome of the fabrication. In contrast to the closed loops of real-time techniques, MDFab invites participation.

**Orchestration**

Machine Delay Fabrication enables us to see the digital fabrication process as an act of orchestration: we decide how—and more importantly, when—the machine, the material, and our design come together. We can orchestrate delays so that, in a John Cage-like manner, things can take place in those delays: state change, machine part adjustments, formwork reconfiguration, documentation, etc. Orchestration can complement improvisation; we can orchestrate delays to improvise in. Orchestrating delays in the digital fabrication machine can be a new form of craft.

**Maintenance**

In Machine Delay Fabrication, we can suspend digital fabrication machines in moments of near-brokenness and, thus, avoid moments of complete failure, which may result in unintended delays. In this Duchampian suspension, we can: re-tune the machine so that it doesn’t break (more than we want it to); observe how brokenness occurs; and plan for the next iteration to break less. Digital fabrication machine maintenance can also be a new form of craft (Fig. 16).

**Tuning**

We can tune the digital fabrication machine to the speed we want to work with. For example, we can: slow the traverse of a robotic arm to study how it approaches a point; increase the speed of a laser cutter to score but not cut; or reduce the passes of a CNC router so that the finish of the milled thing is rougher. Within certain safety parameters, we can choose a fabrication speed that enables us to use the machine to think through our design.
Fig. 16. While trying to print a long, continuous, zig-zagging line in cement, the nozzle clogged several times. The clogging resulted in total failures to print, as well as interesting partial-failures in which particles stuck in the nozzle opening changed the character of the printed line.

**Sketching**

Machine delay offers the possibility of suspending an operation, or “job,” and revisiting it later, perhaps when our design idea has changed. Such a way of working would make the digital fabrication process more akin to sketching, which is non-linear and messy—we can fill machine beds as we do pages in a sketchbook (Fig. 17). In turn, we can use the digitally fabricated thing to better represent the inevitable incompleteness of our design thinking and move past the association of digital fabrication machines with “final production.”

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90 When Final Reviews approach in architecture schools, students always scramble to reserve time on digital fabrication machines. In fact, for many students Final Review time will be the only time that they engage with digital fabrication; the belief is that the machine will enable them to produce the most finished-looking model in the shortest amount of time. Instead, if digital fabrication machines are used in the design process, we can find ways to move beyond the “finished” appearance of their outputs.
Scaling

Machine delay, like architectural design, exists at multiple scales. Through MDFab, we can materialize machine delay in various scales of digital fabrication machines (desktop devices to on-site machinery) and, in doing so, move more fluidly between design and construction. In my research, for example, I observed machine delay in a desktop 3D printer and scaled that delay into an industrial robotic arm in order to understand how to build with it. In the architectural design process, we draw our designs at multiple scales so that we can understand how every component—conceptual and material—comes together. Machine Delay Fabrication opens the possibility of an analog design process through digital fabrication.
Playback

Machine Delay Fabrication moves past cybernetic “feedback” to delayed “playback.” In MDFab, there are no autocorrects or background tasks; there is no machine learning. Instead, the digital file is reconceived of as a memory that is re-presented by the machine for the designer and it is, thus, the designer—not the machine—that needs to pay attention. Digital fabrication playback can be like the tape loop playback that Stockhausen used to inform his compositions.

Conceiving of digital fabrication as a kind of playback brings several instances of Interactive-Machine Delay into focus: the elapsed time between file creation and machine execution; deliberate pauses inserted within the machine code to study or alter the fabrication process; the time in between repetitions of the same file. In digital fabrication playback, machine delay, like Duchamp’s “Delay in Glass,” becomes something that can be worked in and through—it becomes spatialized.

In his book “The Alphabet and The Algorithm,” the architectural theorist Mario Carpo unintentionally alludes to the possibility of playback:

A digital machine (for example, a computer) makes, in the first instance, a sequence of numbers—a digital file. This file must at some later point in time be converted into an object (or a media object) by other machines, applications, or interfaces, which may also in turn be digitally controlled. But their control may be in someone else’s hands; and the process of instantiation (the conversion of the digital script into a physical object) may then be severed in space and time from the making and the makers of the original file.91

I read Carpo’s reference to being “severed in space and time” as an instance of machine delay. Machine Delay Fabrication provides a framework in which to apprehend this delay; to determine when our digital recordings, i.e. files, are played back.

91 Carpo, Mario. The Alphabet and The Algorithm. The MIT Press, 2011, 5.
Fig. 18. I repeated the same 3D print file; in between the repetition, I changed a single parameter, temperature.

Repetition

Related to playback is the possibility of repetition or, more specifically, the difference within repetition. Digital fabrication machines are masters of repetition: they can execute the same file or the same command in the same way every time they are instructed to do so. However, the time in between repetitions ensures that no two instructions are executed in exactly the same way. We can manipulate this time, as well what happens within it, to create subtle differences in the repetition of the digital fabrication process (Fig. 18).

In the next chapter, I will introduce a method of Machine Delay Fabrication in order to demonstrate how these conceptual possibilities can materialize.
7. Pointillistic Time-Based Deposition (Dripping)

Pointillistic Time-Based Deposition, or dripping, is a method for 3D printing concrete that I invented in order to explore the architectural design possibilities of Machine Delay Fabrication. In this chapter, I will discuss the design of dripping, including its workflow, printing material, and machine embodiment.

**WORKFLOW DESIGN**

Dripping is enacted by a robotic arm that I transformed into a concrete 3D printer. In the dripping workflow, the designer programs the 3D printer to deposit concrete at specific points in space, and then instructs it when to revisit each point and in what order. This instruction is an example of Interactive-Machine Delay.

Each point, or drop, has two delays that manipulate the machine delay: *extrusion time*, which is the duration for which the robot extrudes material at the drop, and *wait time*, which is the duration for which the robot waits after extrusion before moving to the next drop (Figs. 19, 20). The drop is a temporal unit and not a geometric unit—there is a multiplicity of possible drop forms.

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92 Dripping is similar to the “Pause” technique developed by W. Andrew Atwood. However, here, the print is composed *only* of pauses: concrete is laid like bricks.
In addition to extrusion time and wait time, there is a third delay called *travel time*. Travel time is the time it takes for the extruder to get from one drop to the next. This time is affected by the distance between drops, the order in which they are visited, and the speed at which the robot is traveling (Figs. 22-24).
Fig. 21. “This is 40 seconds.” diagram (seconds): pairs of different twenty-second drops (extrusion time/wait time) were combined to produce different results.

Fig. 22. The line on the left was printed at 10% speed; the line on the right was printed at 100% speed. The bulbs that form at the ends are a result of the material process continuing after the machine process has stopped. The bulb—or delay—is reduced by moving slower, not faster.

The time elapsed between each visitation of a drop—the *compound delay*—is the sum of the extrusion times, wait times, and travel times that are accumulated while the robot is visiting other drops (Fig. 21). This in-between time determines the localized structure and aesthetics of the overall printed thing. For example, a drop that has not been visited for a long duration will conform less to a new deposit than its more recently visited neighbors.
There is also a critical spatial parameter called *drop height*. The designer determines the drop height based on the amount of precision she would like to have. For example, if she would like drops to be dripped one on top of the other as uniformly as possible then the drop height should be the approximate thickness of each drop, or slightly less. However, if—in a more Kapoorian manner—she would like the drop to will its own placement, then the drop height can exceed the thickness of the drops.

As mentioned in Chapter Four in the section concerning cold joints, current concrete 3D printing methods have delay between one layer and the next. In the dripping method, there is the additional delay of time between geometric points in every layer. Dripping, thus, further breaks up the concrete fabrication process, along with its curing time, and creates the possibility of a new cold joint distribution. I broke the process open so that architectural designers can design ways to piece it back together.

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93 In conventional 3D printing, this variable would be called “layer height.”
Fig. 24. Order of drops diagram; I deposited at drops A, B, C, D, and E in different orders at every course. I expected that the different orders would result in different travel times and therefore different relationships between drops. However, the difference between each stack was not easily perceptible because the drops were too close together.

The robotic arm can revisit the exact location of drops and repeat the exact count between revisitations—it is both spatially and temporally precise (Fig. 24). In dripping, the robot becomes a “material clock” that simultaneously materializes and keeps track of time. The dripped thing slowly emerges from the clock and assumes a materiality that is representative of the time that went into its making.
DRIPPING AS MACHINE DELAY FABRICATION

I would like to make clear which parts of dripping correspond to which types of machine delay in Machine Delay Fabrication:

**Integral-Machine Delay**
- The travel time between each drop.
- The time it takes for the robot to process commands.
- The time it takes for the dripping system to start or stop.

**Interactive-Machine Delay**
- Breaking slices into drops.
- The programmed delays at or between each drop, i.e. the extrusion time and the wait time.
- Any time the print is paused by the designer (e.g., for maintenance).

**Material-Machine Delay**
- The time it takes for the material to stop dripping, i.e. the amount of dripping that occurs after the extrusion time has ended.
- The curing time of the dripped thing, which necessarily delays the completion of the print.\(^{94}\)

We can see that the machine delays in dripping are necessarily interrelated. For example, how long it takes for the material to stop dripping is affected by how much material has been extruded, i.e. the extrusion time—if material has been flowing for a longer period of time, it will require more time to stop. In dripping, the designer can orchestrate the delays and the relationships between them (Fig. 25).

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\(^{94}\) When I use the word “completion” here, I am referring to when a 3D print can be removed from the print bed. However, it is important to note that “completion” in the context of 3D printed concrete is inevitably nebulous, it could be: when the print job has been completed; when the print has cured enough to be moved; when the print has cured enough to be structural; or when the print has cured enough to meet some performance criteria that were specified by the designer.
MACHINE CONTEXT DESIGN

Before we continue, I would like to revisit Negroponte’s concept of “architecture machine” to further illuminate the methodology behind the design of dripping and Machine Delay Fabrication, in general. Negroponte defines architecture machines as machines “that poll information from many designers and inhabitants, directly view the world, and have a congenial dialogue with one specific designer.” Central to the reciprocity of this dialogue is the machine’s ability “to discern changes in meaning brought about by changes in context.” In other words, an architecture machine is one that learns its context, including the designer that takes place in it—the context is learned, not designed.

Machine Delay Fabrication puts forth a different idea of machine context. Here, the architectural designer designs the context that the machine fabricates within, which includes: its material inputs, its physical surroundings, its physical embodiment, and, most importantly, the time it works in. In MDFab, the designer needs to learn the machine (e.g., how it works), so that its context can be designed, not learned.

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95 See page 38.
96 Negroponte, 29.
97 Negroponte, 1.
98 We should recall the work of Snooks and Johns in Chapter Three, as well as the definitions of “machine learning” on page 61.
The fundamental difference between my machine “context” and Negroponte’s machine “context” is that my definition gives designers agency over the entire process—from material to machine to time—instead of only the inputs and outputs. In MDFab, if designers want to change the machine’s outputs, they have the option to change its inputs or its context.

Fig. 26. Current and working iteration of the machine context.

MACHINE BODY DESIGN

As I mentioned at the beginning of this chapter, dripping is enacted by a robotic arm that been transformed into a concrete 3D printer. To put it in Reuleaux’s terms, the robotic arm was combined with other “resistant bodies” so that it can drip. I designed the physical parts as well as the different ways in which they were combined in order to fully understand the context in which dripping works (Fig. 26). The design underwent three iterations, each of which I will now summarize.
Iteration #1: Proprietary Pneumatic Extruder

Overview

- A pneumatic caulk gun—the kind that is typically used for small household construction projects—was rigged with a zip-tie so that it was always in “printing mode.”
- The extruder was toggled on or off by pneumatic outputs on the wrist of the robotic arm; extrusion was controlled directly through instructions in the robot code.
- The “print cartridges” were used caulk tubes that were filled with cement and manually loaded into the caulk gun.

Pros

- Quick experimentation
- Easy to maintain
- Low-cost
Cons

- The size of each print was limited to the volumetric capacity of a standard caulk tube (10.1 ounces).
- The nozzle diameter was limited to the geometry and size of the opening at the end of the caulk tube (7/64”). This caused frequent clogging.
- The appropriation of proprietary parts prevented reconfiguration or addition.

Iteration #2: Pneumatic Extruder with Peristaltic Pump and On-board Electronics

Overview

- The extruder was comprised of: a custom aluminum nozzle and end cap, off-the-shelf PVC parts, and a pneumatic plunger, which used both bought and custom parts.
- The peristaltic pump had a plywood hub with three polyurethane rollers in a plywood housing. A steel drive shaft connected the hub to the motor. The pump was powered by...
a high-torque AC motor that was taken off the back of a defunct concrete mixer. The soft latex tubing in the track of the housing had a 7/8” inside diameter.99

- Material was mixed beforehand and fed through the tubing using a plastic funnel.
- The PVC parts of the extruder had an outlet to the peristaltic pump so that the extruder could be continuously fed with material—the aim was to have the extruder act like a material capacitor.
- The plunger in the extruder used a sensor-ready pneumatic air cylinder, which means that there was a magnet fixed to the top of its piston. A custom hall effect (magnetic) sensor board was attached to the cylinder in order to track the vertical position of the piston. The vertical position of the magnet indicated the fullness of the extruder head. For example, if the piston plunged to its limit, a sensor was triggered, indicating that the extruder head was empty. The “empty” message was sent to the I/O (input/output) board, which sent an impulse to the solid state relay that controlled the peristaltic pump. The pump, in turn, refilled the extruder until the upper sensor had been triggered, signaling “full.”100

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99 To see the motor and the solid state relay work, please visit: https://www.youtube.com/watch?v=6LKqWVMChuE

100 To see the sensors and the overall Iteration #2 system work, please visit: https://www.youtube.com/watch?time_continue=14&v=gAA0W3uUO3w and https://www.youtube.com/watch?v=l_1s4ySgwV4
Pros
- The diameter of the nozzle opening could be changed with relative ease; the starting size was 1/4”.
- Printed volume could be calculated using the plunger depth.
- The sensor readings could be used to create other inputs to the robot.
- The pump could be easily disassembled for maintenance.

Cons
- The extruder could not hold material. Instead, it leaked whatever material was moved into the extruder head without storing it first. I could have added a stop that was also actuated by the robot’s pneumatic outputs, but that would have further complicated the system communication.
- After manually forcing the extruder to be full, I discovered that the plunger could not retract if any concrete granules were left in the extruder head from the previous plunge—the tolerance between the plunger (that I machined) and the PVC pipe (that I bought) was too tight. This constraint precluded further use.

Iteration #3 (Current Iteration): Nozzle and Peristaltic Pump

Overview
- I rebuilt the peristaltic pump to be more robust: the hub is made of aluminum, the wheels are a less frictionious plastic; several ball and sleeve bearings smooth out connections and reduce wear; the drive shaft length is shorter to reduce stress on the couplings; the drive shaft couplings are stronger; failure modes were built in; the tubing is in a semi-rigid plastic housing to minimize its bend radius when it exits the pump; a pneumatic vibrator keeps concrete from settling in the hopper.\textsuperscript{101}
- I feed material into the pump and the pump feeds material directly to an aluminum nozzle (7/16” diameter) that sits in a tool holder at the end of the robotic arm.
- The robot outputs directly to the solid state relay(SSR), which turns the pump on and off. The output instructions are in the robot code.

\textsuperscript{101} The failure modes will be discussed in more detail later in this chapter.
Fig. 30. A simplified system only using a nozzle at the end of a peristaltic pump.

Pros
- Minimal amount of parts and electronics reduces the chances of clogging, jamming, short circuits, or other material failures.
- Most parts are custom and can be easily remade or modified.
- The aluminum hub of the pump is much stronger and works through material more easily.
- Both the pump and the nozzle/holder are easily disassembled for maintenance.
- Failure modes prevent more serious and/or dangerous failures

Cons
- The tubing gets pinched often if it is not carefully set in the plastic housing. Pinching restricts material flow.
- There are too many hose clamp connections that prevent quick adjustments from being made during the dripping process.
The iterative design of the machine body necessarily distilled the parts of the system. The simplified system allows the designer to focus primarily on the interaction between the material and the machine delay. As a result, it is easier to understand how one influences the other.\textsuperscript{102}

![Fig. 31. The evolution of the tool holders demonstrates the evolution of the system, from left to right: Iteration #1(hacked); Iteration #2(overdesigned); Iteration #3(simplified).](image)

**NOZZLE DESIGN**

In each iteration, there was an interplay between the material viscosity and the nozzle design; nozzles with larger diameters or truncated geometries resulted in faster material flow, whereas nozzles with small diameters and elongated geometries did the inverse. I could compensate for increased flow rate by making the material thicker; however, doing so would also result in less bleeding of the material, i.e., Machine-Material Delay.

Another important consideration in the nozzle design was how to prevent clogs. If the material flowed into the nozzle more quickly than it could get through the nozzle opening, material would build up and prevent deposition. The nozzle would also clog if its opening was not large enough to let aggregates in the materials from passing through. The ideal nozzle-material combination struck a balance between the speed of the flow through the opening and the bleed of the material once material was deposited.

\textsuperscript{102} To see the “tuning” and performance of the current machine, please visit: https://vimeo.com/270990944
Fig. 32. Nozzle shape study.

Fig. 33. Nozzle diameter study.
Fig. 34. I experimented with printing glass fiber-reinforced concrete but it did not appear to improve the strength of the material and caused small tears in the tubing of the peristaltic pump.

PRINTING MATERIAL DESIGN

In initial experiments that utilized Iteration #1, I used proprietary white grout as the printing material. Optimizing the water-to-cement ratio for the drops proved to be the most challenging part of the system’s development. My aim was to use a mix that would continue to extrude, or bleed, even after the digital impulse had desisted, thereby invoking an instance of Material-Machine Delay. If the cement was too thick, the mix would only extrude with pressure from the plunger. If it was too thin, the material would slip out and quickly slump into a puddle.

The mix, air pressure, and wait time of each drop all had to be tuned with one another to ensure the continual production of drops. For example, if the mix was too thick and deficient wait time was allotted, the extruder would fail to generate enough repeated pressure and material would not be deposited (Fig. 35). This failure suggested that the wait times were not only materially
productive—e.g., for distributing curing time—but also necessary in that they allowed for the extruder to recover amidst its repetition.

Fig. 35. The extruder was not allowed enough wait time between drops and therefore failed to print as it traversed to the end of each course.

When I decided to scale the system to achieve larger-scale prints, I had to design my own printing material. I designed a mix of concrete specifically to 3D print architectural-scale drops. The ingredients of the mix are Portland cement, fine sand, retarder, superplasticizer, and water. The ideal mix had a 50-50 cement-to-sand ratio, with 30% water, 1.1% plasticizer, and 0.4% retarder. I also experimented with glass fiber reinforcement but found that the fibers frequently got stuck in the pump and caused small tears in the tubing.

I carried out several tests to determine which combination of dripping inputs and proportions of concrete ingredients worked best together to demonstrate dripping’s architectural design possibilities. There were a number of failures—mostly from clogging or desegregation—that

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103 White grout is typically only used for small-scale applications, e.g., bathroom tile.
104 These percentages are proportional to the weight of the dry mix.
occurred before the correct balance of the parameters was met. Please see the Appendix for the full log of drip tests.

Fig. 36. An early experiment in which the ground consisted of only four points in space. As a result, the print had to improvise its own support.

GROUND DESIGN

I want to make a note about the design of the ground—what might be called the “print bed” in conventional 3D printing or the “foundation” in full-scale construction. There are potentially several ways to design the ground in order to give it a larger role in the dripping system: smoothness can promote slumping; absorption can expedite hydration and curing; texture can create better bonding with the initial drops. In this research, I made the default ground a flat piece of plywood, which is relatively neutral in terms of its influence on the drops. In future experimentation, I will give the ground more agency (Fig. 36).
SOFTWARE DESIGN

I designed the Dripping Software (DS) in Grasshopper and C#. In this software, the designer creates the drop “cloud”, including: spacing (vertical and horizontal); ordering; and the distribution of delays, i.e. wait time and extrusion time.

An additional parameter that can be added into DS is physical context. For example, if the designer wanted to drip onto or into something with a specific geometry and/or dimensions. The option of adding a physical context is significant for the possibility of the Responsive Drop that will be discussed in the next chapter.

DS also formats the drops into Kuka Robot Language (the machine language required by the robotic arm) and provides the orientation data (in Eulerian angles) that is required by the robot’s inverse kinematics solver. Calls to the solid state relay that controls the pump are coded in “PULSE OUT” commands and delays are coded by instructing the robot to “WAIT.” Every pulse initiates a drop and every wait initiates a delay. A typical piece of robot pseudo-code would read like this: *Go to point X, Y, Z; instruct the SSR to turn the pump on; wait for a certain amount of time; instruct the SSR to turn the pump off; wait until the material has stopped bleeding (or slightly longer); then move to the next drop and repeat.* The digital drops are uploaded and stored in the robot before becoming physical drops.\(^{105}\)

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\(^{105}\) See the possibility of “playback” on page 69.
To see the drop visualization software with a typical experiment, please visit: https://vimeo.com/270990912
EXPERIMENT DESIGN

In the dripping experiments, there was clear delineation between the roles of the machine and the roles of the designer: the machine deposited the material and kept time; the designer mixed material, fed material to the machine, maintained the machine, and determined where and when the material should be. In other words, the machine was responsible for enacting the delays while the designer was responsible for what happens in the delays.

The typical test print was an array of uniformly stacked and staggered drops (Fig. 38). The uniformity of the stacks allowed for clear observation of the relationships between the system parameters, while the staggering facilitated structural stability and enabled the print to be free-standing, i.e., without supports or formwork. The tool paths were mostly programmed beforehand, though improvised revisitations occurred frequently in order to study, amplify, or correct unexpected material results. In nearly all tests, the robot program speed (i.e., the speed at which it travelled from drop to drop) was kept constant at 100% so that I could more easily perceive, and subsequently tune, the other machine delays.

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106 The responsibilities of the designer and the machine often had to be carried out simultaneously to achieve the desired dripped thing.
Fig. 39. A sheared coupling that was caused by a pebble caught in the pump; the shear pin used here was stronger than the coupling itself, which caused the coupling to break first.

**PEBBLES AND PINS**

Failures were inevitable and necessary in order to prototype the system. There were material failures (e.g., desegregation or cracking) and technological failures (e.g., the robotic arm blows a fuse), but most often failures occurred at the interfaces between material and technological processes. I will now discuss the most frequent failure of this type in order to provide insight into the delicate balance of machine context design, as well as to further distinguish delay from its common perception as a failure mode.

Conventional concrete is full of aggregates that vary in size—from grains of sand to rocks that are bigger than tablespoons. 3D printed concrete, on the other hand, cannot use aggregates larger than what can be pumped through the printer nozzle. Such a constraint restricts aggregates in 3D printed concrete to the finer end of the conventional concrete aggregate spectrum. In the machine parts that I developed, which would be considered small by industrial standards, any particle that exceeded the capacity of my system resulted in clogs that caused paralyzing mechanical or material failures, for example, torn tubes or jammed nozzles.  

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107 We can liken these kinds of material failures to the origin of “debugging” in computer programming, which began when a moth was found in the processor of the Mark II computer at Harvard University. The tiny insect was the source of insurmountable mechanical failure. In both instances, the fragility of the machines is necessarily communicated to its designers so that they can better understand how to expand the limits of their functionality.
The worst consequence of a pebble caught in the pump was the material failure of a mechanical component, e.g., a shaft coupling (Fig. 39). In order to avoid failures of this kind, I had to build “failure modes” into the dripping system. In other words, I had to anticipate failure and design the space for it to happen. I introduced low-strength, aluminum shear pins into the couplings of the motor drive shaft; if the motor had to apply more force than normal (e.g., if there was a pebble obstructing material flow in the pump), these pins sheared and disconnected the motor from the pump, which stopped all printing activity—except for the curing of the concrete—and prevented further damage.

The contrast between the pins and the pebbles raises the important question of what qualifies as an instance of Machine Delay Fabrication. MDFab is the intentional manipulation of machine delay. The pins are an example of MDFab because they are deliberately designed to suspend machine work. The pebbles, on the other hand, are not an example of MDFab because there is no intentionality behind their occurrence—they were put in the pump without the designer’s knowledge.

Another way to understand the distinction between the pin and the pebble is to evaluate the temporality of each occurrence. MDFab is not the manipulation of permanent states (or final products), but the manipulation of constantly changing temporal processes. The pins are an example of MDFab because they produce brokenness, which, to recall from Chapter Four, is only temporary. The pebbles, on the other hand, are not an example of MDFab because they only bring about destruction, which is permanent or, at the very least, less temporary. Whether or not something qualifies as Machine Delay Fabrication is ultimately a question of duration.
8. The Architectural Design Possibilities of Dripping

In this final chapter, I will summarize the experimental findings of both small- and large-scale instantiations of the dripping method. I will also discuss specific experiments in order to speculate on the architectural design possibilities of dripping in future research and practice.

Fig. 40. The cement cured as it was printed, which resulted in a natural material gradient.

SMALL-SCALE EXPERIMENTATION (Iteration #1 and Proprietary White Grout)

In the small-scale experimentation, all variables were kept constant except for extrusion time and wait time. The constants included drop height, order of drops, proximity of drops, mix ratios, air pressure, and nozzle diameter. As mentioned in the previous chapter, the tool path was also the
same in each experiment: moving from left to right at every course, as well as staggering every other course to create more structural stacks of drops.

In the first tests, excessive wait times (fifteen seconds) between drops resulted in the material curing while it was in the extruder head. Consequently, the depositions revealed the natural material gradient of the cement (Fig. 40). Initial courses contained drops; however, less than twenty minutes later the cement became filament-like and distorted the reading of the course altogether (Fig. 41). The filament-like materiality was intriguing, but it also cautioned that too much delay could result in permanent machine or material failure (e.g., the cement hardening in the extruder and preventing extrusion).  

Fig. 41. A more drastic instance of the natural material gradient in which the cement became filament.

108 For scale, please note that all tests were dripped onto ¾” plywood or MDF.
Fig. 42. Top to bottom: uneven delays; three-second extrusions with eight-second waits; five-second extrusions with eight-second waits.
Reducing the wait time to five seconds between each drop produced more uniformity but did not allow the machine enough time to recover. As a result, there were less drops on one side of the print than the other. This asymmetry suggested that the travel time (approx. three seconds) that it took the robot to finish one course and then traverse back to the starting side added enough recovery. Therefore, I determined eight seconds to be the optimal wait time for this scale of dripped thing.

In the penultimate test, the quick curing of the smaller drops prevented them from completely melding into one another upon revisitation. Instead, small holes were formed between successive courses. These voids pointed to one architectural design possibility of dripping.

**SCALE EXPERIMENTATION (Iteration #3 and Custom Concrete Mix)**

My experimentation with the larger system demonstrated many of the same forms of drops that were found in the initial small-scale tests: spheroids, discs, saddles, and coils. The increase in scale enabled me to view each form of the drop with greater resolution so that I could better understand its materiality and its interactions with its neighbors. I saw wrinkles, drizzles, cracks, and traces that hadn’t been apparent before (Fig. 43).

*Fig. 43. The characteristics of the small-scale tests were amplified in the scaled up tests.*
The gradient effect (the material curing while it was being dripped) also recurred; however, the extended durations of the prints revealed new formal subtleties in the state changes of the concrete curing process. The vertical stretching of the drop—from puddle to pile—could be seen throughout the course of one print (Fig. 47).

After I increased the nozzle opening diameter, the extrusion and wait times only had to be five to ten seconds longer than those in the small-scale experimentation (five to eight seconds, on average) in order to produce drops of a considerably larger size. In terms of testing structure and aesthetics, the most productive extrusion and wait times (for the average drip mix) were approximately ten seconds.

The most challenging part of creating drops at a larger scale was tuning the material to the machine. Small miscalculations in any proportion of the mix had drastic consequences on its workability, pump-ability, and drop-ability. I had to precisely weigh each ingredient and clean the tools after each test in order to prevent residual material from affecting the character of the next mix. I attempted to use a portable cement mixer to facilitate continuous mixing, but it could not stay clean enough during the dripping process to produce consistent batches of material. Further, dry cement clumped up in the mixer’s crevices, then found its way into the pump and caused multiple mechanical failures. As a result, all material had to be mixed manually one batch at a time.

The time required to mix each batch could be absorbed by the delays that were already programmed, e.g., wait time or travel time. I could stop at a drop, mix more material, and immediately revisit where I left off—it was a matter of further delaying the delay. The retarder I used in the mix ensured that the concrete would still be relatively fresh when the dripping was resumed. In the longer-duration drip sessions (some lasted up to 10 hours), the different batches produced subtly different material effects throughout the dripped thing.

The larger dripped thing had to be more structural to be free-standing. In some tests, I added stability by mixing a slightly more liquid batch for the first two or three courses. The thinner material slumped more, thereby creating a base for the next courses to sit on. In other tests, the question of support material was more explicitly explored.
Fig. 44. The vertical stretching of drops, from puddles to slumps. Top to bottom: tests #20, 28, and 24.
Fig. 45. The vertical stretching of drops, from bulbs to holes. Top to bottom: tests #25, 22, and 29.
Pattern

Dripping has a unique architectural grammar that is expressed by pairing the repetition of the robot with the unpredictable amorphousness of the material and improvisatory impulses of the architectural designer. In dripping, and in Machine Delay Fabrication in general, repetition occurs in the process, e.g., in rhythmic extrusion times, but not in the product. This repetition can be leveraged to create patterns that are nearly identical in size, but contain distinct wrinkles, folds, ripples, or marks (Fig. 46).
Ornament

Ornaments can be inserted within dripped patterns by programming delays that cause moments of material excess. For example, a long extrusion time can cause a drop to drip down its neighbor and leave a trail of material behind (Fig. 48). The ends of dripped things are unique ornamental conditions because insufficient material build-up causes a breakdown of the structure, which, in turn, causes the drop height to change. The drop is compelled to hold itself up by coiling into a tapestry-like knot (Fig. 51).
Fig. 48. The scales of the drop gradient correlates with the scale of the delay.
Fig. 49. One drop dripped past another, leaving a trail behind.

Fig. 50. The ornamental trim atop a dripped wall.
Fig. 51. The unwound threads at the end of a dripped wall.
Porousness

Apertures of various sizes are made possible by building relationships between the drop spacing, deposition rate, and curing rate. If the drop spacing, the delays between drops (e.g., wait or travel time), and/or curing rate is increased to a certain extent, drops will remain separate from one another and the structure will become porous (Fig. 52).
Texture

The surface textures of dripped things contrast with the typically smooth surfaces of poured concrete and the homogenous stacks of conventionally 3D printed concrete. Dripped things are heterogeneous, asymmetrical, undulating, and bumpy (Fig. 53). The texture of a dripped thing can evolve throughout the course of dripping by depositing various form of drops. The kind of drop is determined by the plasticity of the mix and the extrusion time.
Skin

Textural variation can occur within the drop itself through a variety of different parametric permutations:

- If the extrusion time is long or the drop height is low, the material will start to push on itself from within and the surface will have a crackled appearance. Alternatively, if the extrusion time is short or the drop height is higher than the thickness of the drop, the material will have more slump and the surface will have a rippled appearance.

- Mixes that are dry will appear more rough because they have more resistance to extrusion, while mixes that are too wet will become speckled because they slump into puddles that cure unevenly (Fig. 54).

- Wrinkles, fractures, or folds can also occur as a result of the interactions between drops. For example, if a drop receives excessive pressure from its neighbors.
THE CONSTRUCTIVE POSSIBILITIES OF DRIPPING

The Wall

Drops can create more structural integrity between layers of 3D printed concrete by increasing the surface area of the connection; instead of straight horizontal seams, dripping can produce irregular interlocking joints (Fig. 58). Alternatively, cold joints can be strategically distributed to weaken the structure in certain areas (Fig. 59). In other words, dripping can allow architectural designers to design failure modes into walls. Such failure modes could be useful to minimize overall structural damage (similar to the low-strength shear pins in the peristaltic pump design, see page 92) and could also ensure that some part of the structure remains as a foundation for reconstruction.

Fig. 55. A standard stack of interlocking eight-second drops with ornamental anomalies.
Fig. 56. Drops can stack like stones.

Fig. 57. Drops can overlap like shingles.
Fig. 58. *The interlocking structure of the dripped wall.*

Fig. 59. *A cold joint that formed at a moment of excessive wait time.*
The Responsive Drop

Drops can immediately respond to their physical environmental without sensor feedback; they are materially—and not computationally—responsive (Figs. 60-63). Such responsiveness could be deployed in reconstruction projects where deteriorating architecture elements need urgent, carefully placed supports (for example, if the uneven settling of a foundation resulted in the teetering of a masonry wall). Here, the material itself becomes the interface between the designer, the machine, and the environment, and critical human observation, rather than parametric computation, is required to determine how to proceed.

Drops can also be load-distributing or sealant joints between two dissimilar geometries. The amorphous drop is indiscriminative and will conform to whatever forms are around it (if it is given time to do so).
Fig. 61. The drops leave their marks on the corner formwork.

Fig. 62. The plywood reciprocates by giving texture and shape to the amorphous drops.
Fig. 63. Drops are flattened by the formwork.
The Corner

The corner condition poses a unique problem for concrete 3D printing systems (and architectural design, in general). If the designer does not program the machine to slow down or add a radius at corners, the concrete will twist and/or tear—the material cannot change directions as quickly as the machine can. In desktop 3D-printing, corners are managed by adding an almost imperceptible pause to allow for the directional change. These pauses result in small bump-outs at the corner, which most Makers disdain.

Dripping allows designers to tune the machine process to be even slower than the material process. The only acceleration at the corners of dripped things is the downward acceleration of the material. Instead of twisting or tearing, dripped corners melt or bleed (Figs. 64, 65).
Fig. 65. *The bleed at the corner of a dripped wall.*
The Column

If the delays are long enough, drops can stack vertically to form a column (Fig. 67). The assembly of the column can be facilitated by deliberately decreasing the drop height so that the nozzle becomes partially submerged and leaves behind a small depression in each drop. This cavity becomes a mechanical joint that ensures that the subsequent drop locks into place and maximizes the surface area of the drop-to-drop connection. The dripped column can be reinforced if drops are extruded around preassembled vertical threaded rods. The threaded rods can be held in place during dripping by the nozzle holder.
Fig. 67. With sufficient machine delay, drops can stack into a column.
Fig. 68. Stepover Test: The extruder was offset after each extrusion time so that wait times occurred in a different place—the adjacent bleeding created a build-up that buttresses the structure. The almost-equal proportion of extrusion time-to-wait time made the excess more sparse and, as a result, the support less permanent.

Support Structure

The material bleed from each drop (i.e. what occurs during the wait time), or the travel between drops, could be left at specifics points in space to create support structure for the dripped thing (Figs. 68-73). This support could be more or less permanent depending on the proportion of the extrusion time to the wait time.
Fig. 69. The wait time create a material foundation that supports the extrusion time.
Fig. 70. A detail of the “Stepover Test”—the excess material was dripped next to the drop.

Fig. 71. I continued lines of a conventional concrete 3D print past one another to form a “bulbous” corner support.
Fig. 72. Continuous extrusion with only wait times. The excess material built up into a permanent support that tied the structure together.

Fig. 73. The extrusion was non-linear—drops were visited in a zig-zagging order so that the interior is filled with the path.
What You Want to Leave Behind

In dripping, a human being instructs a machine to put a certain material in a certain place at a certain time: it is a subjective method of digital fabrication. By embracing—rather than fleeing—this subjectivity, architectural designers can begin to digitally fabricate according to their intuitions and aesthetic sensibilities. Further, from within a discipline otherwise ruled by an unquestioned desire for speed, architects can choose to slow the machine. In real-time digital fabrication, the machine is made to anticipate material outcomes; instead, dripping reinstates material uncertainty so that we can begin to rebuild our relationship to machines.¹⁰⁹

¹⁰⁹ This notion is similar to some ideas in relational ethics, which suggest that we need to be especially careful with the relationships we build with the places, people, or things we study. See the article “Telling Secrets, Revealing Lives: Relational Ethics in Research With Intimate Others” by Carolyn Ellis for an account of how relational ethics plays into first-hand research.
Fig. 75. The trace of movement from one drop to the next.
Embodied Waiting (What You Want to Hold On To)

The delays between drops open a space for us to re-experience ourselves—or better, our bodies—at work. Unlike typical designer-3D printer interactions, the dripping process requires that the architectural designer remain physically present—and engaged—while the machine is active. We have to mix material, feed material into the pump, prevent mechanical or material failures, and, if the robotic arm is not in “automatic mode,” hold down the “enabling switch.” (Fig. 76) We have to endure as the machine works and the material cures. In waiting with the machine, we become more aware of the bodies that we are waiting in.

When the robot is not in “Automatic Mode,” the designer must hold the “enabling switch” in order to enable the robot to do work. The word “enable” comes from the Latin word habere, which means “to hold.” Therefore, we could say that to enable also means to hold in, or on.

In “Anti-Oedipus,” Deleuze and Guattari suggest that subjectivity is produced through “the opposition between desiring-machines and the body without organs.” The philosophers contrast the production of the desiring-machine(e.g., “I want this” or “I need this) with the non-production of the body without organs (e.g., “I can be this” or “I can be there”), and describe the ethical dilemmas that occur as we necessarily oscillate between the two modes of embodiment.
Fig. 77. The drop can be used as part of a larger architecture.

Drop Economy

Concrete is a controversial building material because of its high embodied energy. By breaking down 3D printed concrete into its smallest possible instantiation—the drop—we can rebuild the process of 3D printing concrete to be more materially efficient. If we reject the assumption that we have to slice 3D prints, then we can also reject the assumption that 3D printed concrete should be used to construct entire buildings. Dripping empowers architectural designers to print a wall or to ask themselves: what can I design with a single drop?
Epilogue: The (Deferred) End

Digital fabrication machines are moving from studios and labs to homes and construction sites. This shift affords architectural designers the opportunity to build new relationships with the people and places that we design for. For example, we can design with our clients and not for them. We could also choose not to embrace this change, let clients and builders design for themselves, and, in doing so, put ourselves out of a job. Even worse: we could all let the machines do both design and construction on their own. These are not futures that I want to see. Architectural designers need new ways to interact with digital fabrication machines that maintain the vitality of their discipline, while at the same time evolving to produce the architectural design of the future. Machine Delay Fabrication, I argue, opens up the new forms of interaction that we need.

As more people learn how to write the code behind digital fabrication machines, more people will be able to customize their own interactions with them. Architectural designers need to take part in this learning process—we need to learn to code. But more importantly, we need to learn how to communicate with the people we are designing for through digital fabrication, and assert that learning to program a 3D printer is not the same as learning to design with one. Machine Delay Fabrication is a way to frame an architectural design conversation through digital fabrication—architectural designers should learn how to be interlocutors.

To be more concrete, here’s a hypothetical scenario:
An architect stands on an untouched plot of land with her client—a large, robotic arm stands between them. At the end of the monstrous arm is a relatively small nozzle for 3D printing. Wires and tubes extend from the nozzle back into the bowels of the machine—dull vibrations resonating from within are the only indication of its activity.

The architect enters some instructions into the interface of the machine and, almost immediately, the arm moves the nozzle to a certain point in space within the plot. There is a pause—then material slowly leaks from the nozzle onto the ground. The leaking stops, and the material settles into a small mound that resembles a column.

The client stares hard at the recently placed material for a long time. Eventually, he turns to the machine and enters in his own instructions. Once again, the arm moves the nozzle to a certain point in space within the plot of land—this point is about six human-sized paces from the first. Once again, there is a pause—then material slowly leaks from the nozzle onto the ground, even slower than the first time. The deposition is so slow that the material cures and supports itself as it is being deposited. The client apparently has decided that there should be a diagonal beam from the new point to the top of the existing mound. The architect thinks to herself, “I guess that’s where the stairs will be.”

This scenario conceives of architectural design as a drop-by-drop interaction: it is merely leaving a certain amount of material in a certain place at a certain time. Machine Delay Fabrication makes this future possible. In it, the architectural designer can become the orchestrator of the machine delay; she can: build the machine, design the interface, specify the material, and, if the piles seem like they are leading to nothing, ensure that there is always something that can happen next.

Of course, 3D printers are not the only digital fabrication machines that can be rethought through MDFab. One could imagine the principles of MDFab also being applied to subtractive manufacturing techniques, pick-and-place systems, or entirely new methods of digital fabrications that have not been invented yet.

If digital fabrication machines are routinely used on construction sites, what will they do when inevitable construction delays arise? Will they be slowed to meet the realistic speed of construction? Will they stop work? Or (a terrible thought), will human laborers be called in to continue the work at a slower pace? Architectural designers should anticipate a future with robots on construction sites and they should also anticipate that those robots will be slowed by unforeseen circumstances. MDFab offers a way to interrogate and invent what the machine—and the designer—will do in the delay.

The practice and concept of Machine Delay Fabrication that I have introduced in this thesis aims for a future in which architectural design remains in place, in touch, and, above all, in time.
Appendix I: Dripping Test Log
| Date | Test No. | Mix Design (oz.) | Nozzle Diameter (in.) | Drop Height (in.) | Extrusion Time (sec.) | Wait Time (sec.) | Notes |
|------|----------|------------------|-----------------------|-------------------|----------------------|-----------------|-------|
| ---  | 1        | 33   80 120 0 1.3 0.9 | 0.375 2 3 20 | Clogged, then printed after changing tubing angle |
| ---  | 2        | 32   120 80 0 0.8 0.9 | 0.375 2 3 20 | Printed, but somehow too pastey, more water? |
| ---  | 3        | 35   120 80 0 1.3 0.9 | 0.375 2 3 20 | A little runny, but nice puddles, closer... |
| ---  | 4        | 40   130 80 0 1 0.9 | 0.4375 1.5 3 20 | Started with almost good Drops, then got clogged, then material became thread-like, not sure what happened |
| ---  | 5        | 39   120 80 0 1 0.9 | 0.4375 1.5 3 20 | Good flow, bleed, a little too runny, less water? |
| ---  | 6        | 35   100 100 0 0 0.9 | 0.4375 1.5 3 20 | Almost there, maybe 34, controller broke so test |
| ---  | 7        | 33   100 100 0 0 0.9 | 0.4375 n/a n/a n/a | 34 too slumpy, I think 33 with more extrusion time |
| ---  | 8        | 34   100 100 0 0 0.9 | 0.4375 n/a n/a n/a | Too thick, got clogged, maybe forgot to tighten the rollers on the hub |
| ---  | 9        | 17   60 50 1 0.5 0.5 | 0.4375 n/a n/a n/a | Came out pretty good, maybe slightly more liquid but not much. Fiber worked |
| ---  | 10       | 17.5 50 50 0.8 0.6 0.5 | 0.4375 n/a n/a n/a | Clogged, maybe fibers caused tube to stick together, also angle of tubing changed |
| ---  | 11       | 34.3 110 110 1 1 1 | 0.4375 n/a n/a n/a | Clogged, tubing stuck together again, big jam in the tube, guessing at a pinch point, consistency seemed good so try again, maybe less |
| ---  | 12       | 33.3 102 100.5 1 1 1.1 | 0.4375 n/a n/a n/a | Clogged, tubing stuck together again, big jam in the tube, guessing at a pinch point, consistency seemed good so try again, maybe less |
| ---  | 13       | 33.5 100 100 0 1 1 | 0.4375 n/a n/a n/a | Clogged, tubing stuck together again |
| ---  | 14       | 35+  100 100 0 1 1 | 0.4375 n/a n/a n/a | Clogged, tubing stuck together again, pump broke, |
| --- | 15 | 34 | 100 | 100 | 0 | 1 | 1 | 0.4375 | 1.5 | 3 | 20 | Some good drops!! Starting curing fast, so try more retarder and 4 E/10 W. Also Buddy Rhodes plasticizer seems to work better, maybe the plasticizer |
| --- | 16 | 34 | 100 | 100 | 0 | 1 | 1.5 | 0.4375 | 1.5 | 4 | 12 | Tube stuck together again, not sure why |
| --- | 17 | 34 | 100 | 100 | 0 | 1 | 1.5 | 0.4375 | 1.5 | 4 | 12 | Tube stuck together again, must be an issue with |
| --- | 18 | 34 | 100 | 100 | 0 | 1.5 | 1.5 | 0.4375 | 1.5 | 4 | 12 | Way too liquid, but at least the pump works again |
| --- | 19 | 34 | 100 | 100 | 0 | 1.5 | 1.3 | 0.4375 | 1.5 | 4 | 12 | Best one yet! A few changes; even less wait time (8-10 sec), 1.4 plasticizer, lower the layer height to 1", then maybe try playing with drop spacing, also figure out how to do more continuous feed without shaking the funnel, etc. OR just use a very |
| --- | 20 | 34 | 120 | 120 | 0 | 1.5+ | 1.4 | 0.4375 | 1 | 4 | 10 | Something happened with the plasticizer proportion, came out very liquid |
| --- | 21 | 35 | 117 | 117 | 0 | 1.5 | 1.4 | 0.4375 | 1 | 4 | 10 | Closest to the model yet! Have to find a better way to feed the pump, material gets jammed in funnel, should either prime or use a stainless steel, less frictious |
| --- | 22 | 35+ | 120 | 120 | 0 | 1.5 | 1.4 | 0.4375 | 1 | 4 | 10 | Almost as good as #21, a little bit more liquidy, again proportions got messed up, a few more drops of water were required, time for a better scale——could also be the few more ounces of sand and cement; one more of |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| --- | 23 | 38+ | 120 | 120 | 0 | 1.5 | 1.4 | 0.4375 | 1 | 8 | 10 |
| --- | 24 | 35 | 130 | 130 | 0 | 1.5 | 1.4 | 0.4375 | 1 | 4 | 10 |
| --- | 25 | 40.2 | 125 | 125 | 0 | 1.7 | 1.4 | 0.4375 | 1.25 | 5 | 15 |
| --- | 26 | 40.2 | 125 | 125 | 0 | 1.7 | 1.4 | 0.4375 | 1.25 | 6 | 15 |
| --- | 27 | 38 | 125 | 125 | 0 | 1.7 | 1.4 | 0.4375 | 1.25 | 6 | 15 |
| --- | 28 | 38 | 125 | 125 | 0 | 1.5 | 1.4 | 0.4375 | 1.25 | 6 | 15 |
| --- | 29 | 36.2 | 125 | 125 | 0 | 1.5 | 1.4 | 0.4375 | 1 | 7 | 15 |
| --- | 30 | 37 | 125 | 125 | 0 | 1.5 | 1.4 | 0.4375 | 1 | 8 | 15 |
| --- | 31 | 74 | 250 | 250 | 0 | 3 | 3 | 0.4375 | 1 | 9 | 15 |

Had to up the water content last-minute and it was still more viscous than intended, as a result had to double the extrusion time to 8 seconds.

Upped the sand and cement content and was still more liquid than desired, nice dripping though and maybe a new scale works way better, drops are pretty good but base layer needs to bigger for better foundation and less slump, 6E next, MDF.

Some how way too liquid, pay attention to how it pours out of the bucket! Start with 38 water next, PLY.

Okay, but a little too liquid and layer height too large for slump, could not stack past.

There are holes! But it’s just a little too thick and the drops are just a little too small. Also worried about.

Pretty good, retarder should be 1.5, maybe up the layer height, change extrusion time to create larger base,

Only made it halfway. Down retarder to 1.5. LESS RETARDER EQUALS MORE OPEN TIME. Down wait time to 10. Maybe try slightly bigger nozzle. Get sifter. Will
| Date       | Time | Temperature | Output | Output | Wait | Time | Retarder | Mix Proportion | Mix Proportion | Result |
|------------|------|-------------|--------|--------|------|------|----------|----------------|----------------|--------|
| 04.01.18   | 32   | 74          | 250    | 250    | 0    | 3    | 1.2      | 0.4375         | 1              | 9      | 15  |
|            |      |             |        |        |      |      |          |                |                |        |      |
|            | 33   | 1504        | 1504   | 0      | 18   | 7    | 0.4375   |                |                |        |      |
|            |      |             |        |        |      |      |          |                |                |        |      |
|            | 34   | 1504        | 1504   | 0      | 18   | 7    | 0.4375   |                |                |        |      |
| 04.01.18   | 35   | 50          | 50     | 0      | 0.6  | 0.3  | 0.4375   | 1              | VARIES        | 10     |
| 04.01.18   | 36   | 50          | 50     | 0      | 0.6  | 0.3  | 0.4375   | 1              | VARIES        | 10     |
| 04.02.18   | 37   | 44.4        | 150    | 150    | 0    | 1.8  | 0.6      | 0.4375         | 1              | 5      | VARIES |
| 04.02.18   | 38   | 29.6        | 100    | 100    | 0    | 1    | 0.4      | 0.4375         | 1              | 5      | VARIES |

Better but still not sure retarder is working properly, will try a little bit less and less wait time and cement mixer for agitation, corner.

There was a clog because the pump outlet shifted and was getting pinched. Also, the concrete did not get mixed well enough in the cement mixer--next time: dry mix before hand and feed into.

Dry material got stuck in the cement mixer so proportions got messed up. The pump jammed twice and two shear pins had to be replaced. The mix was still more liquid than it should have been so the layer height got messed up and there was more loops than drops. Next time: pre-mix before hand and just use cement mixer to agitate; find a way to sift concrete after mixing to remove pebbles and/or replace wheels with.

Miscalculation, extrusion time test mix desegregated, still can see difference in drops, but they're flattened.

Successful extrusion time.

Mostly successful wait time test, though should try shorter pauses, mix is curing too quickly, try without the vibrator, I think it's settling the mix in.
| Date    | Time | Value 1 | Value 2 | Value 3 | Value 4 | Value 5 | Value 6 | Value 7 | Value 8 | Value 9 | Value 10 | Notes                                                                 |
|---------|------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-----------|------------------------------------------------------------------------|
| 04.02.18 | 39   | 44.4    | 150     | 150     | 0       | 1.5     | 0.6     | 0.4375  | 1       | 8       | 12        | Column, 15" high, toppled                                            |
| 04.03.18 | 40   | 44.4    | 150     | 150     | 0       | 1.5     | 0.6     | 0.4375  | 1       | 8       | 12        | Column, approx. 12", still standing                                  |
| 04.04.18 | 41   | 444     | 1504    | 1504    | 0       | 15      | 7       | 0.4375  | 1       | 9       | 11        | Corner #2, shear pins split several times, concrete mixer cannot be used, try batch |
| 04.05.18 | 42   | 59.2    | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 7       | 11        | ABCDE Test, option 1, successful though had to up plasticizer amount at last |
| 04.05.18 | 43   | 59.2    | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 7       | 11        | ABCDE Test, option 2                                                                 |
| 04.05.18 | 44   | 59.2    | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 7       | 11        | ABCDE Test, option 3, mix got messed up, a little too thick, wonder if these tests are truly demonstrative |
| 04.06.18 | 45   | 29.6    | 100     | 100     | 0       | 1.1     | 0.4     | 0.4375  | n/a     | n/a     | n/a        | Retraction Rate Test, came out as expected though rate was too fast in each case, try again with 1/3/5/7 percents |
| 04.07.18 | 46   | 59.2    | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 9       | 11        | Corner Test proportions were approximated for 10 batches to reach a height of almost 20"; one batch = two layers or 2"; time between batches has to be taken into account |
| 04.11.18 | 47   | 30+     | 100     | 100     | 0       | 1.1     | 0.4     | 0.4375  | n/a     | n/a     | n/a        | "This is 40 seconds" Diagram. A little bit thick (something up with the proportions), but still readable |
| 04.12.18 | 48   | 61      | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 10      | 10        | Freestyle Pile, improvised                                             |
| 04.12.18 | 49   | 61      | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 10      | 10        | Freestyle Pile, form a space                                          |
| 04.12.18 | 50   | 61      | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 10      | 10        | Freestyle Pile, mix too thick, I think there is too much               |
| 04.13.18 | 51   | 61      | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 10      | 10        | Freestyle Pile, mix too thick again, definitely too much sand, pump almost clogged |
| 04.13.18 | 52   | 61      | 200     | 200     | 0       | 2.2     | 0.8     | 0.4375  | 1       | 10      | 10        | Freestyle Pile, move to next point at the end of every extrusion time to visualize |
| Date     | Type | Drops | Drop Spacing | Travel Speed | Thickness | Time | Speed | Result |
|----------|------|-------|--------------|--------------|-----------|------|-------|--------|
| 04.13.18 | 2    | 53    | 200          | 200          | 0         | 2.2  | 0.8   | 0.4375 | 1      | 8     | 4 + 8 |
| 04.14.18 | 2    | 54    | 200          | 200          | 0         | 2.2  | 0.8   | 0.4375 | 1      | n/a   | 10    |
| 04.18.18 | 2    | 55    | 200          | 200          | 0         | 2.2  | 0.8   | 0.4375 | 1      | 9     | 11    |
| 04.21.18 | 2    | 56    | 150          | 150          | 0         | 1.6  | 0.6   | 0.4375 | 1      | 12    | n/a   |
| 04.22.18 | 2    | 57    | 200+         | 190          | 0         | 2.2+ | 0.8   | 0.4375 | 0.375  | n/a   | 10    |
| 04.22.18 | 2    | 58    | 200          | 200          | 0         | 2.2  | 0.8   | 0.4375 | 0.375  | n/a   | 10    |
| 04.27.18 | 2    | 59    | 200          | 200          | 0         | 2.3  | 0.8   | 0.4375 | 1      | 9     | 10    |
| 05.05.18 | 2    | 60    | 200          | 200          | 0         | 2.5  | 0.8   | 0.4375 | 1      | 9     | 10    |

- **04.13.18**: 5 rounds of mixing, stepover test, 4 second wait time at drop, 8 second wait time
- **04.14.18**: 7 rounds of mixing, Wait times only test, some enabling switch errors, but
- **04.18.18**: 6 rounds of mixing, Responsive test, material needs to be even slumpier, could try a different bed position/orientation so that there is more clearance
- **04.21.18**: Proximity of drops diagram: drops were spaced 30" apart and printed at 100% speed, the stacks almost toppled suggesting that either slower speed or greater distance is
- **04.22.18**: Bulb corner: vibrator wasn’t working so had to move material through funnel manually, mix was too liquid, 5% speed too slow to
- **04.22.18**: Bulb corner conceptual success, except mix too thick, vibrator moved material too quickly so clog occurred. 30% speed seems right, except ideal travel speed is different than print speed so material does not cure in tube. Next time try 8
- **04.27.18**: Standard stack, good rhythm
- **05.05.18**: Shot for nozzle-to-drop video, came out a little thick, but the holes were decent
Appendix II: Dripping Videos

Motor and Solid State Relay
https://www.youtube.com/watch?v=6LKqWVMCbuE

Iteration #2 System
https://www.youtube.com/watch?time_continue=14&v=gAA0W3uUO3w
https://www.youtube.com/watch?v=l_Is4ySgwV4

Current System
https://vimeo.com/270990944

Drop Visualization Software
https://vimeo.com/270990912
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