

Fabricating Nature

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Abstract

Nature and the world can be viewed as complex volumetric computation. Historically humans have interacted with nature in a reductive and homogeneous manner. However, inexpensive digital computation is now extending our capabilities - allowing us to understand the complexity of nature and operate in and modify it as such. It is now possible to use computation to control matter, to design and fabricate “natural” solutions and objects - creating a new class of human-made objects that allow more localized, dynamic, sustainable and natural interactions with the world. Unfortunately, current digital design and fabrication systems have failed to fully capitalize on available computation. These systems are non-exact and fundamentally incapable of accurately representing real objects. *Digital Materialization* proposes an approach, system and symbolic basis for two way conversion between reality and information, where reality is represented as information in a dimensionally correct and exact manner and is accessible to human understanding, modification and design.

Keywords

Digital Materialization (DM), Function Representation (FRep), HyperFun, Fab at Home (FaH), volumetric computation, shape modeling, shape engineering, shape language, symbolic language, digital fabrication, solid freeform fabrication, 3D printing, replicator, nature

From implicit to explicit

Through out history, humankind has striven to master control over their material environment. Certain periods of human history are divided and named based on the mastery of different materials and processes related to those materials – the Stone Age, the Bronze Age, and so on. The current to future period of human history has been referred to as the Atomic Age and by some as the Diamond Age [Stephenson 1995, Merkle 1997] as humans are increasingly able to explicitly create and control chemical and atomic interactions. Interestingly and increasingly more common, this period has also been called the Information or Digital Age. It is worth noting the two nomenclatures have their roots in the race to develop nuclear fusion and particularly fission (the atomic and hydrogen bomb). This epoch - the human mastery of information - was made possible by the invention of automated, perfect, and discrete signaling or digital circuits and signals [Lilienfeld 1930, Shannon 1948]. Humans can now explicitly make, capture, copy, modify, maintain, store and trade massive amounts of information instantaneously. However more importantly, digital information can be structured to represent almost anything, take actions and even control physical structures. It is no longer limited to images or written words (as was the case a century ago). The transformation of information from a static, disassociated and flat two dimensional state into multi-dimensional and programmable symbolic languages containing coherent dynamic knowledge that individuals can even carry with them (e.g. embedded devices, mobile phones, laptops) is a profound moment in human history and would be thought of as nothing short of magic or at least science fiction even a century ago. The simple, exact and portable abstraction of information provides a framework for many new and powerful approaches to documenting, understanding and even controlling any desired material, process or system, regardless of complexity or the previous limitations in human thought.

Animals and humans have evolved in an enormously complex, dynamic system known as the natural world without the ability to operate digitally - lacking programmable symbolic languages and the vast computational resources that are now available. Unable to explicitly represent and navigate the complexity of the world, human and animal minds developed the sophisticated ability to represent the world implicitly, as simple, clearly delineated and identifiable boundaries of space or objects [Mach 1906, Farah 1990]. Thus, traditional manufacturing and design processes, which characteristically have been made without the aid of rapid and exact computation, assume that any given object or an independent part of a larger object is made from a single, homogeneous material. Even, raw materials that are extracted from nature are separated and purified for easy use within this homogeneous framework. The lack of explicit computation and the subsequent homogenization of nature results in “human-made” objects that clearly stand apart from nature. Inexpensive digital technology and computation is allowing us to change the way we see and interacted with the world so that it can be understood as heterogeneous and can be operated on and modified accordingly. Computation can now be used to design and even fabricate “natural” solutions and objects with the potential to create products that would be universally superior physiologically, environmentally, and functionally to those made by traditional, homogeneous and reductive processes. Over the last three decades, digitally controlled transformations of objects between the non-tactile digital and the tactile natural world have occurred at increasingly smaller scales and levels of detail. Unfortunately, current digital design and fabrication systems have failed to fully capitalize on available computation. These systems are non-exact and fundamentally incapable of accurately representing real objects.

Controlling matter

Since the 1960s computers, with the advent of Computer Numerical Control originally envisioned by John T. Parsons in 1949 [Parsons 1952], have been used to digitally control matter and directly participate in the manufacturing of physical objects. Extending traditional manufacturing, largely using subtractive processes, computers provided a reliable, high level of precision that was previously impossible. This alone has allowed the advancement and creation of many new types of objects, materials and processes. With the invention of the first working stereolithography system, by Chuck Hull in 1986 [Hull 1986], it has been possible to not only digitally control subtractive processes but also additive processes for the physical construction of objects from a computer. This new advent is profound as it largely strips away many previous manufacturing limitations. This manufacturing capability is analogous to the “replicator” from the TV franchise Star Trek where digital fabrication, taken to the extreme, assembles objects at a molecular level from small and even personal machines. Successful efforts are already underway to make molecular assembly a reality [Douglas 2009]. Currently it is possible to exactly deposit a variety of materials at the near micro-scale.

Currently most of the machines that make this possible are in the tens or hundreds of thousands of US dollars – affordable to only a few. However in addition to these machines several free and open source projects are underway that currently provide cheap desktop solutions. It is likely that in the very near future individuals will be able to own a digital desktop “factory”. These machines can be easily built for a cost of around 2,000 USD. In addition to being cheap, one of these systems, the Fab at Home [Malone & Lipson 2007], was the first machine to allow objects to be printed in multiple usable materials and even allow users to experiment with materials [Figure 1]. The Fab at Home has printed operational batteries, motors and even a flashlight with included circuitry as one integrated object.

Although these printers are capable of creating usable objects, many problems still persist such as precision, resolution, and the complex or even heterogeneous distribution of materials. The precision and resolution of the more expensive machines continues to improve and it is a matter of time before cheaper machines will also obtain resolution of 40 microns (600 DPI) or better. However, it is not clear how to design and drive the explicit construction of complex volumetric objects at such resolutions, much less deposition resolutions expected to near a few micron (the same as some modern ink jet printers).

The biggest limitation facing complex high resolution digital fabrication comes from the software or information systems. Current digital design and fabrication systems have failed to fully capitalize on computation to date since existing systems are non-exact, non-volumetric, proprietary, often complex to use and fundamentally incapable of accurately representing real objects [Vilbrant 2008]. For example, modern computer-aided design (CAD) systems cannot provide for the design of truly heterogeneous or blended objects, such as a Venetian glass vase. If we take for example the informatics of a watermelon, current three dimensional design systems are able to create simple boundaries clearly delineating parts of the watermelon, however if compared to a real watermelon it becomes obvious that the current design systems are unable truly represent such things as the gradual change in structure from the green skin to the pink flesh in a watermelon [Figure 2]. Current design systems do not operate volumetrically. In order to drive not only digital fabrication but future innovation it is necessary to develop new software and information systems that can volumetrically operate at any scale and will map well to human processes.

Mapping matter

In order to understand the lack of volumetric based design systems and find a better specification for representing real objects as information it is important to understand the different ways human think about and represent matter and the physical world. The following simple taxonomy corresponds to the major approaches for representing matter:

simple - surface, boundary or vector based

complex - unit, particle, or voxel based

heterogeneous – blend, continuous or function based

Although these three categories may look as though they are related as they progress from a low level of complexity to a infinite one, in fact each one requires a different thought process invoking significantly different approaches, properties and computational solutions [Figure 3].

As previously described in the introduction, the first category, and most obvious and basic representation for many humans (however complex in processing) is that of simple boundaries that define an object's surface or shape. This is akin to a typical simple line drawing children make. It is fundamental to human thinking and language to partition space and define objects with such boundaries. An example of a natural object that can be easily represented in such a manner is an egg. However, of course matter is never defined by perfect boundaries and even an egg does not have clear definitions between the yoke, the white of the egg and the shell.

Another way that we can represent the world around us is by using complex, detailed sets of blocks, elements or particles that define not just the surface but the volume of the object. This is similar to high detailed pen and ink drawings or Legos stacked on one another to form an object. Cells in a leaf or the rocks stacked in a geological cross section give a good idea of things that require such representations.

Finally humans also represent the world as a continuous heterogeneous blend of space and materials. This can be seen in oil paintings, realistically shaded drawings and photographs. This is the most accurate approach to representing space and reality from a human perspective (outside possibly, the subatomic). A simple example of naturally occurring objects that clearly display the heterogeneous nature of matter might be a space nebula or muddy water.

These three general approaches to describing matter and defining objects is useful to understanding the various ways it is possible to computationally model three dimensional (or higher order) shapes that correctly represent real objects and matter. Interestingly, this same taxonomy is also clearly visible in field of computer shape modeling. The different ways of digitally representing shapes can be divided in the same three main categories or approaches that roughly map to the different ways humans have historically described and thought about shapes. In the same order, from *simple* to *heterogeneous*, they can be formally referred to as boundary representation (B-Rep) [Baumgart 1972], discrete volume representations or voxels and function representation (FRep) [Pasko 1995].

Currently most if not all modeling systems are based on B-Rep. However, in addition to the fact that boundary based representations are not dimensionally accurate representations, the dimensional space they operate in leads to problems in the shape boundary itself. B-Rep modeling often produces cracks in the surface and can fold back on oneself or produce hanging surfaces that are outside the manifold. While such errors, if small, are fine for virtual reality and animation systems, they cause digital fabrication systems to fail or create incomplete objects and poorly represent real objects. Voxel based

representations while volumetric (unlike boundaries), have a fundamental issue with the computational size of an object versus its resolution. As resolutions increase, it becomes more and more difficult for human interaction and design to take place. In addition, old models and objects will become outdated as computational systems continue to exponentially grow. Both boundary and voxel based systems are largely “dumb” data structures without any or little knowledge and relationship to shapes they define.

FRep, originating in Russia around 1986 (by A. Pasko in MEPhI under supervision of Dr. Pilyugin) and has roots in Soviet mathematics back to 1968, is a mathematically based approach for modeling objects (typically with a computer) using real functions. FRep defines an object where a continuous function is zero on the surface, has positive values inside and negative values outside the object. The system is extensible and any function, algorithm or “black box” processing can be used as long as it returns a real value.

Unlike other representations, this system constructively builds an intelligent set of relationships in a shape tree where basic primitives sit at the leaves and the nodes are made up of various types of operations. In addition, the system is based on using a “shape language” called HyperFun (hyperfun.org). Any new mathematical operation or primitive can simply be defined or coded as a user models. Even other HyperFun objects can act as primitives. These models are extremely compact, most do not go over 10k. In addition to the shape, a user can also define any property at any location in the model using the same real functions [Pasko 2001]. In this way, FRep is able to define accurate *heterogeneous* representations of materials and objects and at any complexity and resolution.

Digital Materialization

Digitally based languages and processes, unlike the analogue counterparts, can computationally and spatially describe and control matter in a exact, constructive and accessible manner [Vilbrandt 2004]. However, this requires new approaches that can handle the complexity of natural objects and materials.

Digital Materialization (DM), on the bases of FRep, proposes a deeper understanding and sophisticated manipulation of matter. By using rigorous mathematics as the basis for the description of real objects it becomes possible to compactly describe and understand the surface and internal structures or properties of an object at an infinite resolution. FRep can provide whichever level of detail is necessary at any moment to suit any computational or machine requirements, making is ideally suited for digital fabrication and other kinds of real world interactions. Utilizing FRep, DM systems, can accurately represent matter across all scales making it possible to capture the complexity and quality of natural and real objects. DM surpasses the previous limitations of static disassociated languages and simple human-made objects, to propose systems that are *heterogeneous*, interacting directly and more naturally with the complex world [Figure 4].

DM can loosely be defined as two-way communication or conversion between matter and information that enable people to exactly describe, monitor, manipulate and create any arbitrary real object. DM is a general paradigm and a specific framework that proposes: a holistic, coherent, volumetric modeling system; a symbolic language that is able to handle infinite degrees of freedom and detail in a compact format; and the direct digital fabrication of any object at any spatial resolution without the need for “lossy” or intermediate formats.

DM systems possess the following attributes:

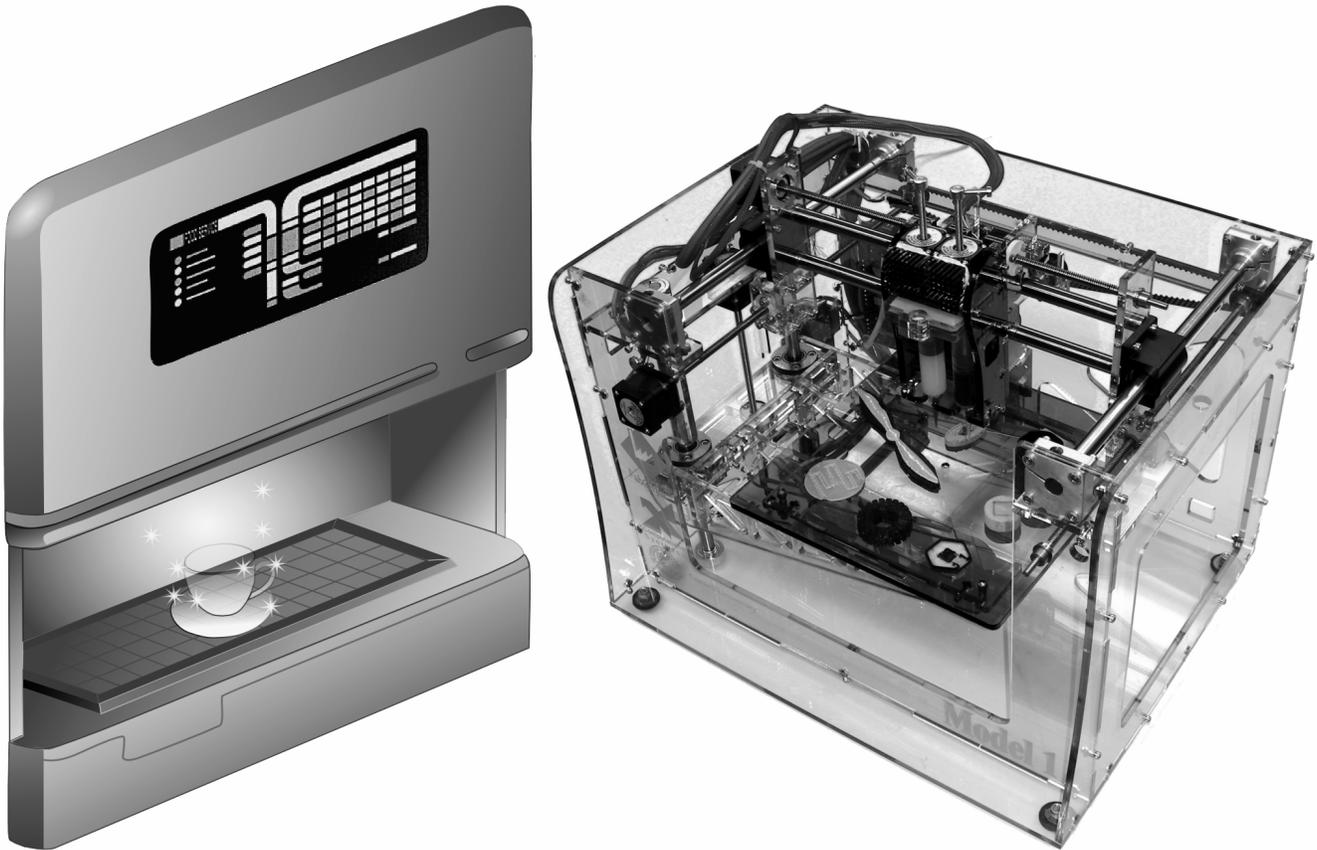
realistic - correct spatial mapping of matter to information
exact - exact language and/or methods for input from and output to matter
infinite - ability to operate at any scale and define infinite detail
symbolic - accessible to individuals for design, creation and modification

DM can not only be applied to tangible objects (as discussed in much of this paper) but can include the conversion of things such as light and sound to/from information and matter. Systems to digitally materialize light and sound already largely exist now - it is why these digital mediums have been so effective (e.g. photo editing, audio mixing, etc.) - but as previously described, the representation, control and creation of tangible matter is poorly support by computational and digital systems. Whether at a near micron or molecular level the ability for individuals to simply design and fabricate complex and “natural” objects from a computer will be a catalytic moment in human history. This will allow for localized peer based production and will usher in a new class of human made objects. No longer will human objects stand apart from nature and natural constructions or processes. Humans will be able to fully engage and interact at every level with the world around them.

References

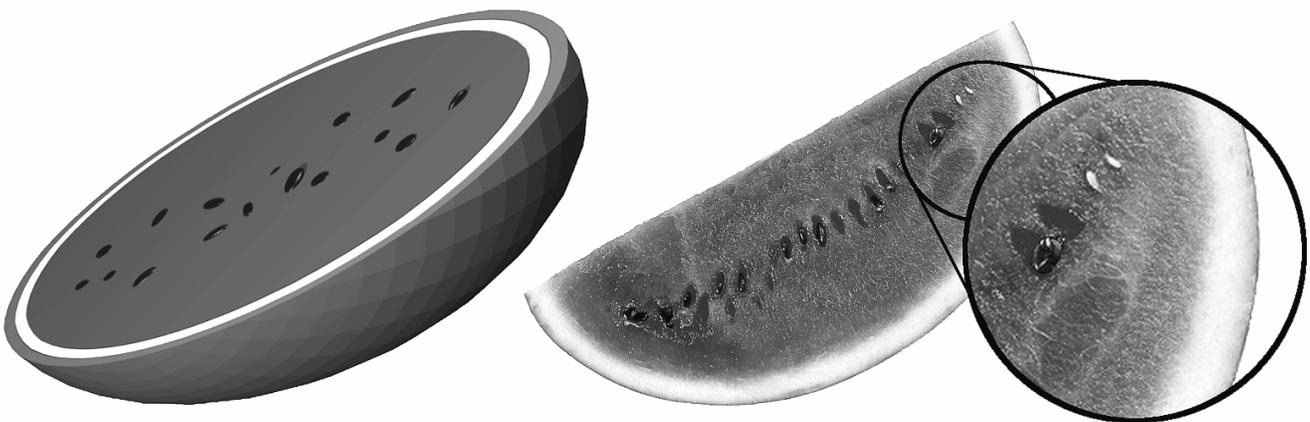
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Figure 1 : replicators



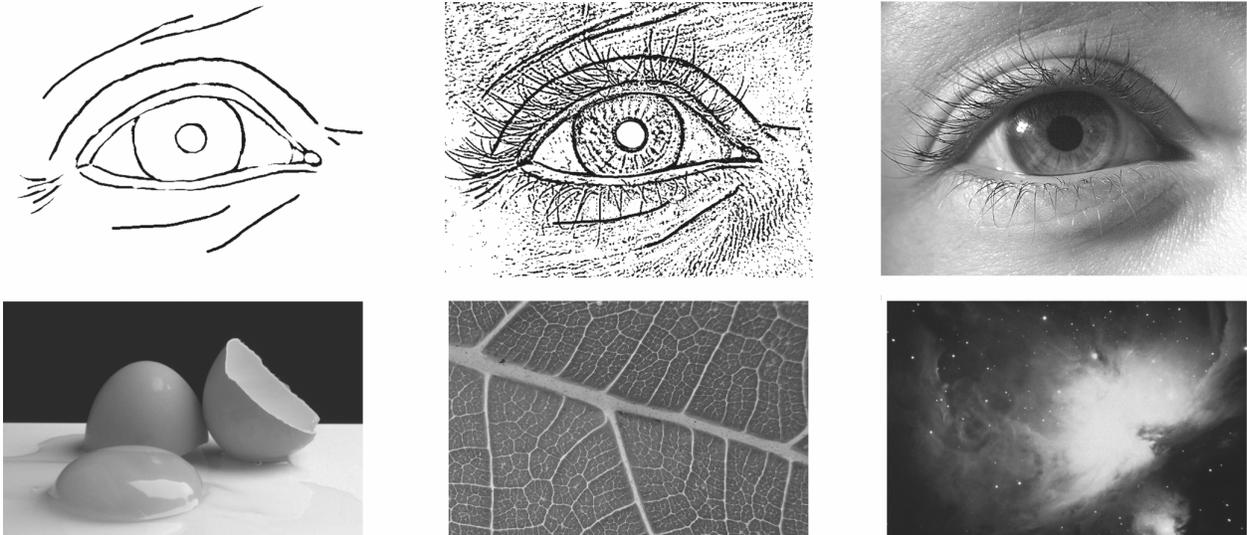
Television's imaginary Star Trek Replicator and the Fab at Home

Figure 2 : watermelon



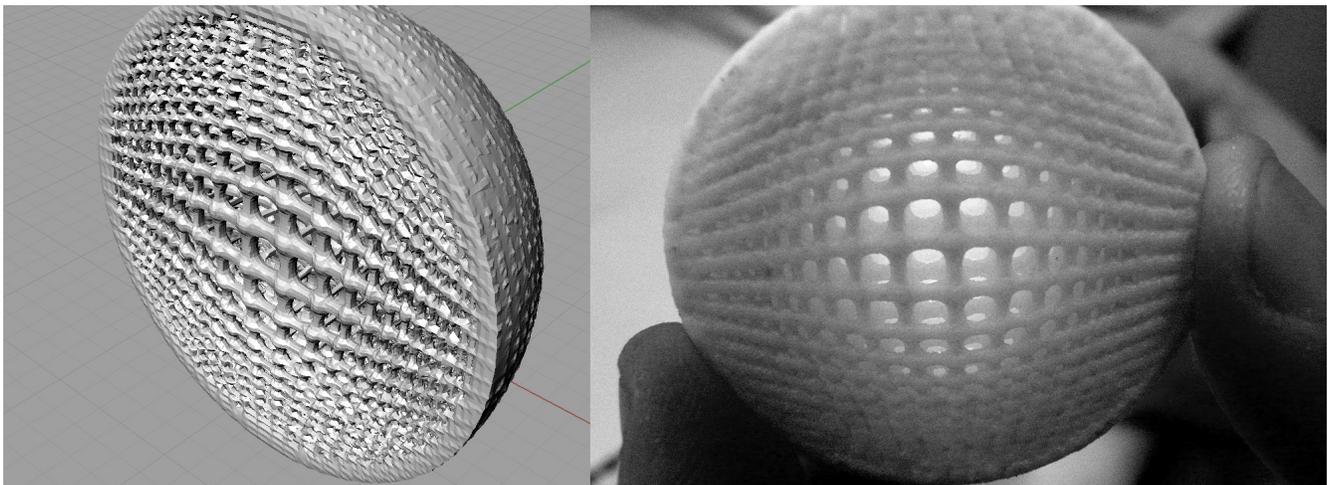
Watermelon informatics – left: traditional simple CAD model; right: real object with heterogeneous internal material distribution

Figure 3 : taxonomy



The top set of images graphically illustrate the differences between the various representations - left: *simple*; middle: *complex*; right: *heterogeneous*. The bottom images are examples of natural objects that visually represent these categories.

Figure 4: micro-structure



Digitally fabricated non-uniform micro-structure created from a 1KB Frep model.