From Digital Materials to Self-Assembly

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CONSTRUCTION INFORMATION

Digital information is everywhere from our computer systems, design software, machine control languages and automated manufacturing techniques. This information has become the fundamental language for communication between the virtual and physical worlds. Code has become the predominant language for various fields from computer science, to engineering, design and manufacturing. However, there has been a limit to the applications of digital information and systems, frequently stopping at the extents of the digital tool, whether it is the computer or the machine. Just as digital information and toolsets have transformed the practice of design, manufacturing and architecture, they will soon bring light to new possibilities of construction and assembly. Digital information is at the brink of a rediscovery, one that will propagate itself within our physical materials and be realized as an inherent phenomenon within the perceived analog world.

The recent opportunities offered by digital generation and fabrication, along with the subsequent discussion of mass-customization have posed a problem, one that becomes apparent when fabricated parts are taken off the machine. This dilemma is based on assembly and the inherent loss of information while going from coded design to machine tool then into the physical world. All of the incredible code that is used for design and fabrication has been destroyed and the cold, sharp, piece of material is left in its place. The desired "architect as master builder," is now burdened with the daunting task of constructing extremely complex and interwoven structures that were generated with elegant algorithms. Quickly the construction worker is called in and faced with the same problem, while not realizing that the error lies in the communication from digital to analog system, not in the person/robot providing the construction. If we look closely at the relationship between digital information and all of the existing methods of assembly that architects or contractors deploy, we can see that there is a disconnect between the newly emerging possibilities in generation and fabrication as compared to the outdated techniques that plague our construction industry. There are fundamentally only a few types of information that we utilize during construction; Type 1: User-As-Information, Type 2: Environment-As-Information and Type 3: Specificity-As-Information.

Type 1: User-As-Information

This is the builder, the brick layer, or the robot arm, each forced to contain all of the information to build the desired structure. The robot arm is no different than the brick layer in that respect. The parts are completely dead, with no information. The builder is left to adapt to circumstances and potentially build the correct structure.

Type 2: Environment-As-Information

This is the Roomba® scenario or the site-specific design solution. The information needed to build is actually embedded in the environment, rather than the builder or the materials. The Roomba® knows nothing about the room it is trying to clean; it simply listens to the walls, has an embedded algorithm and eventually cleans the room with some level of accuracy. The builder, for example, simply listens to the context and adapts each step in the assembly process to update the final result based on the environment.

Type 3: Specificity-As-Information

This is the jigsaw puzzle or Ikea® scenario. Mass-customization allows for completely unique parts, each part having a specific place in the overall structure. All of the information to build the structure is based on the shape of the parts. The user simply (or not-so-simply) needs to find all of the parts in the correct order to assemble the structure. Then, the parts should guarantee that the structure is built accurately (and hope there is no tolerance). However, these parts are only useful for building one thing because they are not universal parts. Even worse, this process can be extremely tedious, finding one part in thousands or millions, as in the number of elements needed to build large buildings, is very difficult.

None of the existing types of information used for construction today, allow the material parts to inform the assembly sequence. If we are going to continually push the boundaries of construction and seek to build new types of structures, larger, more complex or more efficient then we are currently capable of producing, we will ultimately need to take advantage of the code that is used for generation and fabrication by embedding it directly into our materials as instructions for assembly.

DIGITAL COUNTERPARTS & THE FUTURE OF CONSTRUCTION

Nearly every micro scale process in the biological world from our body's proteins to DNA, cell replication and the hydroscopic or hydrophobic molecular interactions, all utilize processes comparable to digital systems with discrete information, error checking, redundancy and self-construction.[1] These biological structures are far more complex, interconnected, precise, have lower energy and higher construction yield rates than any human-built (or machine-built) structure to grace the earth. The processes at play within these systems are even more impressive with self-repairing materials for longevity, self-replication for reproduction and regrowing/mutating structures. The future structures we build are faced with ever-increasing necessities of lower energy consumption as well as economic and environmental consciousness. If we are going to build structures that respond to these demands and provide exciting possibilities for the future, we will need to find smarter systems of assembly and programmable materials (not necessarily smarter external machines). These new systems will offer exciting possibilities for self-assembling structures, building themselves, adapting to design and environmental forces, changing states and offering massive distributing computing directly within the materials. This is the future of construction, one that will look more like biological processes or science fiction then sledge hammers and welders.

DIGITAL INFORMATION & DIGITAL MATERIALS

A digital system, as introduced by Claude Shannon, is a system that transfers discrete information (0 and 1), can produce reliable systems from unreliable components and utilizes redundancy to prohibit errors from accumulating.[2] This type of system actually increases its rate of perfection as the scale increases. Shannon demonstrated this by introducing the idea of a threshold in relation to the amount of noise or error in a system, explaining that "below a certain amount of noise (1/3), the error rate is effectively zero".[3]

If we now apply this idea of a digital system back to our materials and fabrication machines we can imagine a process that relies on local intelligence, discrete information and does not allow errors to propagate with an increase in scale. Based on digital logic and Von Neumann's work on self-replicating systems, Neil Gershenfeld explains how a digital system could actually carry its own assembly instructions, saying "this medium is quite literally its message, internally carrying instructions on its own assembly. Such programmable materials are remote from modern manufacturing practice, but they are all around us." He goes on to describe the ribosome and its sequence of self-programmed folding of proteins as an example of a self-assembling digital process within our human bodies.[45]

> There's a pattern here. Shannon showed that digital coding can allow an imperfect communications system to send a message perfectly. Von Neumann and colleagues showed that digital coding can allow imperfect circuits to calculate perfect answers. And the ribosome demonstrates that digital coding allows imperfect molecules to build perfect proteins. This is how the living things around you, including you, form from atoms on up. It's necessary to precisely place 10^25 or so atoms to make a person, an ongoing miracle that is renewed in everyone ev-

> ery day. The role of error correction in fabrication is as close as anything I know to the secret of life.[6]
>
> The discovery of building with logic is actually a few billion years old; it's fundamental to the emergence of life. Current research is now seeking to do the same with functional materials, creating a fundamentally digital fabrication process based on programming the assembly of microscopic building blocks.[7]

Neil Gershenfeld and George Popescu of the Center for Bits and Atoms at MIT coined this, "digital materials." This notion emerged out of decades of research on mechanical computing, self-replicating machines and the translation from analog to digital communication systems at Bell Labs in the mid twentieth century. A digital material need-not contain electronics or motors; rather it must contain the capabilities of digital information and translate that to the physical world.

A digital material is a material with the following properties:

- The set of all the components used in a digital material is finite (discrete parts)

- The set of the all joints of a digital material are finite (discrete joints)

- The assembly process has complete control over the placement of each component (explicit placement)[8]

With this definition of a Digital Material and Lego® as a simple example of such a material, we can imagine a set of universal building blocks. These materials would auto-align themselves, have discrete joints, universal construction, can be made to transfer information through conductive/non-conductive components and allow structures to be built that are far more precise than a human's (or child's) fine motor skills. This type of material emphasizes that the essence of "digital" can be an inherent capability within raw materials.

LOGIC MATTER: A COMPUTATIONAL MATERIAL

As Shannon, Von Neumann, Gershenfeld and others have shown, it is possible to embed the characteristics of digital information into physical materials. Logic Matter, a project completed at MIT in 2010, attempts to go one step further by embedding computation directly into our material parts.[9] Logic Matter explores the nature of assembly, specifically in the context of complex structures (i.e. assemblies with extremely large numbers of parts or small parts in large numbers) by focusing on the communication between our materials and the people/machines/biology that perform the construction. By taking advantage of the opportunities of digital information as well as digital logic, our parts can perform computation, ensuring that they are assembled correctly, reducing error propagation, offering storage for long/complex sequences of assembly instructions and providing the means for read-write replication.

Logic Matter is composed of a series of physical building blocks that demonstrate digital logic by passively connecting brick-to-brick (i.e. no electronics or motors are needed). The parts engage in a dialog with the user, giving information, taking feedback, computing next moves and analyzing current conditions. Logic Matter parts can be assembled to describe any given geometry (lines, surfaces and volumes) through a linear, chain-like, growth that provides a series of instructions (left, right, up, down) for the user. Further, they implement a digital NAND logic gate to offer a new system of computing with exciting potentials for three dimensional circuit assembly and self-guided-replication.

Within Logic Matter, each of the units takes two inputs, one from the previous unit that it is already attached and a second unit that is newly placed by the user. After each step, there is only one output. This means for every two inputs the system continues to grow from one output, thus there is always a unit of redundancy. As the system grows and begins to turn up/down/left/right, these redundant

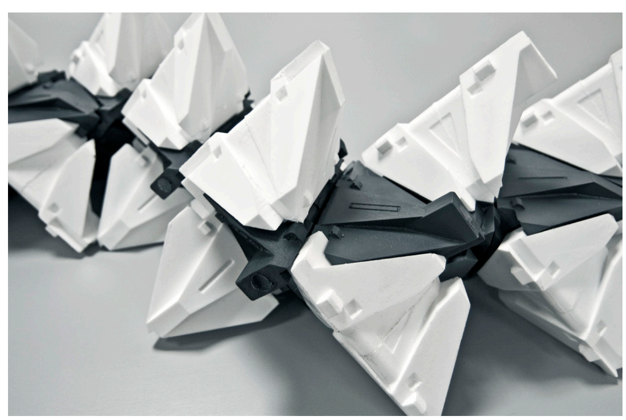

Figure 1. Logic Matter Units & Assembly, 2010.

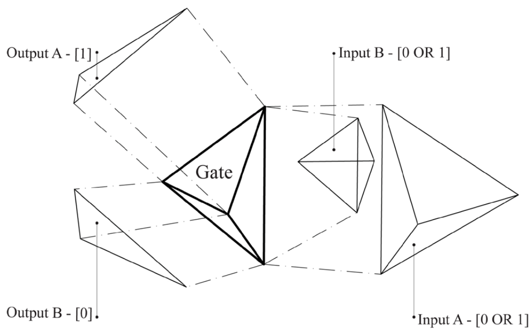

Figure 2. Logic Matter, 2010 – NAND Gate Digital Logic Building Block.

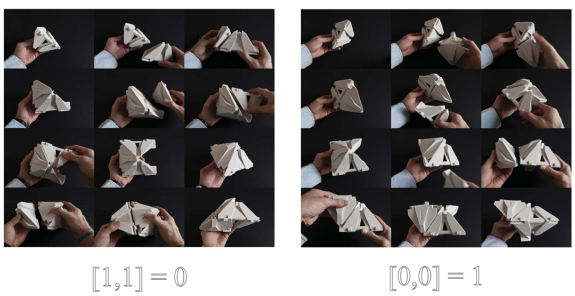

Figure 3. Logic Matter, 2010 – User Programmability.

units interconnect with one another forming strong structural connections and auto-aligning structures. This redundant information also contains one of the inputs as a physical history, or blueprint, of the structure we have built. In order to allow systems to self-replicate, these redundant units are the key ingredient to reading the assembly instructions directly from the material, requiring no additional information to build an exact replica.

This system offers an exciting paradigm for computing, one that materializes the capabilities of a hard drive and processor from a single sequence of inputs. The building blocks compute on the stored sequences of the previous units, then store and recompute the latest output for the next moves. Each move can act as a counter, a storage device or an instruction set, informing the user when to stop as well as next moves to ensure a globally accurate construction. This potentially could ease the repair of structures because the material surrounding a damaged zone would contain the building's blueprint, directly informing the builder how to replace missing parts. Similarly, the material storage sequence could be utilized in a form of self-replication where a decoder device could be sent along the sequence of units to replay the assembly instructions. This system acts as though a building could wear its blueprints as a skin, offering a simple mechanism for replication, repair or morphogenesis.

Some of the most interesting applications are at extreme scales; i.e. biological machines that have limited computation/storage capacity and thus can rely on the deposited material parts for local assembly instructions, much like the impressive power of our Ribosome to decode RNA into a sequence of folds and create complex proteins. Or at extremely large scales, structures with upwards of thousands or millions of parts cannot continue to accrue errors, part-by-part. Many large scale applications could be built faster, more efficiently and with fewer errors simply by encoding computation into the material, thus, computing the blueprints directly within the walls. As we build larger structures we need to have greater guarantees in assembly accuracy, require less skilled labor and have fewer mistakes. The inherent nature of Logic Matter is scale-less because the functionality of the mechanism depends solely on geometry and the interaction with its user; enabling encoded digital assembly for projects large or small.

Logic Matter offers a glimpse at a new computing and construction model and begs the question: *What can our bricks compute and what type of information is necessary for construction*? As a prototype, it demonstrates programmability of digital logic into physical materials and construction information, simply through geometry. From this, we can begin to embed computation and digital information into our everyday materials. Logic Matter aims to ease construction complexity through self-guided-assembly and ultimately compute useful and massively parallel information directly within our materials. Our building material should be able to store sequences of construction information and self-assemble structures similar to the natural processes of our bodies, combining 10^25 parts in fractions of a second, efficiently and consistently.

SELF-ASSEMBLY: BIASED CHAINS & BIASED PLANES

Once we have demonstrated digital-material information and computation then we can introduce material performance and adaptation, i.e. self-assembly, self-replication, self-repair. Von Neumann initiated the quest to demonstrate the amazing ability of natural systems to self-replicate and self-assemble through engineered systems of automata.[10] Penrose followed suit with the development of his physical implementation of a mechanical latching system for self-reproduction.[11] Penrose and Von Neumann demonstrated that the essential qualities for natural reproduction and cellular self-assembly were possible in material and mechanical systems.[12]

If we are going to achieve this state of self-assembling structures then we will need four simple ingredients:

1. Encoded assembly instructions (The DNA for what we want to build)

2. Programmable Parts (Digital Materials: discrete parts, information and relationships)

3. Energy for Activation (The energy to get a system from point A to point B)

4. Redundancy and Error Correction (Ensuring accurate construction)

With these simple parameters we can ensure that the processes of construction look more like the coded processes of design and fabrication or the biological counterparts that similarly rely on underlying coded information to grow, adapt and repair themselves. Automated assembly and programmable materials are the inevitable revolution in construction and the next step in the sequence of digital to analog convergence.

Biased Chains, a prototype developed at MIT in 2010, demonstrates a completely passive system that is capable of self-reconfiguration from 1-Dimensional to 3-Demensional structures. With only one component connected in various orientations, this system utilizes stochastic energy, or shaking by the user, as the source for programming the components. In this example, the orientation of the part dictates the fold angle and thus becomes the simple sequence of instructions for building any rigid 3D structure. The user simply shakes the chain, adding stochastic movement that automatically switches each of the units into the correct orientation to successfully build the rigid structure. The Biased Chains are an example of a completely scaleable system, utilizing passive energy, simple instruction sequences and programmable parts, to produce self-reconfiguration as a construction technique.

Figure 4. Biased Chains Prototype 2010.

Biased Planes, a subsequent prototype developed at MIT in 2011, furthers the research of the 1-Dimensional chain aiming to expand the initial configurations into 2-Dimensional surfaces. Biased Planes consists of a series of parts, connected in a grid or any 2-Dimensional pattern. The connected parts have programmable states within each node. The user similarly shakes the flexible surface of units, simply providing energy for the system. Each of the units utilizes the provided energy to stochastically find their programmed state and collectively assembles the desired structure. Any 2-Dimensional typology can be constructed with this system, from surfaces with single or double curvature to polyhedra. This prototype similarly demonstrates self-assembly or reconfiguration from an initial flexible state with programmed joints to a fully erected, rigid-structure, simply through the use of discrete information, programmable parts, energy input and redundancy.

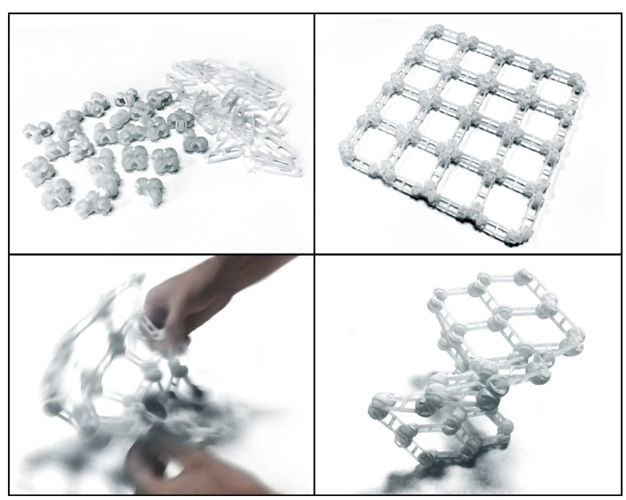

Figure 5. Biased Planes Prototype 2011.

NEW MODES OF ASSEMBLY

The prototypes demonstrated in this paper offer a small glimpse at the possibilities for self-assembly and computational materials. Logic Matter embodies a geometric module for logic operations and can be used as a computational medium for building physical objects. In this example, the material becomes a design media, making local decisions, analyzing existing conditions and working with the user to build structures that might previously been impossible. This proposes a world where building materials compute, design and aid the architect or builder in construction. How can low-level intelligence and simple computational abilities within our bricks help overcome some of the major hurdles facing the construction industry in the coming decades?

The Biased Chains and Biased Planes prototypes focus more on the act of self-assembly and reconfiguration rather than material computing. These prototypes aim at a much broader goal where materials not only have discrete interaction and potentially compute next moves, but that actually change themselves with simple energy input. This speculation can be easily imagined at micro and nano scales, however larger scales will require significant increases in force and energy input. These prototypes offer a glimpse at structures that can analyze external conditions (vertical or lateral loading, temperature change, external frequencies or pressure change etc.) and adapt through physical transformations.

The opportunities offered through material computation and self-assembling structures do not attempt to shift the role of the designer, rather, they provide a material and mechanism for adaptation and collaboration in the design process. The material now becomes a collaborative design medium offering information, contextual insight and analysis. The designer can freely operate between spectrums of the virtual world, machining processes and physical world of construction, seamlessly, with more advanced materials and throughput. The designer may now identify constraints, or possibilities for adaptation. They may give input and wait for the physical reactions, then adapt their input and progress. The design process may appear more like the herding of sheep where constraints and inputs are given but the process flows autonomously from digital to physical, rather than itemized specifications and top-down directions. However, this is precisely the processes at play within our most advanced design software and computational tools, through parametric logic and emergent design algorithms. This will now emerge within our physical design processes rather than merely virtual media.

If we utilize self-assembly as the next design and construction tool in our digital tool belts, then we may be able to solve some of the world's most urgent problems of adaptability, deployability and efficiency. From earthquake resistant structures with programmable and adaptable joints activated by the shaking of the ground, to quickly deployable disaster relief structures dropped from helicopters utilizing wind resistance and gravity to unfold erected and inhabitable. These large-scale problems can be tackled by designing around discrete parts and simple forces. Self-assembly urges the design and building industries to rethink their processes of making, look back at what we have learned from digital information, biology, and mechanical computers to take charge of the powers that are at (or literally within) our fingertips. Self-assembly and material computation is the next revolution of digital information, providing an opportunity for rethinking our practices of construction in the built environment.

ENDNOTES

1 Neil Gershenfeld, *FAB: The Coming Revolution on your Desktop-From Personal Computers to Personal Fabrication*, Basic Books (New York), 2005.

2 Neil Gershenfeld, *FAB*.

3 Neil Gershenfeld, *FAB*.

4 John Von Neumann, *Theory of Self-Reproducing Automata*, University of Illinois Press, Urbana and London, 1966.

5 Neil Gershenfeld, *FAB*.

6 Neil Gershenfeld, *FAB*.

7 Neil Gershenfeld, *FAB*.

8 George A. Popescu, *Digital Materials for Digital Fabrication*, Masters of Science Thesis, MIT 2007.

9 Skylar Tibbits, *Logic Matter: Digital Logic as Heuristics for Physical Self-Guided-Assembly*, Masters of Science Thesis, MIT 2010.

10 John Von Neumann, *Theory of Self-Reproducing Automata*.

11 John Von Neumann, *Theory of Self-Reproducing Automata*.

12 L. S. Penrose. *Self Reproducing Machines*, Scientific American vol. 200. June 1959.