THE SELF-ASSEMBLY LINE

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ABSTRACT

As disciplines converge and programmability becomes ubiquitous from the nano scale to the human scale, architecture and construction will likely inherit new processes for design tools, materials, fabrication, and construction. This paper outlines the key ingredients for self-assembly and computational construction through a recent project, The Self-Assembly Line. This project, commissioned for the 2012 TED Conference, was described as "an installation that builds installations" and was built to show autonomous self-assembly at furniture scales. A new intuition is proposed for the construction of large-scale structures and gives insight for potentially expanding a designer's role in self-assembly processes outside of the discipline of architecture. Future applications are outlined for self-assembly and programmable materials at large-scale lengths.

1 DISCIPLINARY CONVERGENCE

Across disciplines we are seeing a convergence where programmability and computational mediums are being discovered within every substance and at nearly every scale. Biologists are looking more like designers or engineers, controlling biological material to synthetically grow, adapt, contain logic, and execute programmable sequences. Similarly, DNA nanostructures are being designed with CADNano software in wetlabs, not design studios, allowing scientists to program 3D structures through ACTG logic and self-assemble complex 1D, 2D, or 3D structures at nano scales. These DNA structures can contain virus antibodies and have mechanical behaviors deposited throughout the body for unprecedented delivery mechanisms. Chemically, we are also seeing inorganic protocells that behave more like living systems, demonstrating replication and other cellular-like traits that can be programmed and manipulated either directly through the substance's parameters or through environmental influence. Similarly, many disciplines from synthetic biology, neuroscience, material science, chemistry, and physics to computer science are finding fundamental abilities to reprogram matter, build in inherent logic, and compute with Turing-complete functionality across scales. Computation is no longer limited to electronics and digital mediums; rather, we are beginning to see programmability as a fundamental capability, to be discovered anywhere, simply by having the right lens and an ability to communicate or manipulate collectively interacting components (physical/digital/biological/chemical, etc). These developments are clearly extending beyond the life sciences and are intertwining computer science–like properties with evolutionary lifelike characteristics, repurposing labs and experiments into design processes.

2 ARCHITECTURAL INHERITANCE, PROGRAMMABILITY, AND SELF-ASSEMBLY

Historically, architecture has inherited new technologies from a variety of disciplines, repurposing, reimagining, and challenging technologies to push production or design paradigms. Architecture's interdependence on technological progress can be seen through prime examples like the development of the arch, vaulted cathedral ceilings, the elevator and the boom of high-rise structures, wrought-iron, steel, glass, concrete, and other material developments that have led to major architectural movements. More recently, we can see technology's influence through animation, rendering, or software, to fabrication, machines, tools, and techniques. Architecture fundamentally moves forward through cross-disciplinary advancement. If we continue this lineage of architecture's depedency on technological development, given the unprecedented convergence happening across disciplinary scale-lengths with material programmability, how will architecture—from design to production—be influenced?

We will see a shift in scale. Software tools will start to allow designers to work from the nano-scale through macro-scale materials/behaviors to human-scale applications and beyond. Space applications may close the loop where environmental conditions and programmability seamlessly converge with nano-scale environments and design tools. New materials will have programmed adaptation to external and internal changes and have new software tools allowing for scalar gradients of material properties. Will these new material properties contain drop-down menus for multiple state-changes, printed or grown from software to evolving physical characteristics, rather than simply static material properties? Can we advance the lifelike characteristics happening with inorganic materials for replicating and self-repairing materials at macro scales? Fabrication and construction will most likely be more like farming, synthetic biology, or chemistry where designers seed the growth of elementary materials, programming them through internal logics and subtle environmental changes to influence their global configuration, interactions, and evolution. These questions and this soon-to-be reality are not far off; digital worlds are colliding with physical worlds, the boundaries are being blurred, and material computing is happening across scale-lengths. Simulation is no longer limited to prephysical phases or software toolsets. We are finding new ways of linking physical and digital capabilities through feedback and material computation. The question still remains: what are the critical ingredients and applications for large-scale programmability?

figure 1

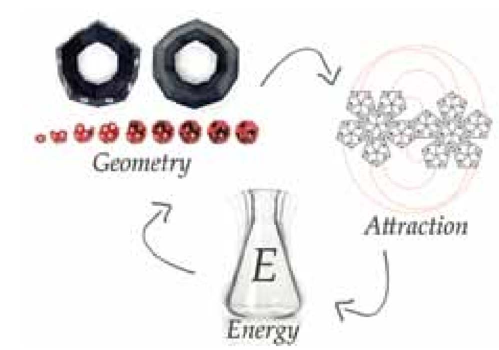

figure 2

figure 1

The Self-Assembly Line. TED Conference, Long Beach, CA, 2012.

figure 2

The Self-Assembly Line: ingredients for successful self-assembly.

3 INGREDIENTS

If we are going to utilize the converging behaviors of neighboring disciplines for a rebirth of computational capabilities, though—this time not merely digitally, but also physically—we will need a user manual for the vital tools, tricks, and trades of the new discipline. We can see similar capabilities in digital design paradigms, from our software toolsets to those utilized at nano scales. We can also see similar fabrication paradigms, from proposals and prototypes of automated manufacturing to the automated DNA sequencing devices. However, the comparisons between human-scale programmability and the programmability available in nearly every other discipline stop there. The three common stages from design to production, on every scale, are design, fabrication, and assembly. Within the assembly stage, there is a fundamental flaw in that architects have developed primarily brute-force construction techniques over the centuries of human-scale architectural projects. As a society, we have developed tools and processes for building everything from furniture to buildings and citywide infrastructure, layer by layer, brick by brick, forcing cold, hard materials to conform to human desires. However, nearly every other process of construction—from biology to chemistry to computer science, robotics, and material science—utilizes a fundamentally

figure3

figure 4

figure 5

figure 3

The Self-Assembly Line, close-up of cage and capsids.

figure 4

The Self-Assembly Line, with static cage and capsids.

figure 5

The Self-Assembly Line, at night with cage rotation.

different process for building, a process called self-assembly. Proteins, DNA, or cells do not have sledgehammers, screwdrivers, or manual labor; they utilize embedded information, state-change, environmental change, and error correction mechanisms. It has been demonstrated that four main ingredients must be utilized for this type of intelligent construction. The self-assembly ingredients include decoded assembly sequences (ACTG of DNA, or the embedded blueprints for what we want to build), programmable parts that execute each step of the sequence, energy for activation, and error correction/redundancy. These ingredients and their interrelationship offer a new paradigm in our methodologies for building the behaviors that, for the moment, we can only dream of designing.

At human scale, we need to begin challenging our intuition for construction. We need to build physical prototypes and tools for learning, which we will use as children and continue to use, generation after generation, from micro to macro scales, and which challenge our conventional stages of design to production. Our means of efficiency and ease of production have a limit; we will soon begin to reach the extent of what is possible with our current processes. Brute force can only take us so far. With ever-increasing demands on energy, with reductions both on a building scale and in our construction processes, and with increasing needs for precision and dynamic materials or at extreme scales or environments, we are beginning to realize that we will need new processes and materials that have embedded information and self-building techniques for construction. These materials and processes can be intelligent and work collaboratively, offering a new paradigm of computational construction.

figure 6

figure 7

figure 8

4 THE SELF-ASSEMBLY LINE

The latest development in a lineage of research that demonstrates the four ingredients of self-assembly and tests a paradigm of computational construction, The Self-Assembly Line, is an installation commissioned and produced for the 2012 TED Conference in Long Beach, CA. The project was initiated with the idea of building "an installation that builds installations," as a collaboration between an architect/computer scientist and a molecular biologist. Both the designer and the biologist were working on macro-scale self-assembly systems, one focusing on the biological developments of virus capsid self-assembly and the other on proteinlike single-strand structures programmed for self-organization through external energy. This project was designed, prototyped, and constructed over the course of several months, while being tested at a variety of scales and environmental characteristics. The project included a large container, roughly 10′ × 10′ × 15′, that rotated about a single axis. Inside the container were autonomous units that tumbled stochastically, eventually finding one another to self-assemble furniture-scale structures.

The *Self-Assembly Line* contained three major elements: geometry, component attraction, and external energy. The first element, geometry, was based on a polio virus capsid with unit geometry containing fivefold symmetry and assembling to form a dodecahedron (12-sided) container. The specifically designed geometry of the units ensured that the accurate global structure would be self-assembled, given the necessary environmental characteristics. The symmetrically designed unit allows each element to come together in one of five ways, for each of the 12 units in a dodecahedron. Due to the probability of the attraction orientations, this nearly guarantees that no dodecahedrons will be assembled in exactly the same way, yet the overall global structure will always form a dodecahedron. In future structures, this feature will hopefully be explored further by various unit patterns that exemplify the stochastic assembly process. For this implementation a deterministic structure, the dodecahedron, was utilized to allow users to judge the success or failure of a given time frame. However, hierarchical assembly is possible with low-level deterministic structures that can add up to nondeterministic global structures.

A single unit was initially 3D printed, and a negative rubber mold was cast. A hollow aluminum unit, roughly ¼" smaller on all sides, was cut with a waterjet cutter and folded to form the internal

figure 6

Capsid assembly starting from 12 units, resulting in a full dodecahedron capsid.

figure 7

Black units made from cast flexible foam, embedded magnets, and hollow aluminum core.

figure 8

Half-capsid and full-capsid assembly, each dodecahedron measuring 24" in diameter.

structure of the unit. Magnets were then fixed to the hollow core, and the core was placed in the rubber mold. The magnets on the unit aligned with magnets embedded in the mold to ensure that the hollow core floated away from all sides of the negative mold. Liquid flexible foam was then poured into the mold and cast around the hollow core and surface magnets. A total of 48 units were cast using this process, either forming a red unit or a black unit (24 each). Because of the flexible foam material, the units were soft to the touch and tumbled quietly in their container, yet they were hollow and rigid for their required assembly characteristics.

The second element necessary for *The Self-Assembly Line* was an embedded unit attraction mechanism, or programmed magnetic patterns. The unit has five faces, each with two magnets, one positive and one negative. The direction of the positive/negative magnetic patterns allows for different attraction patterns. Two sets of units were utilized, black and red; each had a different direction of positive/negative patterns. The red units contained positive/negative/positive patterns, while the black units contained negative/positive/negative patterns. This ensured that correctly paired units attracted one another and that noncomplementary units repelled. The magnetic pattern gave an embedded program and state to the units (connected or disconnected), while also serving as a system for global error correction. Each pair of magnets was individually weak, yet when at least three units came together, the pairing was significantly stronger. This demonstrated two forms of error correction: the first due simply to the alternating pattern, so that black units repelled red units and only attracted complementary pairs; the second due to weak attraction leading to collectively stronger attraction. This ensures that if there is an incorrect connection, i.e., a black unit's magnet connecting to a red unit's magnet, it will be knocked off quickly because of the weak bond, yet aggregates of correct connections will succeed over time. Interestingly, it was observed that due to low energy states, incorrect assemblies might occur that still succeeded over time. This happened infrequently but offered a glimpse of biological mutation at large scales. For example, if a capsid formed rather quickly, a single unit might be trapped inside, unable to escape. This would require a significant increase in the amount of external energy (temperature increase, biologically, or amount of rotation in the container) so that the capsid would break apart and the unit would be able to escape.

The last element necessary in *The Self-Assembly* Line was a variable external energy source, representing the temperature of the biological environment; this was demonstrated by the speed of rotation applied onto the external container. This container was made of HDPE strips that were connected together to self-form the container's curvature. The container sat on large-diameter plates at both ends, inside caster mechanisms that allowed the container to rotate freely. Users were able to rotate the container easily throughout the exhibition, producing more energy by rotating it faster or less energy by rotating it more slowly. If the user rotated the cage with too much speed, the amount of stochastic interaction and the force of the unit's interaction were too strong, such that assembly would not occur and any already assembled units would disassemble. If the speed of the rotation was too slow, the units would not interact enough and assembly would not occur, or would occur at a very slow rate. At a medium speed, the users would produce just the right amount of energy and interaction; the parts would find one another and successively assemble the dodecahedron structure. The quickest assembly time was roughly five minutes, while the average was at least ten minutes. The strength of the magnets and the type of container significantly affected the success of the assembly, and further versions are being tested in order to increase the efficiency of assembly. However, the stochastic interactions between units ensure that the amount of time for assembly cannot be guaranteed precisely. Thus, even with more efficient systems, any given assembly attempt might happen extremely quickly or might take an excessive amount of time. The rough limits on assembly time, however, can be increased so that on average, assembly would occur faster.

The Self-Assembly Line gave an insight into the process of virus assembly at biological scales, and more specifically, a scientist's—and now potentially a designer's—role in developing drug delivery systems. Drug design commonly includes two predominant elements, the shape and the attraction of the elements in hopes of targeting a specific virus. *The Self-Assembly Line* offered a new insight and quickly developed intuition for the process of drug design. Users could easily grasp the aspects and characteristics of the polio virus capsid assembly and soon come to ask themselves, *if this is how a virus assembles, how can I stop it from assembling*? Intuitively, if a designer were able to invent a specific shape and attraction mechanism that could be thrown into the chamber that would stop the virus from assembling or would disassemble an existing virus structure, they would have successfully designed a molecular self-assembly machine for stopping a virus. *The Self-Assembly Line* helped to highlight this process, one that is not considered intuitive due to its extremely small scale and high-level processes, which are normally reserved for expert scientists. The project also shows a potential avenue for expanding the role of the designer and architect into new territories and disciplines, utilizing our refined knowledge of materials, geometries, and assemblies. Simply through a disciplinary convergence and new advances in programmable or self-assembled materials, designers are now able to work with inherent logic and environmental constraints in order to design systems seamlessly, from the nano scale to the human scale.

5 APPLICATIONS

If the disciplinary convergence continues and programmability and computational construction become the next industrial revolution, or even humbly enter the architectural and construction industries, where might we see these techniques and processes starting to take off? Obviously we most likely will not see every construction company jumping at the opportunity for buildings to self-assemble, and we probably will not soon see the next Manhattan skyscraper having *Optimus Prime*–like transformations, yet nonetheless, self-assembly and programmable materials are probably very close. The first applications of such technology will most likely take shape in the most extreme environments, such as space, high altitudes, free-fall scenarios, or deep-sea applications. These environments have the right conditions for self-assembly, such as near zero gravity or where small amounts of energy can lead to significant increases in interaction. These environments also provide a prime application because we currently have significant difficulties or are unable to build in such environments. These environments often have high precision demands and need to minimize energy consumption because of their distance from the existing built environment. One could imagine that these environments will soon be extremely valuable as building sites or as off-site construction farms for conventional sites. We could soon see building materials being preconnected, taken underwater to utilize wave energy for construction, and then lifted out as fully erected multistory structures; or systems dropped from high altitudes to take advantage of free-fall time, near weightlessness, and the wind resistance to unfold structures before touching land. These applications seem extreme, but propose scenarios for extreme building environments where self-assembly could be equal to the challenging construction constraints.

A second set of applications includes scenarios for embedding spatial computing into physical materials. True ubiquitous computing proposes not simply sensors and conventional digital communication; rather, every bit/atom and material can be used to compute processes or store information. As seen in Logic Matter, physical building blocks can provide completely passive abilities to compute digital information and store data about the building, the environment, structural loading, or other miscellaneous information that we might want to use for building occupants. The excessive demand on computing resources, as speeds get faster and processes require more off-site computing power, provides a prime opportunity for utilizing physical materials that are truly ubiquitous in our physical environment. If every brick, beam, and bolt could have low-level computing power, there would be a significant increase in the adaptability and structural aptitude of our structures. Bridges could compute their dynamic loads and update based on stability constraints; walls could be plugged into as a hard drive; and materials could change opacity based on varying light levels. This material could become a functioning computational medium outside of purely construction-related applications.

Alternatively, as a construction tool, information-rich materials and self-assembling systems can be utilized in a variety of applications from radical scenarios to humble bricklaying practices. Architects often spend significant energy, time, and money in controlling the quality of their structures built around the world with explicit drawings, local tolerances, and building practices. Alternatively, information-rich materials could contain assembly logic, be shipped to site, and either ensure complete and accurate assembly by eliminating the possibility for wrong moves, or simply constrain the possible assembly outcomes to a spectrum of acceptable solutions. This proposes building materials as a contractor's designer/sidekick, making decisions and aiding the assembly step by step as the building is constructed. Other construction applications may utilize greater off-site energy and time by infusing materials with information or dynamic capabilities so that while on-site the systems can be quickly deployed, released, and self-assembled. Off-site energy and information input can help minimize on-site time, cost, and energy, which constitute a significant portion of architectural budgets and energy expense. These applications demonstrate a far more humble scenario for utilizing programmable materials and the opportunities afforded by cross-disciplinary advances for a new vision of self-assembled construction.

6 CONTRIBUTIONS

The stage is set for a new paradigm of computation to reach beyond the screen and offer programmability and dynamic behaviors across scales, materials, and design processes. Various disciplines are blurring the boundaries with scientists, engineers, and designers making complementary findings through a variety of mediums and scale-lengths. This is also a time of increasing demands on our processes of physical production and construction, including environmental, energy, labor, time, and cost constraints. Similarly, new software and fabrication technologies are pushing computational processes into new realms, offering potentials for the design and materials that we utilize as architects. We will see increasing opportunities for automated construction techniques and ultimately information-rich materials that can inform the building process and self-construct. As our knowledge base and ability to author computation through software, materials, and construction increase, we will be less reliant on industrial machinery and seek passive and embedded intelligence, where materials inform the people and machines that surround them. Ultimately, designer, machine, material, and program will collaborate seamlessly at nano to macro scales, physically and digitally, utilizing organic and inorganic behaviors for new paradigms of design and production.

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DESIGN ECOLOGIES FOR RESPONSIVE ENVIRONMENTS: RESONANT CHAMBER, AN ACOUSTICALLY PERFORMATIVE SYSTEM

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ABSTRACT

This paper positions the development and performance of a responsive acoustic envelope system, called Resonant Chamber, within discourses in ecology, systems theory and cybernetics. The project is described through two dominant threads. First, a synthetic design process that entails engaging simultaneous computational and physical investigations which inform each other through various feedback and control regimes - from simulation and testing frameworks to material limits and behaviors to geometric, technological and manufacturing limitations or constraints. Second, the paper elaborates on the embedded communication, feedback and actuation systems that transform its performance as a kinetic, responsive environment, allowing for the possibilities of active acoustic control and open-ended interaction with inhabitants. Throughout the process, the designer operates in an adaptive mode; dynamically shaping possibilities, navigating digital, physical and effective logics, constraints, behaviors and opportunities.