SOFTWARE TECTONICS

By Alexandros Tsamis

M.A . Massachusetts Institute of Technology. (MIT)
Dip.A. Aristotle University of Thessaloniki, Greece (A.U.Th)

Submitted to the Department of Architecture
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Signature of Author: ....

Department of Architecture
August 10, 2012

Certified by: ....

George Stiny
Professor of Architecture, MIT
Thesis Advisor

Accepted by: ....

Takehiko Nagakura
Associate Professor of Architecture, MIT
Chair, Department Committee on Graduate Students

Thesis Reader: Terry Knight
Title: Professor of Architecture, Department of Architecture, MIT

Thesis Reader: Mark Goulthorpe
Title: Associate Professor of Architecture, Department of Architecture, MIT

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Abstract

The resent shift of attention in the architectural discourse towards issues of ecological design, coupled with the undeniable role of computation, has already cast a new operative role to the notion of environment. Instead of being the passive, conceptualized or historicized context of an architectural object, environment is quite literally becoming the object of design itself. We are moving away from the imposed-preconceived Cartesian object which negotiates through its boundaries its presence within its immediate context. The discipline is already considering an architecture in which architectural form is only an instance of a designed environment. In many respects, this new understanding of environment aspires to be **actively designed** as a closed system of constant transformation, an autonomous milieu of exchange at all scales and all levels between substances, properties or qualities.

The object of investigation in Software Tectonics is how technologies of design and construction allow newly forming propositions about the role of environment in the discipline to become operational tactics in the design practice. SOFTWARE TECTONICS proposes 3 design research projects.

VSpace is a computer drawing application for designers. Unlike traditional CAD systems that work primarily by representing boundaries (B-reps), VSpace derives form by the representation and direct manipulation of properties (P-reps) in space. Boundaries and Properties here are considered simultaneously in the same design environment.

Cast_it is a multi axis, Computer Numerically Controlled device that prints 3D objects by dynamically mixing at least two distinct but chemically compatible materials. Dynamic mixing allows for gradient transitions between two or more materials, resulting in objects with anisotropic material properties.

CHUNK aims to eliminate a joint as a third mediating member between two building elements with an area of gradient transition. Conceived as a "dynamic insulation" architectural skin, this building technology project challenges the multi-trade and multi-component tectonics of dominant late-industrial building manufacture.

Thesis Advisor: George Stiny
Title: Professor of Architecture, Department of Architecture MIT

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Introduction

> .... a savage tribe (of the kind that only exists in parables) arrives at an evening campsite and finds it well-supplied with fallen timber. Two basic methods of exploiting the environmental potential of that timber exist- Either it may be used to construct a wind-break or rain shed – the structural solution – or it may be used to build a fire – the power-operated solution.[1]

In *"The Architecture of the Well-tempered Environment"*, Reyner Banham asks us to consider a tribe's dilemma:

He argues that given a pile of wood, a tribe has one of two options- It can either build an enclosure to shield itself from the environment, or start a fire to tamper with the environment's meteorology. Although even for Banham this dilemma is rather unusual -After all why not just do both - it is being exploited to make one distinction very clear.

When societies began forming, Banham argues, their spatial experience, their desire to make space - which of course included their need to survive - could be expressed in one of two modes:

Societies would either understand the articulation of space through the production and manipulation of enclosing envelopes or through the production and manipulation of energies. Those who use the former approach tend to "visualize space as they have lived it, that is bounded and contained, limited by walls, floors and ceilings"[2] while the ones who use the latter tend to "inhabit a space whose external boundaries are vague, adjustable according to functional need and rarely regular"[3].

> **This distinction, which will acquire many forms throughout this thesis, boils down to the following statement: In architectural discourse, space is perceived as and operated upon either in terms of Architectural Envelopes - BOUNDARIES - or in terms of environmental effects – PROPERTIES.**

Although one could go on and on about trying to accurately define the terms **Boundary** and **Property**, I will use them in this thesis with common sense. Boundaries will refer to edges,

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[1] Reyner Banham, *The Architecture of the Well-tempered Environment*, The University of Chicago Press, Chicago,(1969), p.19

[2] Ibid pp. 19-20

[3] Ibid p.20

things that define limits between two distinct entities, limits between this and that, here and there, inside and outside and so on. Boundaries describe where one thing stops and another begins and in mathematics they are usually described with descriptive geometry. From a common sense point of view, boundaries describe the shape of things.

On the other hand, properties will refer to qualities. Color, temperature, transparency, density and so on. Properties are also perceptible things and in mathematics are usually described with numerical values. It is of no interest to me, and I think it would deviate from the purposes of this thesis, to enter philosophical debates about a clear distinction, in terms of definition, between Boundaries and Properties. At least for me, common sense will be sufficient here.

Software Tectonics is a design thesis that is concerned with matters of ecology. It oscillates between theory and technical advancements. It will often be the case that the reader will encounter a theoretical comment about the discipline of architecture somewhere between mathematical equations. My attempt here is to establish connections between contemporary theoretical investigations in architectural design and technological advancements in computer science, material science and engineering. In other words, within the framework of ecological design, my attempt is to make more precise the relationship between what we say and what we practice.

Software Tectonics is a design thesis not because it makes specific architectural propositions for specific contexts and specific requirements. Instead, it is a design thesis because it capitalizes on theory to talk about the way we see things in architecture and applies them as a filter to highly technical projects. Software Tectonics recognizes architecture as a distinct discipline with its own preoccupations. Although the focus is on technology and the proposed projects are highly technical and heavily influenced by recent advancements in engineering, the overall scope is focused on how those technologies can be "tweaked" in order to **critically** enter our domain. "Tweak" is a key word here. Any contributions that the reader will identify are in most cases "tweaks". "Tweaks" of existing theoretical constructs. "Tweaks" of highly precise existing technologies. Contributions are always situated between the two.

Software Tectonics is divided into two sections. They are presented as "chunks", each setting its own framework and proposing its own technologies.

The first section - **Software** - addresses issues of ecological design from the perspective of digital computation. Based on the computation work of Lionel March from the 70's, it proposes **VSpace,** a digital design application that reverses the relationship between boundaries and properties in design software. Influenced by the "compound" understanding of SHAPE in Shape Grammars and starting with Alan Turing's original speculations on the mathematical laws of morphogenesis, the *VSpace* software uses Voxels as *property place holders*, Painting and Cellular Automata as two distinct design strategies for calculating with properties and the Marching Cubes Algorithm as a background engine that allows us to establish relationships between Properties and Boundaries.

The second section - **Tectonics** - is concerned with issues of transition from design to construction as they emerge within the framework of ecological design. Tectonics is heavily influenced by the design work of Reiser + Umemoto and proposes alternatives to their "Atlas of Novel Tectonics" by shifting the attention from boundaries to properties. Advocating for the construction of "non-assembly", and based on the work of MIT's Local Composition Control Group (LCC) from the 90's, tectonics proposes **Cast_it**, a Computer Numerically Controlled 3D printing machine that attempts to address issues of construction at an architectural scale. Furthermore tectonics proposes **CHUNK**, a research project in building technology, that demonstrates the impacts of such technologies to architecture in terms of their expressive potential.

1. SOFTWARE

In Banham's "The Triumph of Software" [4], a distinction also exists. Comparing two films, Stanley Kubrick's *2001: A Space Odyssey (1968)* and Robert Vadim's *Barbarella* (1968), Banham recasts the terms "Hardware" and "Software" to characterize their respective architectural settings. He writes of *Barbarella*'s "ambience of curved, pliable, continuous, breathing, adaptable surfaces" and juxtaposes it with "all that grey plastic and crackle-finish metal, and knobs and switches, all that ... yeah ... hardware!' in *2001: A Space Odyssey.*

In 1968, the word hardware was most probably commonly understood as equipment-things that could be touched by hand, machine parts, knobs, switches, etc.

On the other hand, the term software was just beginning to emerge in the fields of information theory and computer science. It was still up for grabs. For Banham, *Barbarella's* "software" environment is a responsive environment. "Responsive environment in the sense of not being rigid and unyielding; articulated only by hinges between disparate rigid parts".

Overall, Banham, who evidently favors the softer side of things, finds equivalents in architectural speculation to *Barbarella's* "software" environment and distinguishes among other things, inflatable structures. He finds them equally pliable and continuous but above all participating in the ever evolving transformations of their environment.

However, as Sylvia Lavin rightfully points out in her 2002 essay "Plasticity at Work"[5], Banham's distinction between "Hardware" and "Software" merely brings to the surface the softer side of "hardware". In other words, "Software", for Lavin, is relating to another kind of Hardware, albeit a different kind of formal expression that is plastic, pliable, and continuous. Given our previous distinction between **Boundary** and **Property**, Lavin's reading, puts Banham's "Software" in the realm of soft Boundary.

Nevertheless, there is another kind of "Software" in Barbarella; even softer that the "curved, pliable, continuous, breathing, adaptable surfaces" with which Banham very much obsesses. Although Jane Fonda makes it hard for most of us to focus anywhere else, all we have to do to find it is look outside the window of her spaceship (Figures 1, 2). When Vadim is called to "render" the outside he doesn't build a set. For him, the spaceship's environment can effectively

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[4] Banham, Reyner, *'The Triumph of Software'*, New Society, Harrison Raison, London (October 31, Volume 12, No. 318, 1968), pp 629-630.

[5] Lavin, Sylvia, '*Plasticity at Work*', Mood River, Ohio: Wexner Centre for the Arts, (2002), pp.74-81.

be portrayed as a collection of bubbles floating in a translucent viscous liquid; as a colorful lit mixture of water and oil; as the igniting of hand-held fireworks (the kind that you probably get as an ornament on your fancy summer cocktail) or like milk, as it drops on a well oiled up glass surface. He relies on effects of fleeting physical phenomena; the kind of environmental effects that **Boundaries** cannot capture, regardless of how pliable they are. Quite literally, Vadim films environments of evolving chemical phenomena, juxtaposes them against the space ship window and allows them to assume the role of the outside. Here, the architectural setting of outside is understood and visualized as pure **Property.**

In this thesis, a "Software" understanding of space implies precisely this: Space can be perceived as, and operated upon, as an environment of pure Property.

In *"The Architecture of the Well-tempered Environment"* Banham pushes for the "abandonment of the ethics of the structural solution in favor of the performative space of fire"[6], he claims that architecture as we know it (the history, perception and production of enclosing envelopes) is only a special case of what he called the production of "fit environments". Today, in an age of great ecological concern, the architectural community - theoreticians and practitioners alike - have put the notion of environment and its relation to architectural thought and practice under great scrutiny.

Just some numerous recent propositions are enough to map the conceptual territory of today's role of environment in ecological design. From a historical point of view, Lydia Kallipoliti[7] who looks at a large set of experimental ,"opportunistic", ecological projects from the 60's and 70's suggests that they are not "performative agents of amelioration; rather they are, in themselves, their own ecologies, producing new worlds."[8] She points to the cover of *Cassabella* magazine of 1976, to discuss among other things the trend of experimental architects of the period to refocus the attention of the discipline from objects to isolated environments (Figure 3).

According to Mark Jarzombek, at least when looking at the sustainability discourse from its technical or pragmatic perspective, "Sustainability emphasizes an environment that it defines

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[6] Hight, Cristopher, *'Putting out the Fire with Gasoline: Parables of Entropy and Homeostasis from the Second Machnine Age to the Information Age', in Softspace,* From a Representation of Form to a Simulation of Space (ed.) Sean Lally & Jessica Young, Routledge, London (2007) pp.18-19.

[7] Lydia Kallipoliti's Ecoredux archive of ecological experiments in architecture has effectively shown how today's ideas and attitudes towards ecological design stem from the junction of information theory and ecology as separate disciplines in the 60ies and seventies. www.ecoredux.com

[8] Kallipoliti, Lydia, 'EcoRedux: Environmental Architectures from Object to System to Cloud' in Praxis: Journal of Writing and Building, No.13 (Eco-Logics), 2012.

Figure 1: Barbarella's Environment (screen shots)

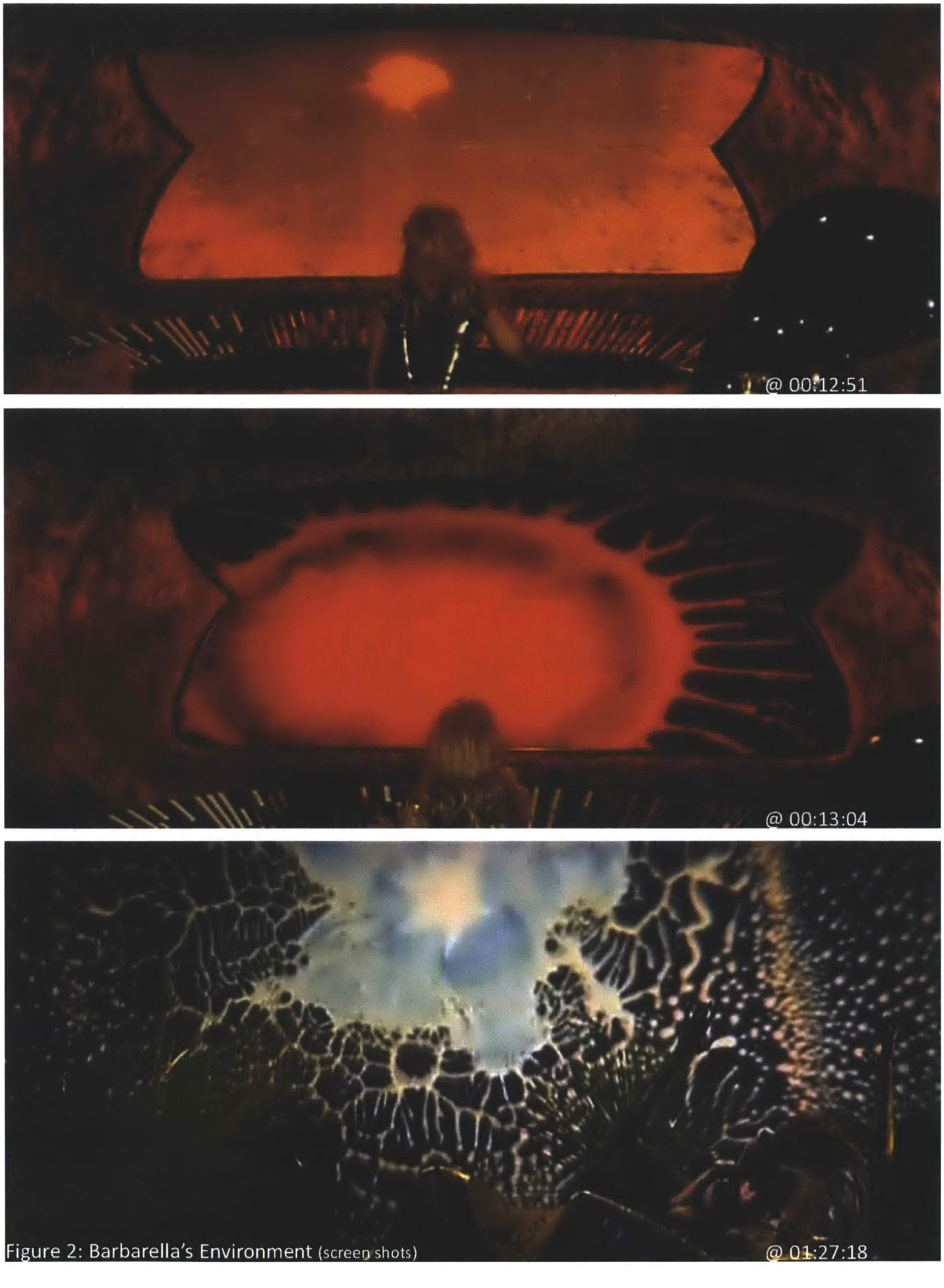

Figure 2: Barbarella's Environment (screen shots)

– A piece of nature.

Figure 3: Cover of *Casabella*, Milan, No. 411, March 1976 Image by Haus-Rucker-Co "Ein Stuck Natur"

as a world-of-chemicals-in-dynamic-interaction"[9]. Most speculatively, Sanford Kwinter who has been arguing for some time now that "Matter is the new Space"[10] recently proposed that "Morphogenesis (in architecture) is dead!"[11] and also that "Space is the result of matter energy and information coming together"[12]. Jeffrey Kipnis accurately describes ecology as a kind of topology, and offers insight on how architectural topology can exceed geometric topology if it is thought of as "intrinsic unities that unite vast numbers of conjugate variables enabling to mutate from one to another"[13]. In 2010, Sean Lally suggests that in architectural practice what seems to become the object of design is the "active context". He juxtaposes Greg Lynn's "active context" as an influence or a force that shapes a building's envelope to the "active context" as the design focus and medium itself.[14]

It seems to me (and all this is pure conjecture or bias on my part) that the 'ecological project'[15] in architecture, coupled with the undeniable role of computation in design, has already - at least in theory - cast a new role in the notion of environment.

Instead of being the passive, conceptualized or historicized context of an architectural object, environment is quite literally becoming the object of design itself. We are moving away from the imposed-preconceived Cartesian object (pliable or not) which negotiates through its

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[9] Jarzombek, Mark. *'Molecules, Money, and Design'* in Thresholds 18. Design and Money, editors : Andrew Miller, Garyfallia Katsavounidou, James P O;Brien. MIT Journal, Fall 1999, p.32.

[10] Quoted in Jason Payne, *'Heather Roberge, Matter and Sense'* in Softspace, From a Representation of Form to a Simulation of Space, editors Sean Lally & Jessica Young, Routelage, London (2007), p.127.

[11] With the statement "Morphogenesis is dead" I assume Kwinter means that form can no longer be the sole object of inquiry in design.

[12] Kwinter's last two statements come directly from my notes of his lecture at the NEAR Conference: *At the Intersection of Architecture, Nature, Technology* held at Pratt University on March 24-25,2011.

[13] Kipnis, Jeffrey, *A Family Affair*, in Mark Rappolt (ed) Greg Lynn Form, Rizzoli, New York (2008), p.201.

[14] Lally, Sean, *'Eat Me Drink Me,* in Architectural Design (AD): Territory Architecture Beyond Environment, (ed.) David Gissen, John Wiley & Sons Limited, London (May/June 2010) pp.16-19.

[15] The 'ecological project' refers to the architecture community's recent attempt to define a sustainable aesthetic. It seems that we are oscillating between three categories of sustainable approaches: first, the 'techno-rationalist', who understand buildings as hyper-efficient machines populated with solar panels and live greenery in the hope that more optimized components and systems will solve the problems that previous components and systems have caused; second, the 'bio-organicist', who design buildings as if they are exotic plants in the hope that they will live harmoniously with the rest of the plants on the planet; and third, the 'neo-vernacularist', who promote going back to living in the mountains in the hope of growing their own tomatoes and living happily ever after.

boundaries its presence within its immediate context[16].

Instead the discipline is already considering an architecture in which the "hardware" of form is only an instance of the "software" of environment.

Furthermore, beyond the technical pragmatics of clean, renewable, passive energy and all the performance anxieties[17] they have induced, ecological design as a coherent cultural practice now entails the consideration of an artificial, composed, synthetic environment. An environment whose potentially designed properties (matter, energy, and information) locally participate in a perpetual exchange. In -many respects, this new understanding of environment aspires to be actively designed as a closed system of constant transformation, an autonomous milieu of exchange at all scales and all levels between substances, properties or qualities. Quite literally, **Environment has become architecture's new interior**.

My interest as a designer starts precisely here. How do newly forming propositions about the role of environment in the discipline become operational tactics in the design practice? The object of investigation of **SOFTWARE** in **Software Tectonics** is how the tendency to prioritize **property** over **boundary** in the perception of space can constitute for a practitioner a **MANIPULABE** endeavor. Before going deeper into exploring some of the technical possibilities that these propositions put forward and ultimately answering some of those questions, let me be clear on what I term **manipulable** in design practice. Here is a familiar example.

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[16] Tsamis, Alexandros, *'Go Brown. Inner-disciplinary Conjectures'* in Architectural Design (AD) : Ecoredux. Design Remedies for an Ailing Planet, (Ed) Kallipoliti Lydia, John Wiley and Sons, London (June 2010), p. 80.

[17] Term borrowed from Kipnis, Jeffrey, *'Performance anxiety?'* in 2G no.16 (4) 2000, p.4-9.

1.1 Manipulability. The Curious Case of Representation

A mode of representation, it can be argued, preconditions our perception, in that the way in which we represent "things" leaves out those aspects of perception that are left unrepresented. And yet, paradoxically, they are precisely those boundaries of our representations that allow us to perceive and therefore manipulate new things.

Coming from music, Jeanne Bamberger makes a distinction between "units of perception" and "units of description," in which she writes:

> Individuals in particular disciplines tend to take the objects and relations named by descriptive, symbolic conventions associated with the discipline as just those that exist in the particular domain. Through practice, symbol-based entities become the objects, features, and relations that tacitly shape the theory and structure of the domain- how users think, what they know, teach to others, and thus what they take to be knowledge. As a result, units of *description* may come perilously close to (pretending to be) units of *perception* – we hear and see (only) what we can say.[18]

For example, Descartes' method of coordinates, which was conceived as a generalization of the proportional diagrams of the artist and architect, translated the form of a curve and the position of a point into numbers.[19] Moreover, it was D'Arcy Thompson who employed Descartes' method in order to translate for example the form of a fish into a precise mathematical entity. By inscribing it onto a grid of rectangular coordinates, the fish's (now its outline) can be reconstructed. These coordinates could then be altered- mathematically deformed- to obtain new, transformed figures from an original set of coordinates.[20] Thompson claims that what he has made precise, and thereby manipulable, is Aristotle's verbal description of the characteristics of excess or defect between species, relative to the platonic ideal.[21] His attempt to mathematically describe the difference between species, gave him the tool to manipulate "imprecise" geometrical objects through a comparison of their related forms.

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[18] Bamberger, Jeanne & Dissea, Andrea *'Music as Embodied Mathematics: A Study of a Mutually Informing Affinity'*, International Journal of Computers for Mathematical Learning 8, Kluwer Academic Publishers, Netherlands (2003), p.132.

[19] Thompson, D'Arcy, *'On Growth and Form'*, Cambridge University Press, Cambridge (1992), p.271.

[20] Ibid. 271-2

[21] Ibid. 273

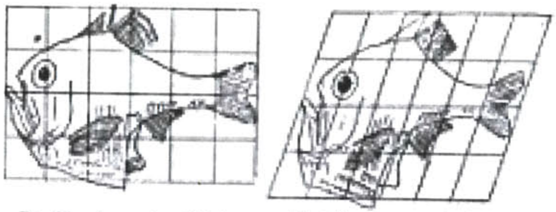

Figure 4 : Thompson's illustration of the transformation of *Argyropelecus olfersi* into *Sternoptyx diaphana* by applying a 20° shear mapping.

Thompson's "theory of transformation" makes precise mathematical definitions of forms that were previously only described verbally or studied in isolation. He suggested a precise method in which forms are studied relative to one another. In *Growth and Form* he makes an observation about the modes of operation within the scientific world.

> The study of form may be descriptive merely, or it may become analytical. We begin by describing the shape of an object in the simple words of common speech; we end by defining it in the precise language of mathematics; and the one method tends to follow the other in strict scientific order and historical continuity. Thus for instance the form of the earth or of the raindrop or the rainbow or the hanging chain or the path of the stone thrown up into the air, may all be described, however inadequately, in common words; but we have learned to comprehend and to define the sphere, the catenary, or the parabola we have made a wonderful and perhaps a manifold advance.[22]

It must be that Thompson operates under the assumption that verbal descriptions precede scientific ones.

By this, I assume he means that approximate description, which is closer to perception, precedes (scientific) representation. But is this truly the case? Is it not also the case that the mathematically defined object, the represented object, is also there to be perceived? - i.e. isn't the "thing" in front of you?

As we can deduce from Thompson's observations on form, "things" can be mathematically defined: the earth is now the sphere, the raindrop is the catenary, and the hanging chain the parabola. The assumption that the earth is a sphere is a case in point regarding how perception

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[22] Ibid. 17.

and therefore ability to manipulate is preconditioned by existing modes of representation, in this case geometry. Kepler's famous *"ubi material, ibi geometria"*[23] reflects this same frame of mind. The scientist, now having a choice, works with representations of "things" instead of the "things" themselves. But as George Stiny would say, for a designer this is not a problem. In design, unlike in science, representations of "things" are only temporary and when they exist they become "things" themselves, autonomous "things". Literally, representations are the "material" of design.

Thompson's theory of transformation, more generally known as the mathematics of topology, caught the attention of the 90's architectural discourse, lending it as a conceptual and at the same time an operational tool with which to handle approximation. In other words topology, as it was embedded in animation and later associative geometry (parametric) software, it allowed designers to put their hands on issues of plasticity as they were described earlier in this chapter. Topology is already embedded in the architect's CAD software. A NURBS surface- within 3D modeling software- is by default topologically defined; a possible relocation of any control point throughout the surface affects the position of its neighboring points, which are redefined respectively. It is a surface defined by equations and relationships, rather than a singular form projected on the screen. The designer was able, through transformational geometry, to visualize and manipulate formal approximations, which do not belong to the realm of the square and the compass. Topological transformations are the more general continuous transformations that maintain the geometrical properties of the original set of coordinates of a figure.

> The pliant and curvilinear architectures are understood and practiced as being the result of processes of manipulation and deformation of form itself, by means of continuous non-linear transformations.[24]

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[23] Where there is material, there is geometry.

[24] Di Christina, Giuseppa, *'The Topological Tendency in Architecture'* in *Architectural Design: Architecture and Science*, (ed) Giuseppa Di Christina, Willey Academy, Great Britain, (2001), p.7.

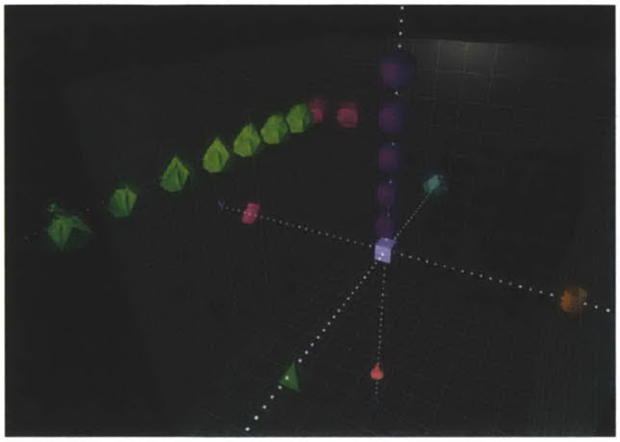

Figure 5: Mark Burry, “Our World.”

Mark Burry’s design experiment “Our World,” serves as a case in point of the way topology, in its most open-ended and customized form of application (parametrics), has been explored for its variable, expressive possibilities. The context for this experiment is a cubic virtual environment, at the core of which Burry has placed the orthogonally intersecting three axes that normatively define three-dimensional space (x,y,z). At the end of each pole of the axes, there is a geometric primitive, more specifically a sphere, a cone, a cylinder, a pyramid etc, whereas at the intersection of the system there is a cube. At the project’s inception, the focus was on the parametric description of each volume, so that one volume could transform into another, which was not possible through traditional geometric definitions. The traditional definition of a cube-defined by 12 edges, 6 sides, or 4 points - would thereby be insufficient for its transformation into a cone. New principles of formal definitions would have to be inscribed in each primitive in order to enable it to morph into another.[25] In the same vein, Markos Novak appropriately remarks- “a cube is not less topological than a blob.” What matters in topology is the information encoded in an object, its germinal capacity to shift states of being; its current form is merely an incidence in time. Burry’s initial scope for his project was to embed the necessary information in the geometric primitives that each state of transformation would require. As he says,

> The task is simple: to work towards a mutual understanding of the topologies of various Phileban forms (cubes, spheres, pyramids etc.) so that we can computationally adjust the spatial characteristics of their respected geographies

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[25] Ibid, 12

in order to represent transitional states –the morphing of one into the other. [26]

His interest, though, in the project did not reside in the orchestrated *morphs* along the linear axes- along the planned transformation from one geometric primitive to the other. Instead, it laid in unpredictable permutations. An example would be the morphing of a cube towards a sphere, which, before acquiring the sphere's characteristics, would begin morphing into a prism and then into a cone, and so on and so forth. This last computational operation is what intrigued digital architects of the period. A designers' engagement with a transformative process extended their creative, imaginative potential by providing them with an excess of visual material that they can then interrogate for its spatial characteristics. It was processes such as these that made Greg Lynn's "pliant" realities manipulable. Similar processes of formal manipulation and the mathematics that undergird CAD software today, allowed Bernard Cache to suggest that architecture is a fusion of landscape all the way to furniture.[27] Such propositions escaped the realm of preposterous and instead became for designers manipulable realities through the use of geometric topology.

Nevertheless, if we apply our distinction between boundary and property we will see that all operations of geometric topological transformations are associated with boundaries; "soft" and pliable boundaries. If we do consider cache's fusion of landscape all the way to furniture as a model of thought for architecture's production[28], there is nothing in geometric topology that would allow us to manipulate the material ramifications of such fusion. As a model for design, topological boundary transformations have nothing to offer when considering the fusion of wet mud with plush pillows.[29] I couldn't agree more with Michael Meredith who advocates the transition from "control to design"[30]. Control (manipulability) is not the end of the game. It doesn't mean much by itself. It doesn't give value to any project. Nevertheless, it serves as a pre-condition for the act of design. Especially when we are dealing with digital computers and their strict mathematical (parametric or algorithmic) definitions.

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[26] Burry, Mark, *'Beyond Animation'*, Architectural Design (AD), Vol. 71, No.2, John Wiley & Sons Limited, London (April 2001), p.9.

[27] See Cache, Bernard, *'Earth Moves: the Furnishing of Territories'*, MIT Press, Cambridge Mass (2006).

[28] a model that would allow us theoretically to conceive of architectural space as a complete environment of exchange.

[29] a similar thought was expressed in my Master's Thesis. see Tsamis, Alexandros, *'Digital Graft. Towards a Non-Homogeneous Materiality'*, MSc Thesis, MIT 2004, pp 20-21.

[30] Meredith, Michael (Author, Editor), Aranda-lasch (Editor), Mutsuro Sasaki (Editor), *'From Control to Design: Parametric/Algorithmic Architecture'*, Actar (2008).

1. 2 Boundary – Property. Hierarchies between boundaries and properties in design practice

In CAD

A Boundary representation (B-Rep) in CAD is a method of representation for shapes that uses limits as their defining element. For example in B-rep software a curve is defined in two distinct steps. First a mathematical equation describes an infinite version of the curve and then it is bound (cut) by two points that determine its start and the end points. What is displayed on the computer screen is the limited segment of the infinite curve.

Similarly, a plane or any surface is first defined as infinite -through equations - and then is chopped using lines as its boundaries. Generally, In B-rep software, points are boundaries of curves, curves are boundaries of surfaces and surfaces are boundaries of solids. Furthermore, in CAD, the following hierarchical structure exists between those basic geometric elements. Points come first, then lines come from points, surfaces from lines and solids from surfaces. This structure is fixed and therefore non-negotiable.

Boundary representations where first introduced in the early 70's independently by Ian C. Braid[31] and Bruce G. Baumgart[32] and almost instantly saturated commercial CAD software. Most surface and solid modelers today use B-Reps as the main mode of representation of objects. Most design operations in CAD happen with B-Reps. Even NURBS curves and surfaces are a special case of Boundary representations. In CAD, boundary representations can be instantiated and transformed and ultimately combined to make new boundary representations. All design activity happens at the level of boundary representation. The manipulable entities in CAD software are Boundary Representations (B-Reps).

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[31] Braid Ian C., *Boundary Modeling,* in *Fundamental Developments of Computer-Aided Geometric Modeling,* edited by Les Piegl, Academic Press, London (1993), pp. 165-183.

[32] Baumgart, Bruce G., *Geometric Modeling for Computer Vision,* PhD Thesis, Stanford University, (1974).

Properties also exist in CAD software. In its most simple form, a color can be assigned to B-Reps. In the case of computer visualization (rendering), a material i.e. a texture, a level of transparency and so on can be assigned to B-Reps. In more sophisticated, solid modeling environments, solid B_Reps can have among other things, a material density or a structural stiffness. In advanced simulation software, like Autodesk's Ecotect Analysis software , properties and their resultant behaviors are assigned to B-Reps also. Ecotect is one of the predominant software packages for "sustainable design"[33] and will serve as a case in point to see how issues of ecological design become manipulable in CAD. As Autodesk states, Ecotect "offers a wide range of simulation and building energy analysis, functionality that can improve performance of existing buildings and new building designs"[34]. Ecotect is a "concept-to-detail design analysis solution with architect-designed desktop tools that help measure the impact of environmental factors of a building's performance…"[35].

All objects are designed first (perhaps in some other Autodesk software) and are then analyzed in Ecotect. Ecotect is our sustainability inspector. It tells us if what we designed is right or wrong[36]. It participates in the design process as a regulator. Design happens before or after Ecotect. The sophisticated methods that are used to evaluate heat gains, solar radiation, energy use, carbon emissions and so on, are all non-manipulable entities. They are only there to tell us YES or NO. Although I am being a harsh critic here - after all Ecotect can prove very useful when one has to get LEED certified - the fact remains the same. Properties, from the most basic modeling software to the most sophisticated simulation analysis tools, are NOT manipulable entities. They only come as attachments on Boundary Representations. Colors, materials, performance, optimizations etc do not actively participate in the design process. They are always afterthoughts. The reason is simple:

Properties are always **assigned** to boundaries. There is always a hierarchical relationship between the two. B_Reps always come first and properties are always assigned to them. Consequently, during the design process, properties in B-Rep software are not under negotiation. They are literally "dead entities". Unlike B-Reps that can be instantiated, transformed and combined to derive new B-Reps, properties can only be assigned and observed. They literally act as labels attached to B-Reps. They cannot be combined to derive new properties. Properties cannot become the object of design in CAD. They can only be evaluated.

In the special case of properties as materials, the digital has rightfully so often been

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[33] this claims comes directly from their website : http://usa.autodesk.com/ecotect-analysis/

[34] from the Ecotect software description. see http://usa.autodesk.com/ecotect-analysis/

[35] from the Ecotect brochure. download at http://usa.autodesk.com/ecotect-analysis/

[36] ecotect knows.

criticized as being devoid of physical materiality[37]. If we accept Antoine Picon's argument that such criticism is premature, and that the medium, instead, should be interrogated for its capacity to redefine materiality[38], I would agree. However, this will only hold true if in CAD we can make materiality a manipulable entity.

In Shape Grammars

The distinction between Boundary and Property can also be found in the Shape Grammar theory, put forward by George Stiny and James Gips in 1972[39]. This distinction can be traced as that between Basic Elements and Weights[40]. Unlike any computation taking place within a digital computer (a Turing machine), Shape Grammar's primary goal is to describe both theoretically and in practice a precise computation for design (a language) that occurs **without a predetermined structure**. It is important for the Shape Grammarian to be able to visually detect a shape, apply to that shape (on the fly) a rule of transformation, derive a new shape and finally (if needed) forget about the rule (and the shape for that matter). The resultant design is offered for visual inspection, new shapes can be detected and new rules can be applied. A structure can always be established, but only if we trace the design steps backwards. In Stiny's own terms, in Shape Grammars there could be algebras for Shapes , algebras for Labels[41] and algebras for Weights.

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[37] See Frampton, Kenneth, *'Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture'*, MIT Press, Cambridge Mass (1995).

[38] See Antoine Picon, '*Architecture and the Virtual: Towards a New Materiality*', *Praxis: Journal of Writing and Building*, issue 6: New Technologies, New Architectures. p.114-121

[39] Stiny, George and Gips James, *'Shape Grammars and the Generative Specification of Painting and Sculpture'*, in Information Processing 71, (ed.) C.V. Friedman, Amsterdam: North Holand,1972, pp 1460-1465.

[40] Stiny, George, *'Weights'*, Environment and Planning B: Planning and Design 19 (1992), pp.413-430.

[41] algebras of Labels are a special case of algebras of Weights.

He writes:

> In a more ambitious fashion, basic elements may also have properties associated with them that interact as basic elements do when they are combined. I call these weights. Weights go together with basic elements to get shapes .... points have area , lines have thickness and planes have tones. Among other things, weights include different graphical properties such as color and surface texture, but any material property will do, and more abstract things like sets of labels, numerical values that vary in some way, or combinations of sets and values are fine, too[42].

As we can infer, the distinction between Boundaries and Properties can be found as the distinction between basic elements and weights; between points and area, lines and thickness planes and tones and so on. In my understanding, a miss-interpretation has taken place over the years regarding the parts of SHAPES in Shape Grammars. Perhaps because most of the work with Shape Grammars has been conducted with Basic Elements (points, lines, planes etc - the entities I call Boundaries) and the set of rules that apply to them are referred to as algebras of shapes, shapes tend to be thought of and communicated solely as boundaries. Shapes and Boundaries are often understood as one and the same. It might also be that since their inception in the early 70's, Shape Grammars have evolved to include Properties as integral parts of SHAPES. In the original shape grammar paper this held true for shapes:

> A *class of paintings* is defined by the double (S,M). S is a specification of a class of shapes and consists of a shape grammar, defining a language of two dimensional shapes, and a selection rule. M is a specification of material representations for the shapes defined by S and consists of a finite list of painting rules and a canvas shape (limiting shape)[43].

Today, a close inspection of Shape Grammars reveals that a SHAPE can be bound by Basic Elements (points, lines, planes etc) and can have Properties associated with it. Points are boundaries of lines, lines of planes and planes of solids. In other words SHAPES can **have** basic

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[42] Stiny, George, *'Shape. Talking About Seeing and Doing'* MIT Press, Cambridge Mass (2006), pp. 215-216.

[43] Stiny, George and Gips James, *'Shape Grammars and the Generative Specification of Painting and Sculpture',* in Information Processing 71, (ed.) C.V. Friedman, Amsterdam: North Holand,1972, pp 1460-1465.

elements and can **have** properties. Unlike CAD in which B-Reps define shapes in a predetermined way, here Basic elements (boundaries) and properties do not define a SHAPE. Instead, they are only characteristics of them. As there isn't a structure that predetermines the relationship between basic elements and properties, the different parts of SHAPES (basic elements + properties) all meld together to form a composite entity without any hierarchical relationship between them. For example, a plane can have lines as basic elements and color as weight. In the formalism of shape grammars, both lines and color of a plane are only there if you apply a rule that identifies them. Most importantly, for shape grammars, a smudge of a dirty finger on a piece of paper is as much of a plane as a red square.

Terry knight effectively demonstrated with Color Grammars[44] how computations with weights can take place. She showed how color or material can become a manipulable entity during the design process. Knight identifies situations where "the application of a rule places a color region over or into another color region already present in the design"[45] and makes these overlapping regions the object of her investigation. She writes:

> In color Grammars, overlapping color regions are handled formally with *rankings*. When two regions coincide, either one region is ranked *above* (denoted by the symbol >) and covers the other region, or the two regions are ranked *equally* (denoted by the symbol <>) and blend to form a composite color.[46]

She further explains how colors can be either transparent or opaque and how, in the case of transparency, overlapping colors blend to produce a composite while an opaque color conceals another one. She even takes it a step further when she applies similar strategies to deal with materials or construction (their representations) as they occur during the design process. In the case that a masonry wall overlaps a stud wall, if the two elements rank as equal, they produce a third material or construction member at their intersection i.e. steel. If on the other hand they rank as unequal, one material covers or overtakes the other[47]. All of these rules are a matter of choice.

The distinction between boundary and property exists here too. In Color Grammars, it

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[44] Knight, Terry W., *'Color grammars: designing with lines and colors'*, Environment and Planning B, 16 (1989), pp. 417-449.

[45] Knight, Terry W., 'Color Grammars: The representation of Form and Color in Designs', in Leonardo, Vol 26. No. 2 (1993), p.119

[46] ibid

[47] ibid

takes the form of region and color. But, unlike CAD, there is no hierarchical relationship between them. Rules can be applied to either regions or colors independently. A rule applied to a region can affect a rule applied to a color/material and vice versa. The overlap rules are a good example of this. What Color Grammars does, is indicate how color or material (properties or qualities in general) can become the object of design not by mere observation, as it happens with CAD, but as a manipulable entity. It further shows as that there isn't a fixed hierarchy in the relationship between Boundaries and Properties. Rather, every time a rule is applied this relationship can change. Boundary is no more important than Property and vise versa. Structure is only temporary and appears only when a rule is applied.

In Color Grammars as well as all other Weight Algebras I have come across, a property within a region is always homogeneous. This means that a color can be replaced with a label (for example the word red). Although this would not make it visual and would defeat the purpose, the homogeneity hypothesis is not negotiable. And this assumption works well when one has to deal with a composition of objects, when, in Banham's words, the "structural approach" is underlying. But what happens to the finger smudge? The smudge is not always consistent and furthermore a single region is not always visible. Although theoretically it is possible for Shape Grammars to deal with varying properties, in practice, it has not been the case. For example, Jacquelyn Martino, an artist who did her PhD on Shape Grammars and expanded them to include curves, chose to treat heterogeneous color blending informally (Figure 6).

(a) Sun (b) Thunder

(c) Moon (d) Fire

Figure 6 : Jacquelyn A. Martino. Digital Paintings.

In a caption of this work she writes: "Final digital paintings. Each of these paintings is a combination of formal shape rules and informal color usage."[48] Here, the distinction between boundary and property can be identified as a distinction between formal shape rules (in this case curves) and informal color usage. Although it is evident that regions do not have homogeneous color distributions, there are no direct formal rules that speak of manipulability. For me the question here, and the question for Shape Grammars too, still remains open. In the case of property heterogeneity, if we choose to prioritize, even for a moment, Properties over Boundaries, how can they become manipulable entities in computation? Moreover, if we are to prioritize Banham's "power operated solution", how can we deal formally with the camp fire's gradient heat distribution? Is there a way we can imagine designing without lines[49], without surfaces; that is, without defining boundaries first and then assigning properties to them? In painting this question has been theoretically addressed.

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[48] Martino, Jacquelyn A., *'The Immediacy of the Artist's Mark in Shape Computation: From Visualization to Representation'*, PhD Dissertation, MIT (2006), p. 65.

[49] The question here looks back at the following statement by George Stiny : "And it is the same today-try to imagine designing without lines" in George Stiny, *'Shape. Talking About Seeing and Doing'*, MIT Press, Cambridge Mass (2006), p.214.

In Art

For John Ruskin, a flamboyant proto-ecologist and fervent anti-industrialist, Joseph Mallord William Turner with his paintings combine light, air and water into a compositional machine that never ends. Almost from the inception the industrial revolution and while societies were starting to reorganize around principles of industrialization, scientists, sociologists, art critics, artist and architects went back and forth challenging the very foundations of contemporary thought and practice. In a scientific society saturated with Newtonian (mechanistic) physics, Ruskin found in Turner a practitioner of thermodynamics.

Figure 7 : Joseph Mallord William Turner.
"Rain, Steam and Speed – The Great Western Railway".

Since Ruskin, many have put Turner´s work under the magnifying glass. Regarding Turner's paintings, Michel Serres writes:

> *The perception of the stochastic replaces the art of drawing the form*...[50] Man has constructed a thing-Nature. The painter makes one see the entrails of this thing: stochastic bundles, dualism of sources, winking fires, its material entrails, which are the very womb of the word, sun, rain, ice, clouds, and showers. Heaven, sea, earth, and thunder are the interior of a boiler which bakes the material of the world...[51]

According to Michael Serres, Turner's painting 'Rain, Steam and Speed – The Great Western Railway' has passed "from geometry to matter or from representation to work."[52] I would argue instead that working with color, light, and brushstroke is another kind of representation, albeit a different kind; the kind that David Thomas calls "mattery"[53]. My distinction between boundary and property, though, is parallel to the distinction that Serres makes between geometry and material in Turner's painting. As we established before a perceived "thing" **has** *a boundary* the same way it **has** a color, a texture, a reflection, etc. Serres goes on to argue that in Turner's paintings "the perception of the stochastic replaces the art of drawing the form"[54]. The apparent imprecision of form does not necessarily mean an equivalent imprecision of work, just because the painting appears to be "stochastic". On the contrary there could be a precise methodology or a rule set producing the work. After all, Turner uses a paintbrush with watercolor on a white canvas. If painters can do it, can designers also make the object of their investigation *the material world as if it is the interior of a boiler*? Here is a story.

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[50] Quoted in Tomas, David, *Beyond the Image Machine: a history of visual technologies*. Continuum Books: New York (2004), p. 20 (emphases in the original).

[51] Ibid. 20

[52] Thomas, David, 'Beyond the Image Machine: a History of Visual Technologies' Continuum Books, New York (2004), p. 21

[53] Ibid.

[54] Ibid.

1.3 The Sky. From Brunelleschi to Von Neumann

In the *Ten Books on Architecture*, which establishes the architectural principles of order and proportion- *utilitas, firmitas*, and *venustas* – Vitruvius lists geometry as one essential component of an architect's skill set, along with astronomy, music, philosophy, history, natural drawing skills, etc. Within the very first pages, in the chapter "Education of the Architect," he writes:

> Geometry, also, is of much assistance in architecture, and in particular it teaches us the use of the rule and the compasses, by which especially we require readiness in making plans for buildings in their grounds, and rightly apply the square, the level, and the plummet.... It is true that it is by arithmetic that the total cost of buildings is calculated and measurements are computed, but difficult questions involving symmetry are solved by means of geometrical theories and methods.[55]

Geometry's merits are both pragmatic and artistic. It is also mentioned by Vitruvius as a surveying tool, to determine the "healthy" sitting for new towns, to illustrate the direction of wind currents and directional flows, and to devise the ideal layout of the town's street structure.[56] Geometric interpretation extends to the Vitruvian man, in which he describes the body's basic systems of proportion through symmetrical principles.

> Therefore, since nature has designed the human body so that its members are duly proportioned to the frame as a whole, it appears the ancients had good reason for their rule, that in perfect buildings the different members must be in exact symmetrical relations to the whole general scheme.[57]

By inscribing the human body within the circle and the square, he becomes aware of the body's modularity, symmetry, and beauty. This knowledge grants geometry the status of an epistemological model, from which the world is visually remade, allowing the architect to reconstruct visual information through an explicit system.

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[55] Vitruvius, '*Ten Books on Architecture*', (ed.) Morgan H. Morris, Kessinger Publishing, Whitefish(2010), p. 4.

[56] Ibid. 4

[57] Ibid. 78

Vitruvius's book was rediscovered during the time of the Renaissance, becoming a foundational text for its era's architects and artists. While building upon classical knowledge, through drawing, the Renaissance architect essentially reinvents himself. Up until then, painting, sculpture and architecture were mechanical arts; in the medieval ages the architect was equivalent to a mason and carpenter. Through the achievements of drawing and linear perspective, which rendered the 3 dimensional world in 2 dimensions, the architect takes command of the building process, not because he can build, but because he can draw and so he is promoted from a builder to an intellectual. In 1415 Brunelleschi is credited with creating the first perspectival image. The following excerpt from a biography of Brunelleschi's written by Manetti in the mid-15th century, describes these experiments:

> He first demonstrated his system of perspective in a small panel about half a braccio[58] square. He made a representation of the exterior of San Giovanni in Florence, encompassing as much of that temple as can be seen at a glance from the outside...He painted it with such care and delicacy and with such great precision in the black and white colours of the marble that no miniaturist could have done it better...And he placed burnished silver where the sky had to be represented, that is to say, where the buildings of the paintings were free in the air, so that the real air and atmosphere were reflected in it, and thus the clouds seen in the silver are carried along by the wind as it blows.[59]

The sky poses a challenge to Brunelleschi's precise geometric method, as the one element that defies representation.[60] The unusual decision in his first study of perspective, to keep the burnished silver in order to reflect the sky, is better understood if we consider that he was already employing a metal panel [61], as was common practice at the time, with which to paint the scene in reverse. Unable to depict the sky otherwise, through the use of reflection he captures the sky's changing properties. Brunelleschi chooses not to give form to the sky's dynamic, particulate nature.

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[58] Approximately one square foot.

[59] See Manetti, Antonio di Tuccio; Saalman, Howard, *'The Life or Brunelleschi'*, University Park (1970).

[60] Ingraham, Catherine, *'Why all these birds? Birds in the sky, Birds in the Hand'*, in Antoine Picon and Alessandra Ponte Architecture and the Sciences: Exchanging Metaphors, Princeton Architectural Press, New York (2003) p. 231.

[61] Wright, Lawrence, *'Perspective in Perspective'*, Routledge & Kegan Paul, London (1983), p.58.

It comes as no surprise that clouds also caught the attention of Ruskin (the usual suspect again), who is considered today - by many - as one of the first *"environmentalists".* Perceived as an ill omen of the industrial revolution, carried by a tormented "plague-wind" [62], the storm cloud of 1871 was for him an object worthy of scientific investigation. Ruskin, a painter and avid cloud-watcher, while addressing the Meteorological Society of London in 1884, defines a cloud, most simply, as a "Visible vapor of water floating at a certain height in the air."[63] The question that interests him is the particulate nature of the clouds and how they become visible and differentiated- from the basic sky cloud, earth cloud, and mist[64] to the stationary cloud reflecting unresolved light and fast-flying cloud transmitting resolved light[65]. Mocking the mechanistic - Newtonian in its origins, science community he says:

> ...the scientific men are as busy as ants, examining the sun, and the moon, and the seven stars, and can tell me all about *them*, I believe, by this time; and how they move, and what they are made of. And I do not care, for my part, two copper spangles, how they move nor what they are made of. I can't move them any other way than they go, nor make them of anything else, better than they are made. But I would care much and give much, if I could be told where this bitter wind comes from and what it is made of. For perhaps, with forethought, and fine laboratory science, one might make it of something else.[66]

According to Ruskin, the understanding of the complex phenomenon of the weather, or the practice of meteorology, could not be left to hobbyists, but demanded the combined skills of an array of different fields - from chemists and geometers to archaeologists and geographers- in order to become a rigorous science. Ruskin's study of meteorology could not be conducted in isolation, in laboratories conjuring the sky, but would require a team of multiple disciplines to observe and document it prolifically on site, an endeavor that would necessitate its study on a global scale [67]. And what is Ruskin's drive for all this? It is not enough for him to observe its formation. He wants to make something else out of the cloud. He wants to put his hands on it. In other words he wants to make the cloud an entity that is manipulable.

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[62] Ruskin, John, *The Storm Clouds of the 19th Century*, J.W. Lovell co., New York (1885), p.45.

[63] Ibid. 12

[64] Ibid. 19-20

[65] Ibid. 31

[66] Ibid. 47

[67] Ibid. 31

In 1904, a Norwegian meteorologist Bilhelm Bjerknes, promoted the idea of a program of numerical meteorology, in which the laws of physics would be applied to the atmosphere.[68] He recognized that the most serious impediment was the length of the calculations, which might (under even the most favorable conditions) require three months to calculate three hours of weather.[69]

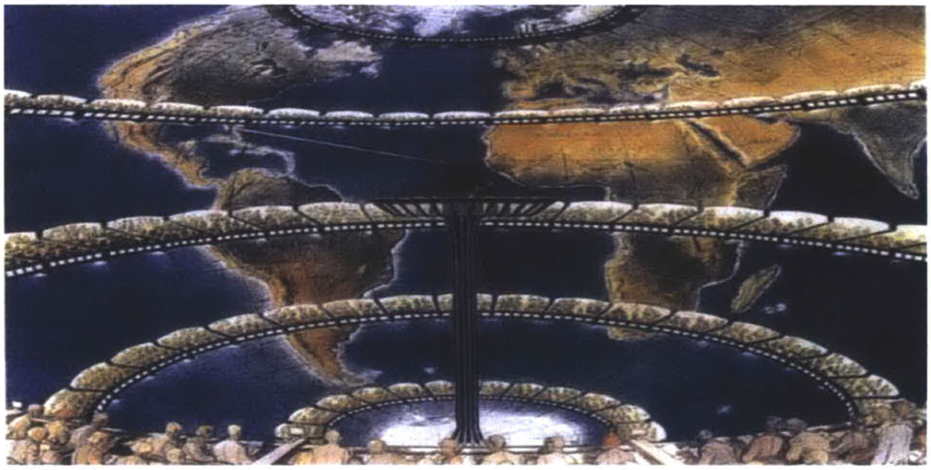

Figure 8: Artists impression of Richardson's Forecast Factory, Francois Schuiten.

Bjerknes hoped this would develop beyond theoretical application into a method for weather prediction, which demanded faster calculations. Lewis Fry Richardson, a British meteorologist familiar with Bjerknes' work, introduces a more practical process "of finite differences for the approximate solution of differential equations."[70] This was later refined and applied to a numerical method for weather computation, in a fantastically surreal scenario- a Forecast Factory. Weather calculations would occur in the factory by using "computers," (people), calculating for each region of the world in one huge circular, tiered hall, orchestrated by a man at the center who alerts people who are either calculating too fast or too slowly with red and blue

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[68] Asprey, William, *John Von Neumann and the Origins of Modern Computing*, MIT Press, Cambridge Mass (1990), p. 124-5.

[69] Ibid. 125

[70] Ibid. 127

lights illuminating them, respectively. The Forecast Factory is basically a supercomputer where, "A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to the one equation or part of an equation."[71] Richardson believed it would take 64,000 people working together to successfully calculate the weather,[72] ultimately and regrettably making it an untenable approach.

In the 1940's, meteorology finally received a crucial tool for its advancement as a mathematical science - the digital computer- which decreased the time it took to complete calculations by a factor of, at least, 10,000.[73] The mathematician Von Neumann was especially interested in using the computer in conducting weather forecasting calculations because "the physics of the atmosphere was one of those complex, nonlinear problems that he regarded as a particularly fertile area for mathematical research."[74] Particularly indicative of Von Neumann's attitude towards computation was his interest in the work of the electrical engineer, Vladimir Zworkin:

> I remember in late 1945 or early 1946 reading a rather fantastic proposal of Zworkin's for the construction of an analogue computer which would scan two-dimensional distributions of weather data projected on a screen and then compute the future weather by analogue techniques; by varying the input continuously and observing the output one could determine how most efficiently to modify the input to produce a given output.[75]

As a modality, numerical computation allowed for precise atmospheric calculations. Non-linear equations, which were previously impossible for the forecaster to handle at such magnitude, became accessible through the use of the digital computer. For Von Neumann however, beyond the ability to calculate massive amounts of data, what was put forward by the medium was its

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[71] Jule Charney quoted in Pearce, Robert P., *Meteorology at the Millenium*, p. 117. Charney worked with Von Nuemann from 1948 until 1956, as a principle meteorologist.

[72] Pearce, Robert P., *'Meteorology at the Millennium'*, Academic Press, San Diego (2002), p. 118. Pearce states that Richardson underestimated; the endeavor would actually have taken 200,000.

[73] Asprey, William, *John Von Neumann and the Origins of Modern Computing*, MIT Press, Cambridge Mass (1990), p.130.

[74] Ibid. 130

[75] Quoted in Asprey, William, *John Von Neumann and the Origins of Modern Computing*, MIT Press, Cambridge Mass (1990), pp 130-131. Vladimir Zworkin was an electrical engineer who was developing meteorological instrumentation; Von Neumann was in contact with Zworkin and later worked with him and the U.S. Weather Bureau in 1946.

facility to be used as a heuristic device. He advocated that a scientist would have to engage in a process in which calculation and observation form a reciprocal relationship. In other words, not unlike design, the results of calculations would have to be interpreted visually, which in turn would inform further calculations in a loop.

> The computer is used heuristically to build highly simplified models as a means to discover new relationships within complex phenomena, such as the nonlinear relationships in the atmosphere.[76]

Today, meteorology relies heavily - if not exclusively - on the calculating power of digital computers. Sean Lally, with his practice "Weathers", tells us that meteorologists have finally reached a point where by building databases of "atmospheric temperatures, wind speeds, atmospheric pressures, humidity, etc", they have managed to predict a storm´s behavior. As he says, meteorologists have shifted from "representing the formal logics (of a storm) to simulating environmental behaviors".[77]

For this thesis, this shift is not between representation and simulation but between two modes of representation. Environmental behaviors, through the use of intense digital calculation, have now become manipulable entities. Brunelleschi's problem, in one way or another, is partially addressed.

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[76] Ibid. 153

[77] Weathers, Sean Lally, *'Potential Energies',* in Softspace, From a Representation of Form to a Simulation of Space (ed.) Sean Lally & Jessica Young, Routledge, London (2007), p.30.

1.4 Alan Turing and the Belouzov – Zabotinski type reaction

In a lecture given to Manchester University in 1952, Alan Turing speculated upon the chemical basis of morphogenesis. He suggested that "a system of chemical substances, called morphogens, reacting together and diffusing through a tissue, is adequate to account for the main phenomena of morphogenesis. Such a system, although it may be originally quite homogeneous, may later develop a pattern or structure due to an instability of the homogeneous equilibrium, which is triggered off by random disturbances."[78] The scope of this theoretical paper is to describe how patterns observed in animals could be explained as a result of the interactions between chemical substances operating within a mass of tissue.

> What laws are to control the development of this situation? They are quite simple. The diffusion follows the ordinary laws of diffusion, i.e. each morphogen [chemical substance] moves from regions of greater to regions of less concentration, at a rate proportional to the gradient of the concentration, and also proportional to the 'diffusability' of the substance.[79]

The Belousov-Zhabotinsky type reaction introduced by Belousov in the early 1950's and further investigated by Zhabotinsky in 1964, proved Alan Turing's speculations to be true.[80] Wave-like patterns emerged from the catalytic oxidation of malonic acid by potassium bromate.[81] By changing the properties of the environment through exposure to different lighting conditions, or by changing the concentration of either substance in the mixture, the system appeared to produce steady states.[82]

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[78] Turing, Alan, '*The Chemical Basis of Morphogenesis*', Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences, Vol. 237, No. 641. (August 14, 1952), p. 37.

[79] Ibid. 40

[80] (Field and Burger 1985). See Nicholas G. Rambidi, "Chemical-Based Computing," *Molecular Computing* ed. Tanya Sienko, Andrew Adamtzky, Nicholas G. Rambidi, and Michael Conrad, MIT Press, Cambridge Mass (2003), p.109.

[81] Nicholas G. Rambidi, "Chemical-Based Computing," *Molecular Computing* ed. Tanya Sienko, Andrew Adamtzky, Nicholas G. Rambidi, and Michael Conrad. Cambridge: MIT Press, 2003. pp109

[82] Ibid.

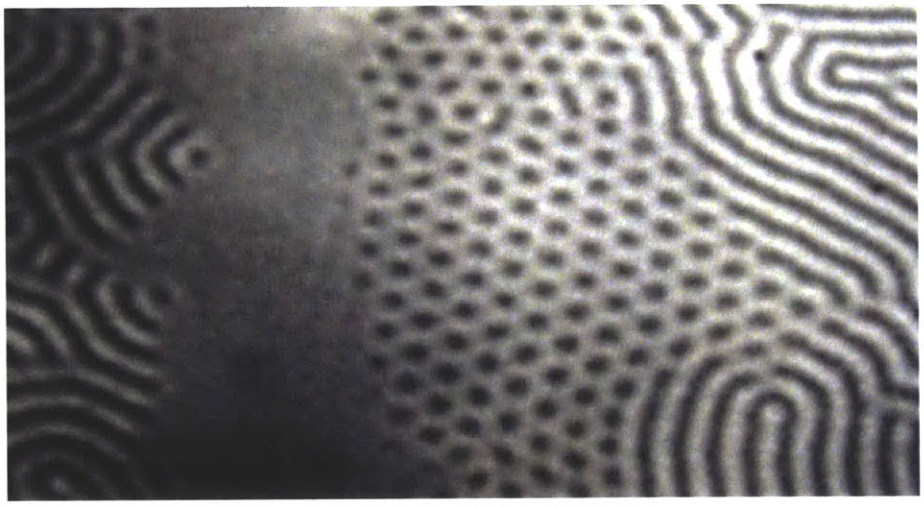

Figure 9: Turing patterns, J. Boissonade, E.Dulos, and P. De Kepper.

The phenomenon led to speculations regarding the possibility of using such multi-state systems for the production of non-digital computers.[83] Further investigations by J. Boissonade, E.Dulos, and P. De Kepper in 1995, have substantiated the relationship between conditions in the environment and the results of such reactions. Narrow, uniform regions, regions of clear spot exhibiting a hexagonal arrangement, striped areas, and areas of intricate mixtures of stripes and spots, all co-exist in one sample, depending on the variation in concentration of the substances. By varying the section of the container in which the reactions take place, they trigger non-homogeneous pattern formations. They go on to make explicit, that the geometry of the container does not participate in any way in this process, its role is to control the concentration of substances within it.[84] Phenomena such as this, have given way to theories of self-organization and complexity.

Over the past 30 years, the notion of self-organization has appeared in reaction to the dominant, reductionist approach in the sciences. On this topic, Christopher G. Langton makes a distinction between dynamical and mechanical systems[85]. He explains that dynamical systems of representation are non-linear and depend critically on the interactions between parts: parts are

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[83] Michael Conrad's pioneering works include: "Molecular information processing in the central nervous system" (1974), "On design principles for a molecular computer" (1985), "The brain-machine disanalogy" (1989). Also see Tanya Sienko, Andrew Adamtzky, Nicholas G. Rambidi, and Michael Conrad, *Molecular Computing*.

[84] Ibid. 242-6

[85] Langton, Christopher G., *'Artificial Life'*, MIT Press, Cambridge Mass (2000), p. 40.

treated in each other's presence while in mechanics, parts are treated in isolation.[86] Disciplines such as physics, chemistry and biology are using self-organization principles in order to study the behavior of basic interacting units within a given environment. From a more technical perspective:

> Self-organization (Coveney & Highfield 1995) is the spontaneous emergence of non-equilibrium structural organization on a macroscopic level, due to the collective interactions between a large number of (usually simple) microscopic objects. Such structural organization may be of a spatial, temporal or spatio-temporal nature, and is thus an *emergent* property.[87]

The self-organization phenomena, when translated into computational methods, have been expressed through Boolean variables made up of binary digits. [88] Beyond the ability to explain biological phenomena[89], Turing's precise mathematical speculations of morphogenesis, gave way to a now model of work. It is now possible to imagine environments, quite literally, becoming the object of design itself. It is possible to imagine moving away from the imposed-preconceived Cartesian object which negotiates through its boundaries its presence within its immediate context, and instead design an environment that gives rise to form from within.[90]

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86 The parts in these kinds of definitions are relating to each other in a fixed way, and the word dynamic here refers to an observed, automated phenomenon in time, rather than a dynamic change of relationships. The design process, on the other hand, is as self-organizing as it gets; parts in relationships are constantly redefined. The distinction I want to make clear is that the dynamical system, as described by Langton, is executed by a calculating machine, while the dynamical system explained in Shape Grammars, is calculated by a human. The *VSpace* project attempts to negotiate between the two. The ultimate goal is that at any moment a machine computation is taking place a designer can freeze the computation and intervene.

87 Coveney, Peter V., *'Self-Organization and Complexity: A New Age for Theory, Computation and Experiment', Philosophical Transactions: Mathematical, Physical and Engineering Sciences,* Vol. 361, No.1807, Self-Organization: The Quest for the Origin and Evolution of Structure. (Jun. 15, 2003), p. 1057.

88 Ibid.1063

89 For a detailed account of the reaction-diffusion morphogenetic phenomena see Goodwin, Brian C., *'Structuralist Research Program in Developmental Biology'*, in Mark Rappolt (ed), Greg Lynn Form, Rizzoli, New York (2008), p 177.

90 A parallel thought was presented by Tsamis at Harvard University's First International Conference on Critical Digital: *What Matter(s)*, April 2008

1.5 VSpace

1.5.1 About

VSpace[91] is a prototype computer application that demonstrates a reverse hierarchy between boundary and property. Unlike current design software (i.e Rhinoceros , Autocad, 3d studio, Generative Components, Catia and all other usual suspects) that use boundary representations (vectors and their by-products) as the sole manipulable entities in a digital environment, VSpace treats boundary and property as concurrent- one influencing the other in equal terms. VSpace sets the foundations and establishes the principles for the development of a *Property Representation* (P-rep) design tool by examining its relationship to existing digital design tools. VSpace attempts to make properties manipulable entities during the design process. VSpace attempts to be a "software" software.

VSpace uses as precedent and expands the computation work of Lionel March from the 70's. "The boolean description of a class of build forms"[92], although still within the "structural solution"[93] logic, is re-interpreted as a viable computer model of reversing the relationship between boundaries and properties in design software. Influenced by the "compound" understanding of SHAPE in Shape Grammars and starting with Alan Turing's original speculations on the mathematical laws of morphogenesis, the *VSpace* software uses Voxels as *property place holders*, Painting and Cellular Automata as two distinct design strategies for calculating with properties and the Marching Cubes Algorithm as a background engine that allows us to establish relationships between Properties and Boundaries. Each aspect of the project is first analyzed separately and then are all demonstrated together as a **complementary** design paradigm. The goal here is to identify similarities and differences between Boundary Representation software and VSpace (or Property Representation Software), determine design operands equivalent to the ones that exist in B-Rep software and explain their differences. Ultimately, through examples, I discuss new possibilities but also limitations that such mode of work may afford.

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[91] VSpace started as a design project in collaboration with Kaustuv DeBiswas in 2008. It was first published in the Ecoredux exhibition in Columbia University, Avery Hall (October- December 2009). More recently it acquired the name VSpace and was developed as a mockup software package as part of a research project at Adolfo Ibanez University, Chile.

[92] March, Lionel, *'The Architecture of Form',* Cambridge University Press, (1976), p. 41.

[93] "the structural solution" as it is understood in Reiner Banham.

1.5.2 Voxels and the *Voxel Constituent Space*

A Voxel is a three-dimensional volume element equivalent to a pixel in a two dimensional bitmap. Like pixels, Voxels have dimensions. They are volumetric units with minimal X, Y and Z dimensions. William J Mitchell suggests in his book *"The Logic of Architecture"*, that Voxels first made their appearance as a mode of architectural representation as early as 1936. He writes:

> In a three-dimensional Cartesian coordinate system, space can be filled, to any desired density, with a cubic array of points. When states are associated with these gridpoints they are known as Voxels-volumetric elements: Voxel (point(x,y,z), **State**) ... In this case the description of state is elaborated to allow representation of spatial distribution of material, thus: Voxel (point(x,y,z), **Material**).[94]

He goes on to give the example of Albert Farwell Bemis' discussion on modular coordination (1936) in which architectural forms could be built up from four-inch cubes. I could not agree more with Mitchell's statement that "In practice, it rarely proves useful to adopt such an extreme atomistic viewpoint."[95] But that is only because in this "Point World"[96] Voxels are reduced to essentially what would be the physical equivalent of a brick. Although this mode could work well as a representation of an existing design, it would almost be to the level of obsessive compulsive absurdity to assume that objects or space could be designed in this fashion. It would be as absurd as to suggest that a bitmap image would be conceived and drawn pixel by pixel. Nevertheless, allow me to observe here that this point of view also assumes that objects - or more generally space - can only be conceived as or designed as a composition of boundaries - in this case Voxels. In other words, Voxels are dismissed - in my opinion prematurely - because rightfully so, in the contemporary architectural scene of the 90's, they could not fit the "structural"[97] approach to design.

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[94] Mitchell, William J., *'The Logic of Architecture'*, MIT Press, Cambridge Mass (1990), p.40.

[95] ibid

[96] "Point Worlds" is the title of Mitchell's chapter in : Mitchell, William J., *'The Logic of Architecture'*, MIT Press, Cambridge Mass (1990), p.39.

[97] Structural refers here to the Banham's distinction between the "structural" and the "power operated".

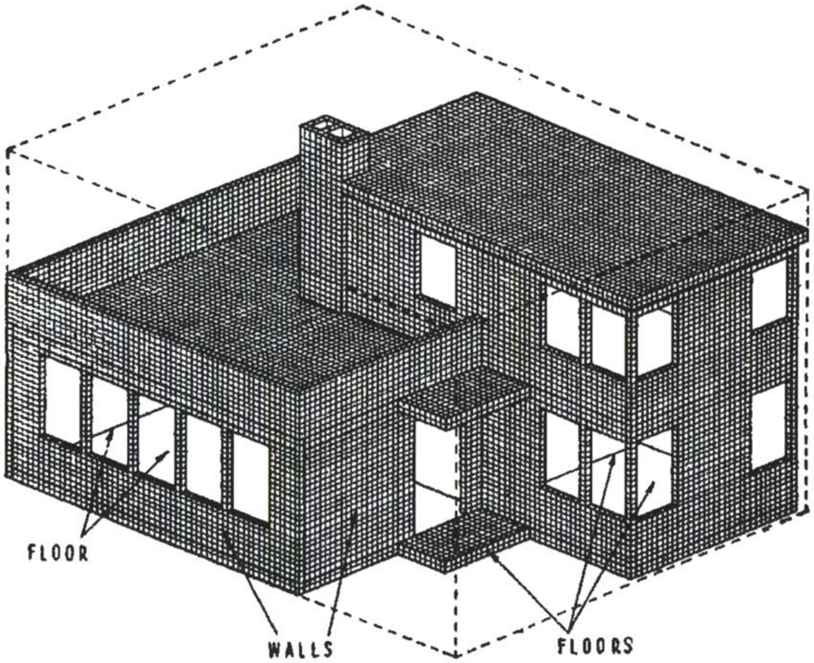

Figure 10: House structure defined within a matrix of cubelets. Albert Farwell Bemis (1936)

The work of Lionel March demonstrates how voxels - or "cubelets" - can be systematically used to enable a comprehensive description of a type of architectural forms. He describes a computation that uses cubelets, in an attempt to link architectural design with the pragmatics of industrial technologies. Starting from an argument about the existing reality of "the increasing use of techniques of mass production in the building industry"[98], March justifies Bemis' choice of the four inch module as it directly corresponded to the imperial standard and also the 100mm metric standard. He goes on to explain how sets of those cubelets, which he calls "multi-modules"[99], can be derived to express architectural elements like doors, windows and partition units, the dimensions of which can in turn be determined by technical considerations. For March, transportation, raw material sizes, production engineering requirements or more architectural considerations like door height, cupboard size or bed width can provide valid design reasons for dimensioning the different cubelet sets. He even goes a step further to explain how in a more

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[98] March, Lionel and Steadman, Philip, *'The geometry of Environment'*, RIBA Publications Limited, London (1971), p. 199.

[99] ibid p.201

general case, the human body - in this case Corbusier's *Modulor* - could provide accurate guiding principles of dimension.[100] He demonstrates how different cupboard sizes can be derived from "modular coordination" but even more importantly, how the plan of Mies' Farnsworth House can perfectly fit within this computation model. Lionel March, by making a direct association with the ideologies of the "high modern", utilizes Voxels to satisfy the "structural" approach to design.

In a later publication, Lionel March, generalizes this approach by using boolean algebras to provide a precise mathematical description of the cubelet sets. In "the boolean description of a class of build forms" he shows that within a two-dimensional array (grid) of cubelets, sets can be derived as combinations. He explains how within a two by two grid one can derive 2^4 subsets (Figure 11), and further demonstrates how those sets can be used to describe existing plan configurations. Just like Bemis did, March here describes the plan of Le Corbusier's Maison Minimum using a "hexadecimal code".[101]

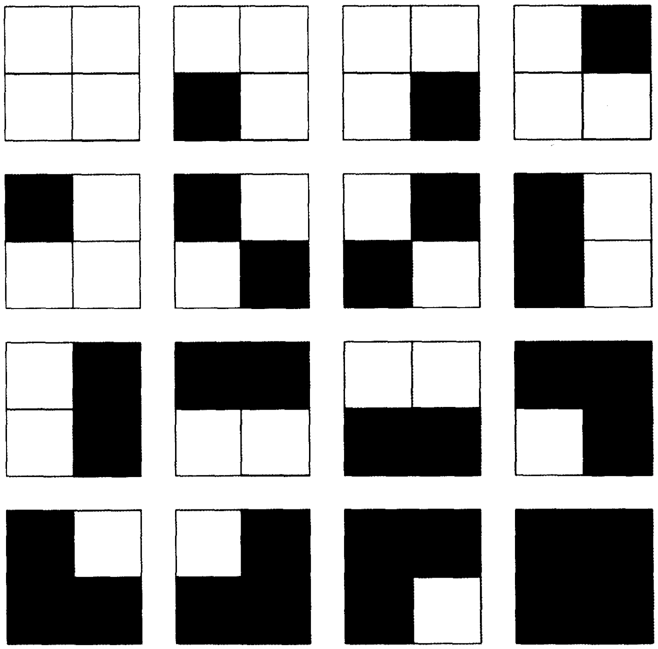

Figure 11: 16 distinct subsets of a two by two grid. (Lionel March, redrawn)

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[100] ibid 202

[101] March, Lionel, *The Architecture of Form,* Cambridge University Press, (1976), p. 60

What becomes important for this design thesis is that within the Lionel March model it is clear that there is an embedded logic, an ideology if you will, of the "structural" solution. Architectural design is described as a composition of objects using a combinatorial approach. Furthermore, other than the apparent "ethics" of industrial production, when the model becomes more general, a combinatorial logic is limited to only describe existing designs. What I am interested in here is to propose a computer application that uses properties as manipulable entities and suggest a new mode of work. My attempt to make the "active context" the object of design utilizes Voxels with a different perspective to form the *Voxel Constituent Space*.

Before going into the technical specifications of what I term a *Voxel Constituent Space* and how it is used in the *VSpace* project, it is important to shed light on the nature of this modality and how it draws parallels to other disciplines using Voxels as a method of representation.

Although Voxels have been used extensively since the early nineties in computer science - among other functions in the gaming industry - to effectively represent complex 3D geometries[102], it is the medical imaging industry that catches my attention.

In a class of imaging techniques, known as nuclear medicine imaging[103], the broad term *reconstruction* refers to a process of recording a body's substance, defying the qualitative presence of organs and systemic functions. Minimal spatial entities (Voxels) become registration devices of variant properties used for recovering a volumetric representation of the body. Essentially, "reconstruction is the abstract "rebuilding" of something that has been torn apart"[104]. Underpinning this technique of visualization is the assessment that in numerous medical inquiries the *physiologic function* of the body is equally significant to comprehend at its entirety as its *anatomy*[105].

For this project, importance lies on the view that the body cannot **only** be understood as a series of organs or systems that form interrelations but rather can **also** be understood as a constituent body of matter and energy, substance and heat.

The discussion of the difference between the *reconstruction* of the body and the *anatomy* of the body as techniques being used for advanced visualization of digital environments serves as a

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[102] http://www.3d-coat.com/ or http://www.Voxelogic.com/

[103] Brooks R.A. and Dichiro G., *"Principles of Computer Assisted Tomography (CAT) in Radiographic and Radioisotope Imaging"* in **Physics of Medical Biology** (1976; 5: 689-732).

[104] ibid

[105] Habib Zaidi, *"Medical Imaging: Current Status and Future Perspectives"*, Division of Nuclear
Medicine, Geneva University Hospital, CH-1211 Geneva. Switzerland. In
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.15.5208&rep=rep1&type=pdf

case in point for the possible exploitation of a *Voxel Constituent Space* as a generative mechanism for the production of a *property informed* architecture. Through this analysis an attempt is made to understand the nature of a Voxel space and how it can gain meaning for our perception of architectural space[106].

In *reconstruction*, a priory definition of the body's functions is suspended. It is fundamentally different than the traditional understanding – representation of the body as there is no presence of parts with single functions but instead there is only distribution of properties. In this case, the human body is not understood as a collection of parts or in more contemporary terms as a system composed of subsystems. Rather, it is understood as a distribution of substances, an evolving chemical environment. Applied to architectural design, the principles of medical reconstruction exude potential in challenging given assumptions deeply instilled in architecture, such as the perception of space, exclusively via configurations of parts or systems. As a modality, it becomes a vehicle for design, which defers immediate formal expression. In this realm, *Space can be thought of as a scaffold of distributed properties and behaviors.* For instance, material properties, conditions of light, performative or behavioral aspects and form are treated simultaneously through principles of proximity, coincidence and relevance.[107]

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[106] This inquiry started during my Master's Thesis. see Tsamis, Alexandros, *'Digital Graft. Towards a Non-Homogeneous Materiality'*, MSc Thesis, MIT 2004.

[107] A parallel thought was presented in the non-standrad praxis conference MIT, by Dritsas, Kalli-politi and Tsamis, (2004).

1.5.3 Voxels and the *Voxel constituent space*. Technical specifications

> As with pixels in a bitmap, Voxels themselves do not typically have their position (their coordinates) explicitly encoded along with their values. Instead, the position of a Voxel is inferred based upon its position relative to other Voxels (i.e., its position in the data structure that makes up a single volumetric image).[108]

In other words, although Voxels have a fixed dimension and appear to have a location in space (x, y and z coordinates), they differ from a 3 dimensional array of cubes modeled in any B-Rep representation tool. Their difference lies on the fact that their locations are defined only relative to each other V (I,j,k) and not relative to an external coordinate system. They are more of a spatial data structure – *a Voxel space*[109] - rather than an accumulation of objects. In computational terms, a *Voxel Constituent Space* allows one to query any position in space (have computational access) and simultaneously access all neighboring positions. Furthermore, Voxels can have properties that are associated with them.

Like pixels, they can have a color (in R, G, B or C, M, Y, K) space and an Alpha (transparency). In its least capacity, a Voxel space can allow for the definition of a six manifold topology[110] (I, J, K, R, G and B). In a Voxel space one can assign properties to or retrieve properties from a specific location in space. In addition, because of the aforementioned data structure, the *Voxel constituent space* is a digitally defined space where properties can interact locally to give rise to new properties. For the current study, Voxels are used as *property placeholders*[111] and are privileged over other methods of representation such as Vectors or Tensors as they can be visualized like pixels and therefore address visually, the distribution of properties in space. Although Voxel data structures are computationally intensive and in the project following a *Voxel space* is limited in size (i.e 60x60x60), ultimately or theoretically it is not there to impose its boundary. Similarly to how the extend of a digital image in a photo editing software can be negotiated or the resolution (made out of pixels) of a computer screen does not limit the objects drawn with a B-Rep software, a *Voxel constituent space* is conceived here as an abstract "filled" space that can expand and contract on

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[108] http://en.wikipedia.org/wiki/Voxel on March 24, 2011

[109] Dritsas, Kallipoliti, Tsamis.], *Voxel space –material distributions*. Non-Standrad Praxis conference MIT. (2004)

[110] Alexandros Tsamis, Go Brown, in Ecoredux, Architectural Design Magazine. kallipolti lydia (ed) November 2010

[111] Tsamis, Alexandros, *'Digital Graft. Towards a Non-Homogeneous Materiality'*, MSc Thesis, MIT 2004

demand – increase or decrease resolution on demand. Zooming in an out could theoretically mean increasing or decreasing resolution.

For the development of the *VSpace* software an initial consideration is the design space that exists prior to any design input. Unlike any B-Rep software that starts with the definition of a Cartesian coordinate system, *VSpace* starts with an empty Voxel Space as it is described above. A voxel is basically a space-filling polyhedron. In its most basic form it resembles a cube. Other polyhedra could be used to create a voxel space such as a combination of tetrahedra and octahedra,[112] but for the purposes of this demonstration I will choose cubic Voxels. It is important to note here that in this computer application a predetermined subdivision of space is necessary. Even if we choose a space filling strategy other than the cubic one, and although a voxel space does not impose its overall boundary, it does impose its structure. Similarly to how B-rep software require a Cartesian coordinate system, *VSpace* requires a predetermined voxel space. Although outside the scope of this thesis, ideally, at any step during the design process this subdivision would also be actively designed.[113] For now it will be fixed.

Before the design process begins, the number of Voxels can be conventionally defined in an I,J and K axis independently with an initial value of at least 1 in all three directions. Although the number of units can be changed (increased or decreased) at any moment during the design process and in all 3 axis independently, for the purposes of this demonstration, the empty Voxel space is defined as 60 x 60 x 60 unit space and remains the same for the sake of comparison between examples.

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[112] for a thorough account of space-filling solids please see Wolfram : http://mathworld.wolfram.com/Space-FillingPolyhedron.html

[113] What I am implying here is that I recognize the limits that such decisions impose. The whole investigation that follows works with this constraint. In an ideal world, perhaps not within a digital computer, calculations in a voxel space would allow for the concurrent negotiation of any subdivision. An interesting space feeling strategy has been proposed by Gerorge Stiny. See Stiny, George, *'Ice ray : a note on the generation of Chinese lattice designs',* Environment and Planning B, (1977), volume 4, pp. 89-89.

In short, the characteristics of cubic Voxels in a *Voxel Space* are:

1) Voxels V (i,j,k) have a position defined relative to all other Voxels. We will call this **location in space.**
2) Voxels V (i,j,k) can store a number of Properties. We will call these **Property A,B,C** etc
3) Properties have a value associated with them. This value infinitely ranges from zero to one and will be called **Concentration (CN).** CN indicates how much of property A, B, C etc is contained in a Voxel. For example for Property A that has concentration 0.47654 we will have CNa = 0.47654
4) In the case of 3 properties A, B and C, Voxels are visualized with colors in RGB space. This color visually indicates the concentrations CN of each property. For example a Voxel V (i,j,k) that stores Properties A,B and C will have color (R,G,B) = (CNa*255, CNb*255,CNc*255)[114]

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[114] In computer graphics R,G,B values that compose a digital color on a computer screen range from 0 to 255.

1.5.4 VSpace - Instantiation of Property Distributions

Any B-Rep software allows you to begin by drawing points, lines and surfaces[115] (the geometry primitives) or even more composite primitives like cubes, spheres, donuts, teapots and bunnies. These primitives are "built-in" and although one might have 10 different drawing methods for each, those are predefined and fixed. In VSpace (or P-Rep software) the equivalent to drawing boundaries (points, lines, surfaces) is drawing with properties or better yet **distributing properties**. For the purposes of distribution in this demonstration, three property primitives are chosen A, B and C whose concentration CN ranges from Zero to One[116]. Each Voxel in a *Voxel Space* can store/represent all three property primitives and each of them becomes visual information for further manipulation as they correspond to an R, G and B color value respectively (Figure 12). Simply put, it is like drawing using raster based software in which pixels hold information in RGB color space, only here in 3D. Any change in the value of A, B or C corresponds to a color change in *VSpace*.

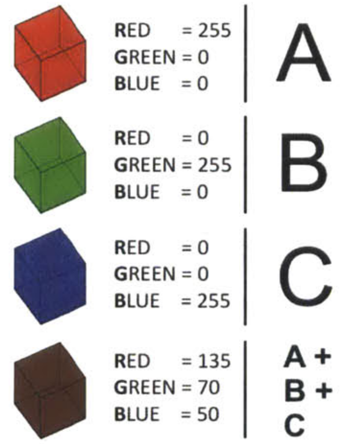

Figure 12 : RGB values stored in voxels

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[115] For a thorough account of digital design primitives see: Mitchell, William J., *'The Logic of Architecture'*, MIT Press, Cambridge Mass (1990), pp. 37-57

[116] 0 and 1 are not boolean states. Instead the value of A,B and C can infinitely vary between 0 and 1 (i.e Ca=0.628) with the maximum decimal precision that a digital computer allows.

In B-Rep software lines are drawn from points, surfaces from lines and solids from surfaces. Therefore, if there is an atomic component in B-rep software that cannot be negotiated that is a Point P(x,y,z) with coordinates in Cartesian space. Everything else defined is based on points. Equivalently in *VSpace* the atomic component that cannot be negotiated is the property i.e. the numeric value that is represented with color in a single Voxel in a Voxel Space. All subsequent operations are based on this atomic primitive.

So far, in *VSpace* three different modes of property instantiation have been developed. All three modes can be used as a starting point or during any subsequent phase in the design process.

Instantiation - Distribution of Painted Properties

Paint (Figure 13)

This first mode of instantiation I call **Distribution of Painted Properties**. Like any B-Rep software that allows us to draw using basic primitives like points and lines in *VSpace* the designer is literally able to paint properties on Voxels using a digital paint brush tool. This is perhaps the most basic of instantiation methods. Using a brush, designers can instantiate Voxel property values one by one. The Voxel Space becomes a canvas on which, in a gestural manner, properties can be assigned in space. This method allows designers to treat the design space in a visual way, drawing patterns in an interactive way. The brush can have opacity and hardness radius as well as have painting filters just like in any photo editing software.

Furthermore, the designer can draw anywhere on the Voxel space canvas or pre-select areas and draw within them. So far an interface has not been developed that allows for painting directly in 3 dimensions, although recent research projects like the *Kinect 3d Finger Painting*[117] developed at the University of Copenhagen point towards this direction. In *VSpace* the designer first selects a Voxel slice in any direction (I, J, K) and then by selecting a color, paints properties in any Voxel within. For simplification purposes painting has been implemented in a 2d version of *VSpace*.

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[117] http://www.kinecthacks.com/kinect-3d-finger-painting/

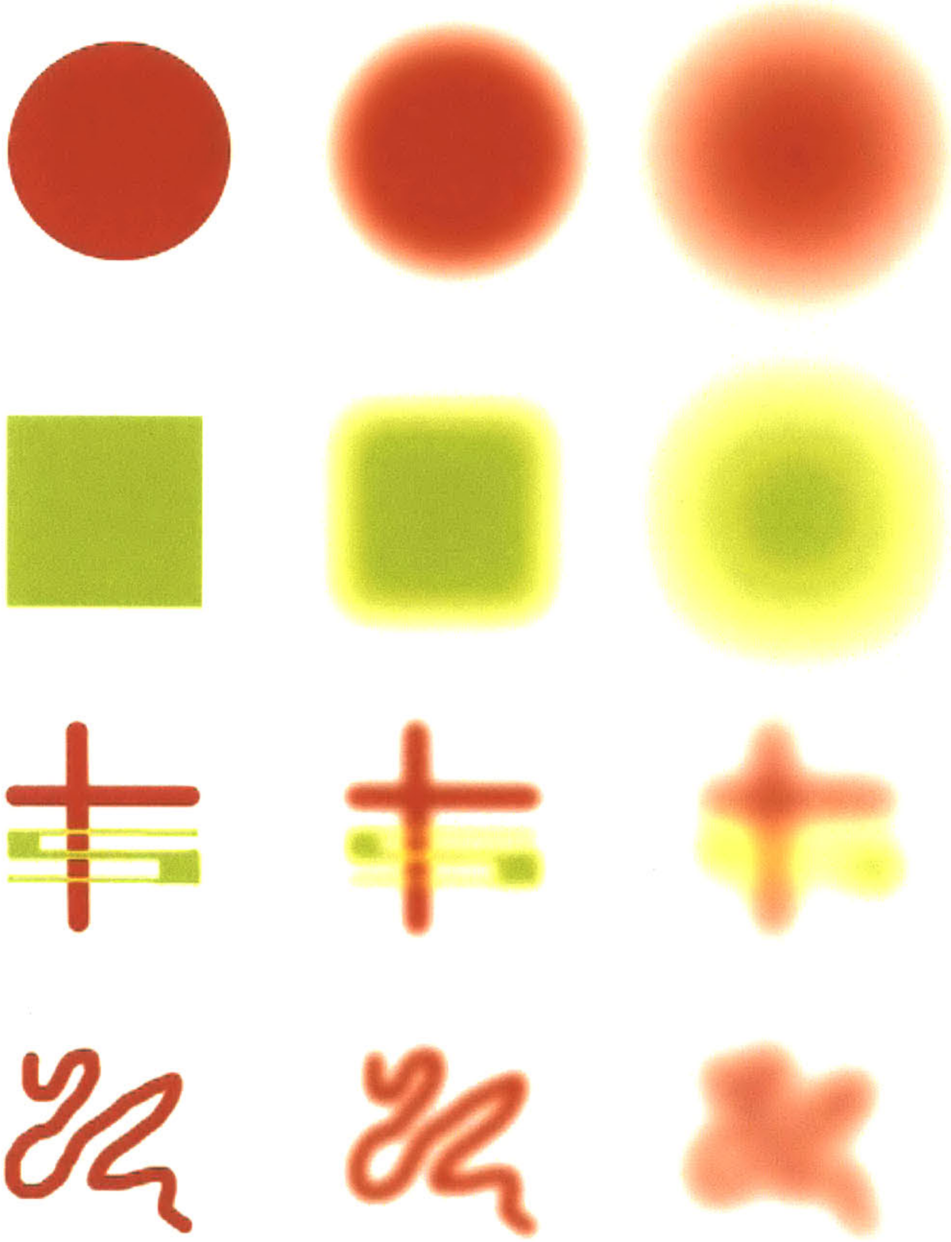

Figure 13: Drawing in VSpace 2D

Property Solids (Figure 13)

A special case of **Distribution of Painted Properties** - a special case of painting - is that in which the designer is given methods to draw predefined Property Solids. For example a solid sphere can be drawn by specifying a Voxel (i, j, k) as a center C, a radius R measured in Voxel units and a color (r, g, b). Similarly, one can draw a solid cube, a solid 3 sided pyramid and all other solid shapes that come prepackaged in any B-rep software. The difference between these shapes and the ones found in B-rep software is that in VSpace solid shapes are not defined only by their boundaries but instead as solids filled with properties. In VSpace the perceived edge of a shape is not defined in a different way than its interior. For simplification purposes drawing solid shapes has been implemented in a 2d version of *VSpace,* in which a sphere is substituted by a disk, a cube by square plane and so forth.

Instantiation - Distribution of Pattern Primitives

The second mode of instantiation I call **distribution of predetermined patterns**. The equivalent to drawing boundary primitives in B-Rep is to **distributing pattern primitives** in VSpace. In a similar manner to B-Rep software that allows you to start by drawing compound solids such as cubes, spheres and bunnies, VSpace allows you to distribute color patterns. The patterns that follow are only examples, they are "built-in" *VSpace* and are as "arbitrary" as the cubes, spheres, teapots and bunnies.

Primitive-Constant Fill (Figure 14)

The simplest form of pattern distribution is that of a homogeneous and isotropic field of properties. In this case, all Voxels in the 60x60x60 Voxel space are filled with a constant concentration/value CN (a, b, c). The dark green color in color space (R=67, G=83, B=44) corresponds to a constant concentration of CNa = 0.26, CNb = 0.32, CNc = 0.17. Although these values can be given as input numerically, what is more important (and will remain important in all subsequent examples) is that these values can be given as input visually, as a color chosen from a color palette by the designer.

Primitive - Slice Fill (Figure 15)

In this general case the Voxel space can be divided in parallel slices in any direction I,J or K with a resolution that is equal or less than the amount of Voxels in that direction. Each slice can get a different value for CNa, CNb and CNc and within each slice the distribution of properties is homogeneous. In Figure 14 the Voxel space is divided in the Y direction in 9 slices. In a pattern of multiples of 3, the Voxels in each slice is filled with either (CNa=1, CNb=0, CNc=0) or (CNa=0, CNb=1, CNc=0) or (CNa=0, CNb=0, CNc=1). Represented in RGB color space these concentrations become (R=255,G=0,B=0) - pure **R**GB red or (R=0,G=255,B=0) - pure R**G**B green or (R=0,G=0,B=255) - pure RG**B** blue respectively.

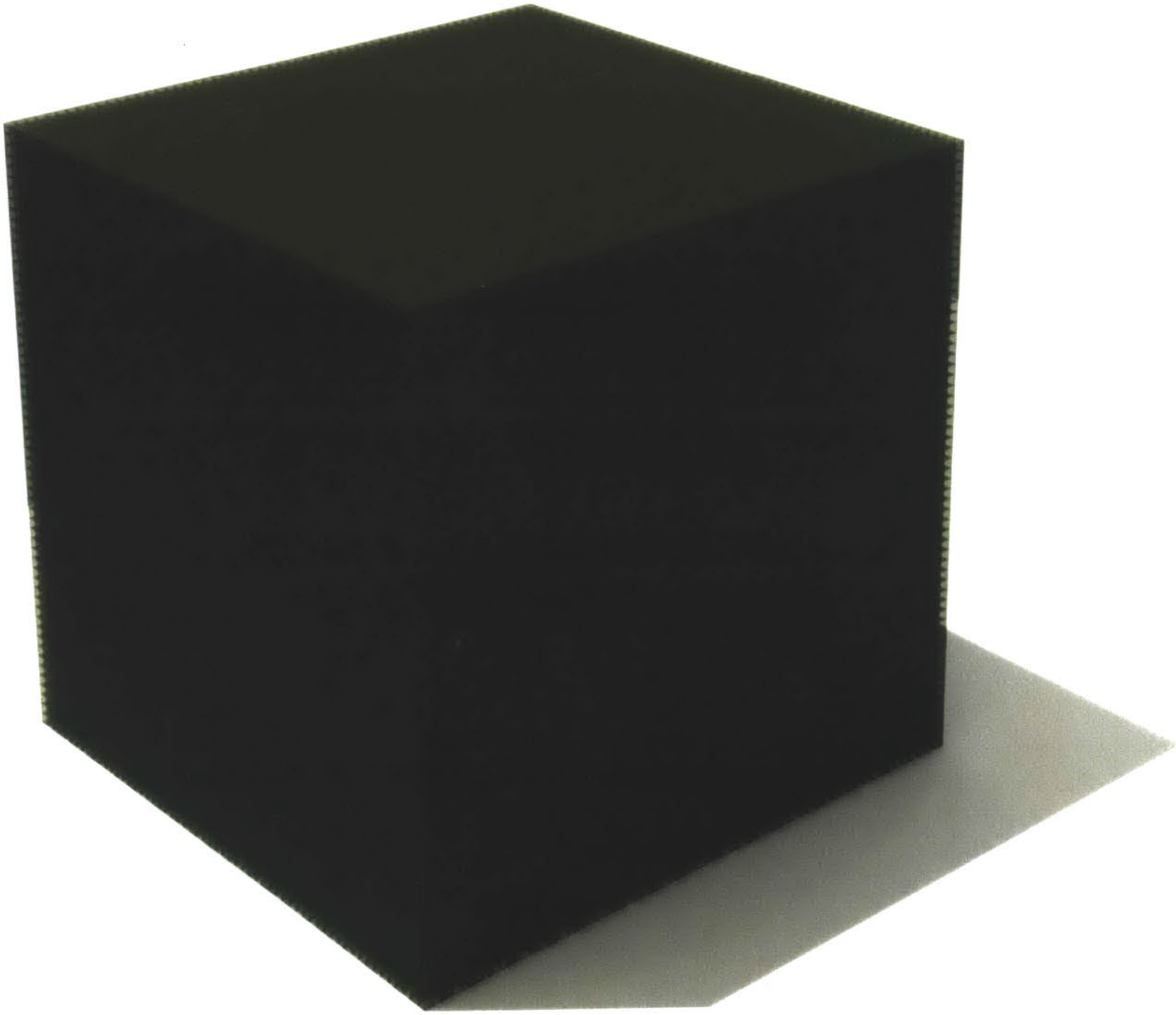

Figure 14: Primitive - Constant Fill. VSpace 3D

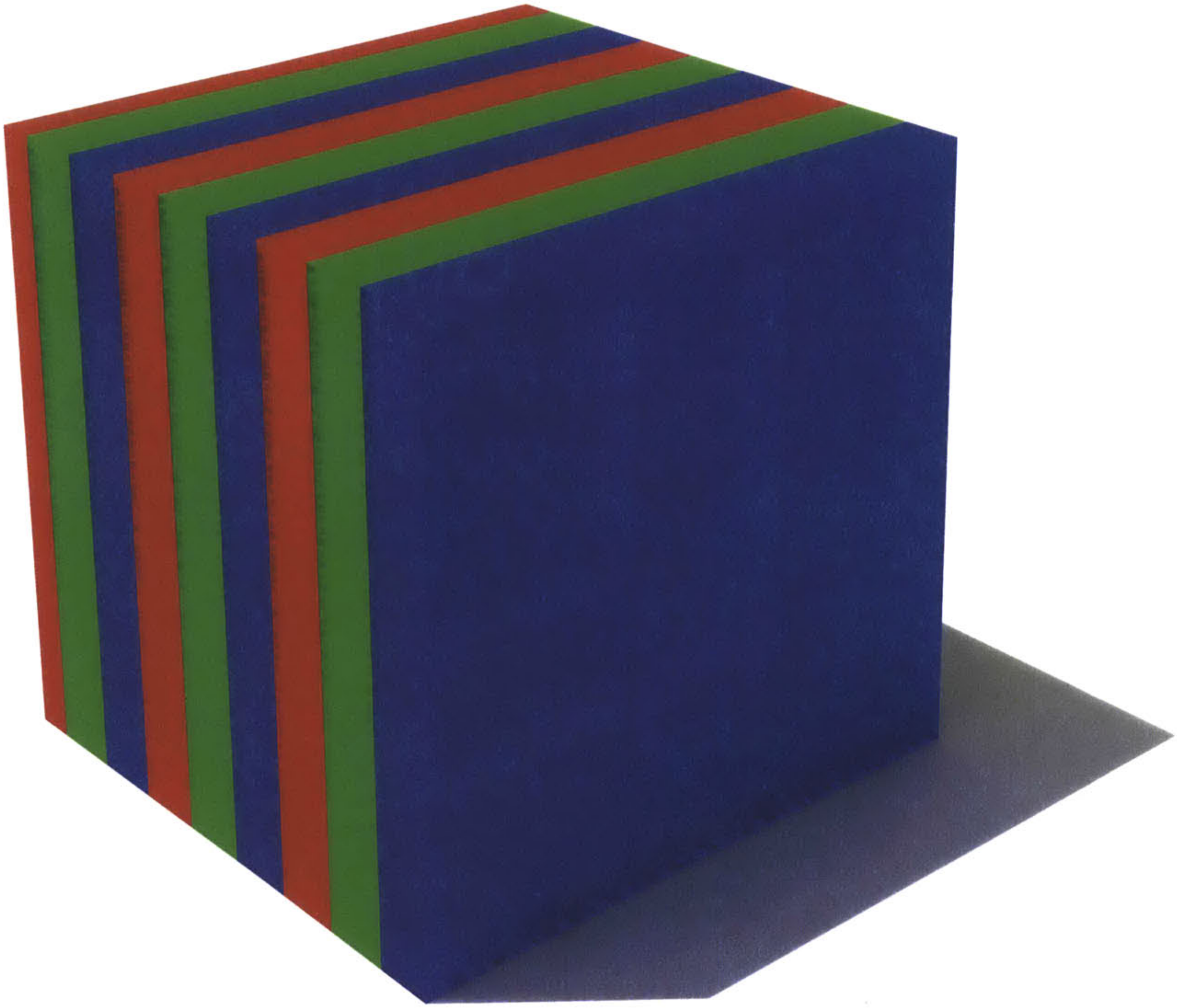

Figure 15 : Primitive - Slice Fill. VSpace 3D

Primitive Grid Fill (Figures 16 - 20)

In this general case the Voxel space can be divided in a grid with a resolution that is equal or less to the amount of Voxels in all directions. Each grid cell can get a different value for CNa, CNb and CNc. In all following cases, within each cell, the distribution of properties is homogeneous.

In Figure 16 the Voxel space is divided in a 3x3x3 grid and in a pattern of multiples of 3, the Voxels in each slice are filled with either (CNa=1, CNb=0, CNc=0) or (CNa=0, CNb=1, CNc=0) or (CNa=0, CNb=0, CNc=1). Represented in RGB color space these concentrations become (R=255,G=0,B=0) - pure **R**GB red or (R=0,G=255,B=0) - pure R**G**B green or (R=0,G=0,B=255) - pure RG**B** blue respectively.

In Figure 17 the same 3x3x3 grid is filled with different concentrations for each cell. The values for each CNa, CNb and CNc concentration, as mentioned before, can be given as input either numerically or visually through a color RGB palette. Within each cell the distribution of properties is homogeneous.

In Figure 18 the same 3x3x3 grid is again filled with different concentrations for each cell. The difference here is that with the way the distribution happens the pattern of the original grid is **visually** lost. Bigger regions of homogeneous color/properties can be drawn by the designer by inputting different colors in different regions.

In Figure 19 the grid cell size becomes equal to the size of the Voxel. Even though the Voxel space resolution can at any point increase or decrease, within the given 60x60x60 Voxel space, the grid subdivision has reached its maximum capacity. In this example each Voxel V(i,j,k) is accessed separately and is assigned a random value for CNa, CNb and CNc. In an algorithmic loop each Voxel gets assigned a value (CNa = rnd (0 ,1), CNb = rnd (0 ,1), CNc = rnd (0 ,1)). Although here the distribution can also be considered "statistically" homogeneous - if you blur your eyes you will see what I mean - this time, compared to Figure 16, the mixture is anisotropic. Since the grid cell coincides here with the Voxel it is redundant to say that within each cell the distribution of properties is homogeneous.

The examples that we have seen so far are all based - one way or another - on the unification of the underlying Voxel space into chunks of homogeneous distribution. Although each example is treated in isolation, there is nothing that prevents the designer from **distributing** multiple of these patterns in a single Voxel space. One could think of grid cells with different resolutions in different regions, with slabs and grids, homogeneous and random distributions combined (Figure 20). Although in almost all cases so far edges are clearly distinguishable, the resulting shapes differ from their equivalent drawn in a B-Rep software. Here, the shapes are represented as solids, as volumes filled with properties. Their edges are not in any way more unique than their interior.

Primitive - Equation Fill (Figures 21, 22)

This case of a predefined distribution links the location of a single Voxel V (i, j, k) with a concentration CN (a, b, c) that it contains. In Figure 21 each Voxel V (i, j, k) gets a concentration according to the following formulas:

CNa = Sin (pos(i)/28) * Pi
CNb = Cos (pos(j)/28) * Pi
CNc = Cos (pos(k)/28) * Pi

For a 60x60x60 Voxel space the pattern corresponds in all three directions to a little bit more than a complete wave function cycle. 60/28 * Pi to be more precise. Similarly in Figure 22 each Voxel V (i, j, k) gets a concentration CN (a,b,c) that satisfies :

CNa = Sin(pos(y)/10) * Pi
CNb = Cos(pos(x)/10) * Pi
CNc = Cos (pos(z)/10) * Pi

For a 60x60x60 Voxel space the pattern corresponds in all three directions to a 6*Pi wave function cycle. These equations are predefined and are "built-in" VSpace. They are chosen arbitrarily. Let us consider those our teapots.

Any isolated chunk of the Voxel constituent space - other than the single Voxel - contains a heterogeneous – in this case **gradient** - distribution of properties. As a more general mode of input, VSpace would allow the designer to distribute properties by expressing mathematical relationships between a Voxel's location in space V(i, j, k) and its concentration CN (a, b, c).

CN (a,b,c)= F V(i,j,k)

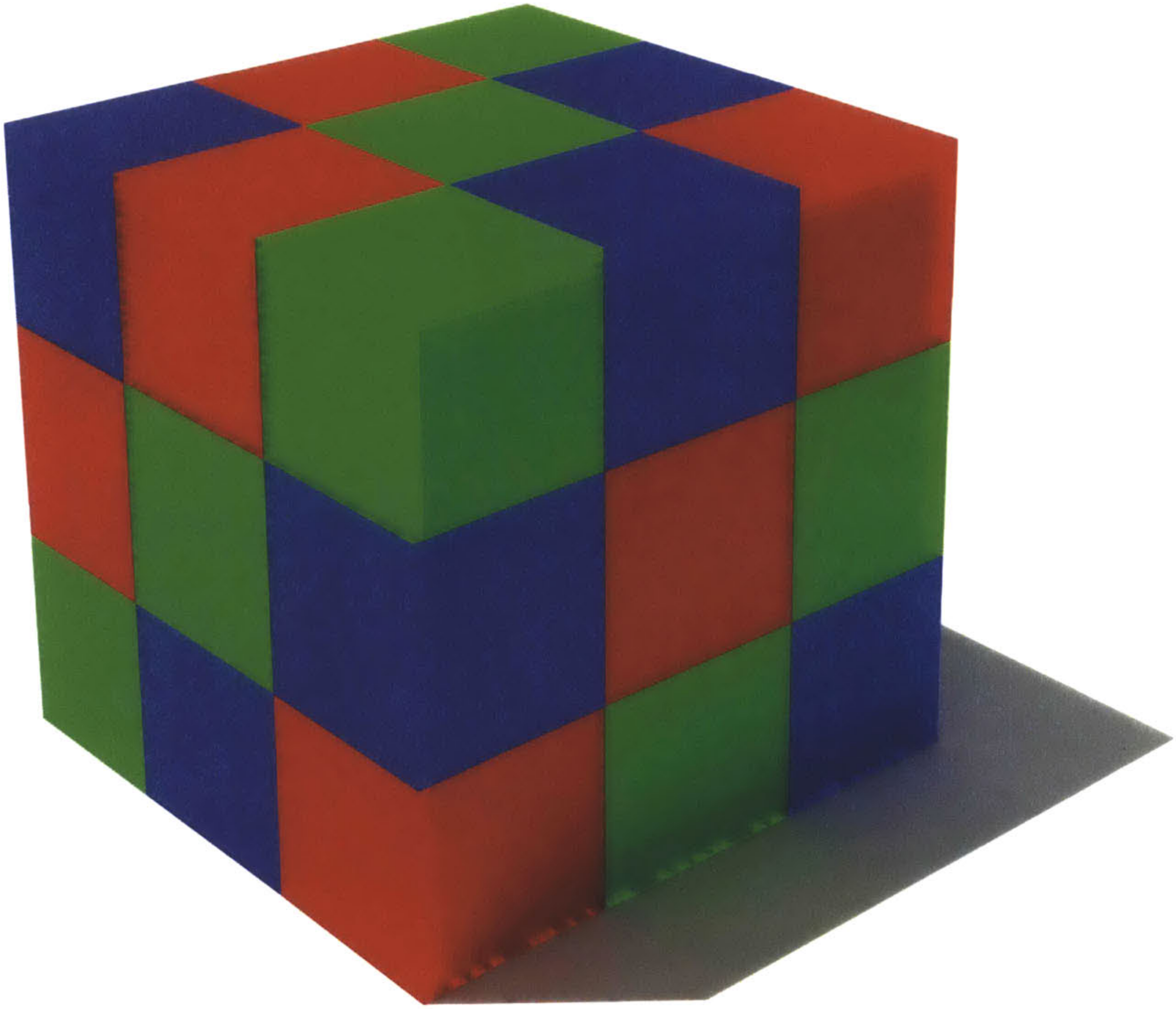

Figure 16: Primitive - Grid Fill 1. VSpace 3D

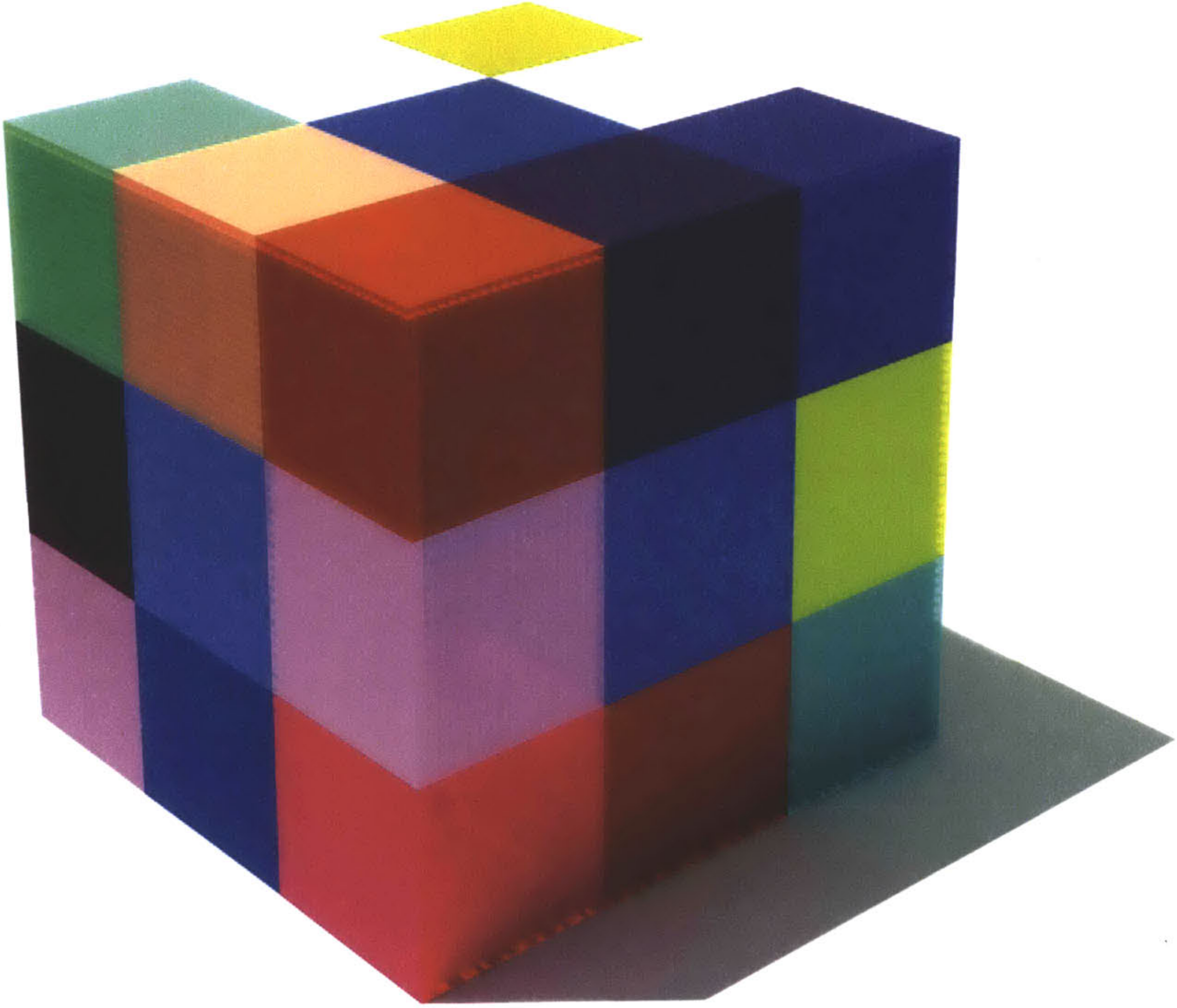

Figure 17: Primitive - Grid Fill 2. VSpace 3D

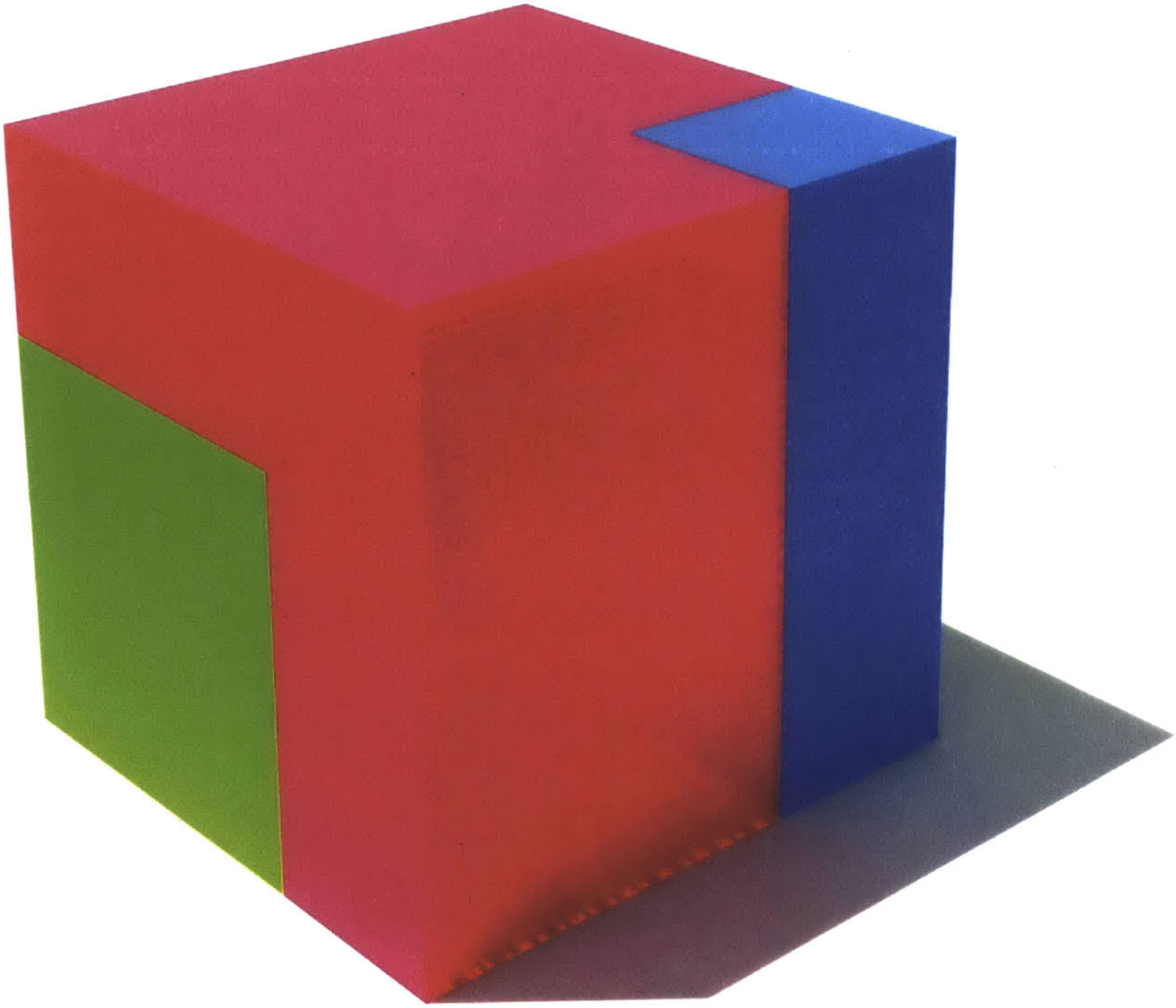

Figure 18: Primitive - Grid Fill 3. VSpace 3D

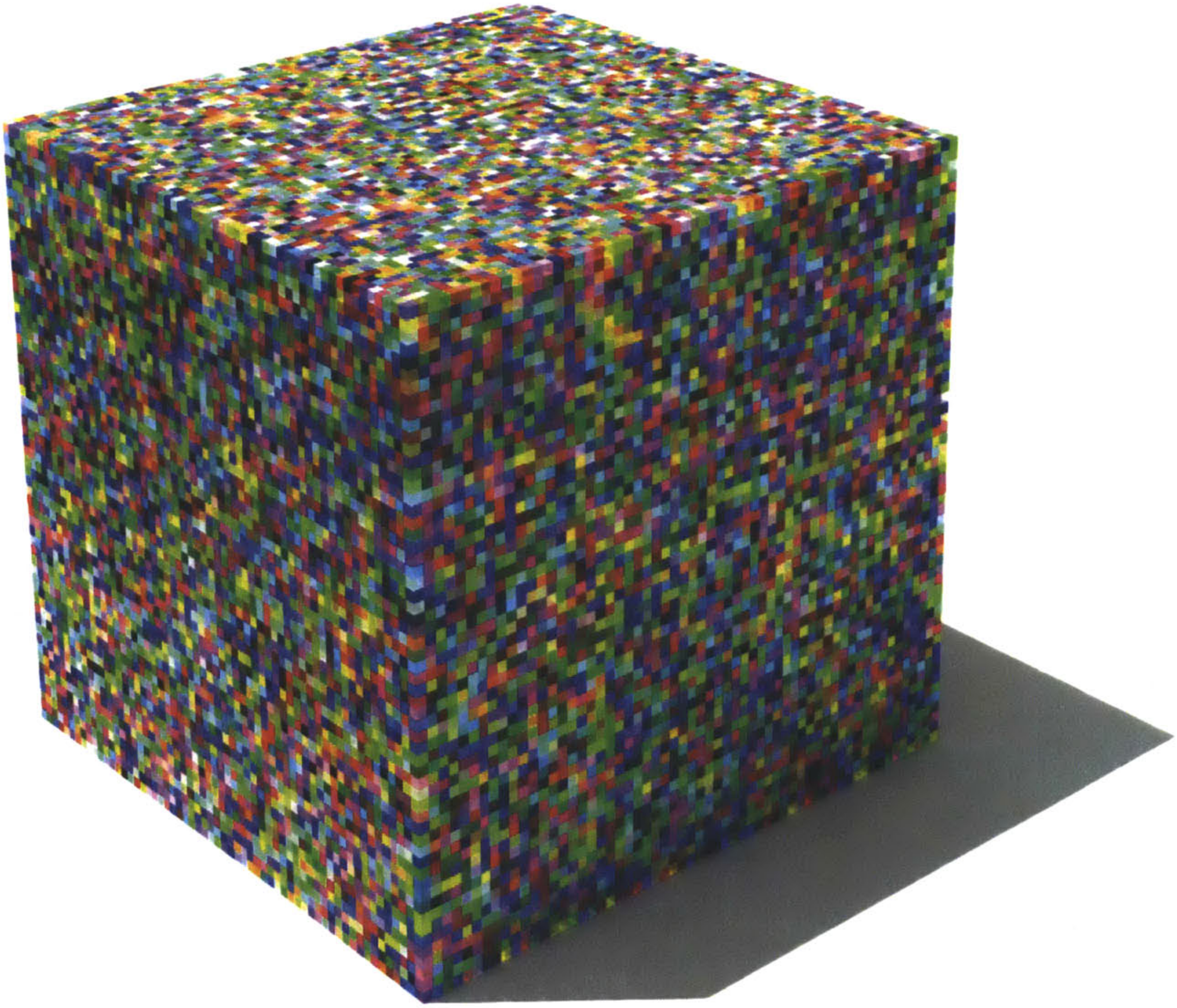

Figure 19 : Primitive - Grid Fill 4. VSpace 3D

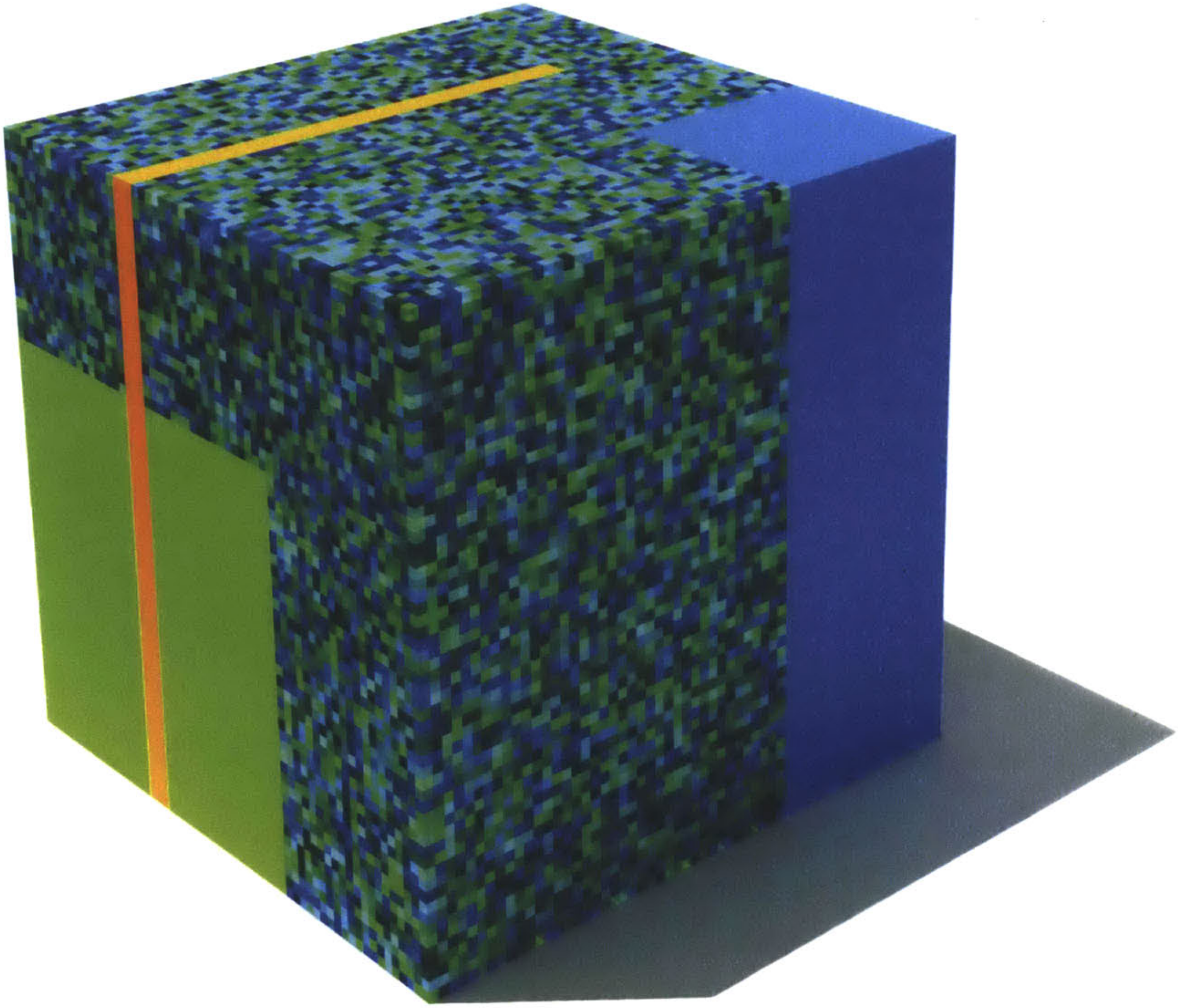

Figure 20: Primitive - Grid Fill 5. VSpace 3D

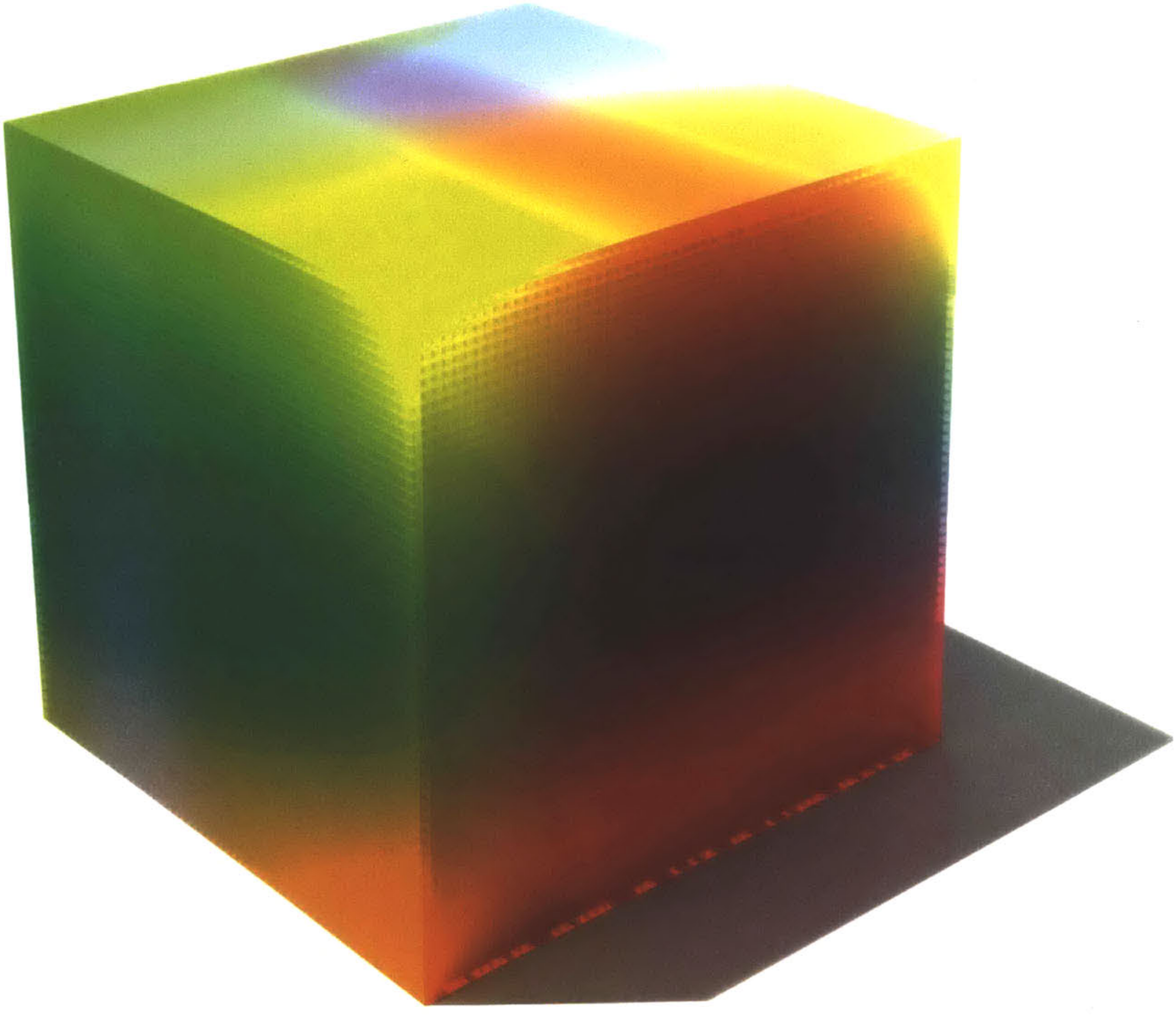

Figure 21: Equation Fill 1. VSpace 3D

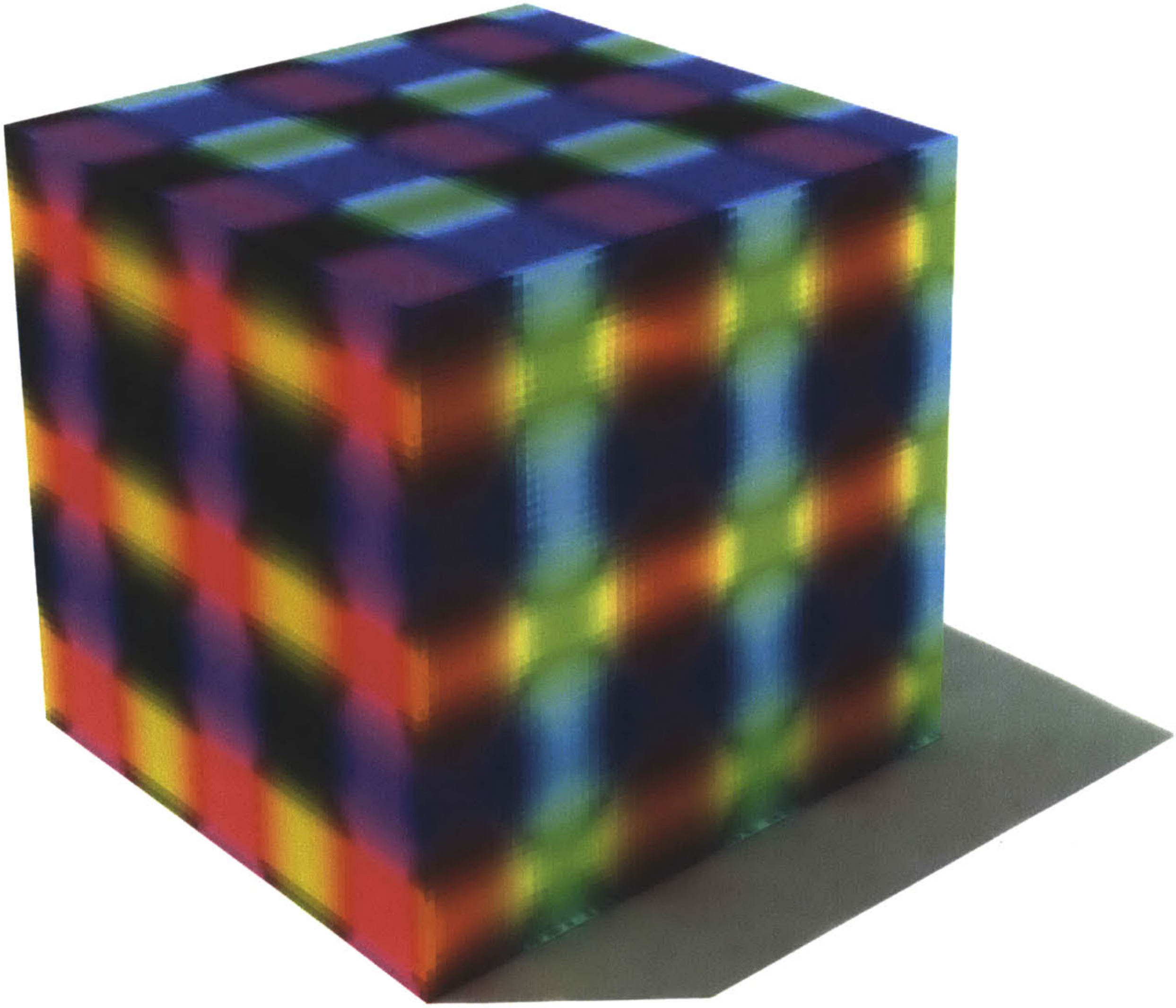

Figure 22: Equation Fill 2. VSpace 3D

Instantiation - Distribution of Interpolated Properties

The third mode of instantiation I call **Distribution of Interpolated Properties**. Like any B-rep software that allows us to construct a three dimensional object by combining lower dimension B-Reps that are first drawn on a plane - for example in plan or section - *VSpace* allows the construction of three dimensional property distributions by first distributing propeties on a single Voxel slice in any X,Y or Z direction. The designer can draw distributions by either directly painting on the slice or by using any set of predetermined patterns on the slice. This operation involves two steps: In the first step, the designer chooses a direction and a single Voxel slice and distributes properties constrained to it and in the second, a **blending** function is implemented that generates a three dimensional distribution by interpolating colors between the sections. If we compare this mode of input in *VSpace* and equivalent modes in B-Rep software, more or less, the **Blend** function in VSpace corresponds to the **Extrude** function for a single curve in B-Rep or to the **Loft** function between curves.

Interpolate - Constant Fill (Figure 23)

The designer first isolates a direction and a Voxel slice and fills each Voxel V (i, j, k) of that plane with a specific concentration CN (a, b, c). In Figure 23 the (Direction, VSlice) = (Z, 0) is filled with concentration CN (0.99, 0.86, 0), the (Direction, VSlice) = (Z, 15) is filled with concentration CN (1, 0.2, 0) and the (Direction, VSlice) = (Z, 60) is filled with concentration CN (0.02, 1, 0.4). As in the examples before, the concentrations can be given as input either numerically or visually through the choice of colors from an RGB color palette. The subsequent blending function, interpolates between those limit concentrations to generate a three dimensional, linear gradient distribution. Any isolated chunk of Voxel space contains a linearly anisotropic distribution of properties. The constant fill can be substituted for any painted distribution.

Interpolate - Bitmap Fill (Figure 24)

The designer first isolates a direction and a VSlice. Unlike the previous case in which a constant concentration is distributed, here a distinct bitmap image is loaded for each VSlice separately. The specific algorithm receives as input a bitmap image, reads and stores its pixel RGB values and then assigns them as concentrations CN (a, b, c) on all Voxels V (i, j, k) of a VSlice respectively. In Figure 23 the (Direction, VSlice) = (J, 0) is filled with Bitmap 01 and (Direction,VSlice) = (J, 60) is filled with Bitmap 02. The subsequent blending function, interpolates between those limit concentrations to generate a three dimensional, linear gradient distribution. Any isolated chunk of the Voxel Space contains an anisotropic distribution of properties.

The particular images used in this example are heat scans. Using a heat photo capturing device, images are taken that depict the existing heat gradients of a specific context. It would be easy to extend this logic using other devices that would, for example, capture light intensities or humidity distributions. In other words, this instantiation method can also be thought of as a process of "environmental" reconstruction in which a 3 dimensional space of information is reproduced in a Voxel space[118]. Unlike in B-Rep software in which environments are created by using simulations based on the interactions of objects (see Autodesk - Ecotect Analysis 2010), the process described here, accepts an aspect of the environment with its local intricacies without attempting to rationalize it. It absorbs complexity as such; it does not a priori determine the reasons behind its formation. As a result, abstraction does not come at the stage of collecting information from the environment; rather, it comes later, in the process of interpreting that information. In this sense, this instantiation method gathers information in a 'raw' form or as 'raw' material and makes it readily available for further manipulation and allocation. Consequently, the "rationalization" of environmental information happens during the design process and not before hand.

So far we have seen 3 distinct methods of instantiating properties in a Voxel space. As in any B-Rep software in which the basic form of instantiation is that of a point P with coordinates (x, y, z), the basic form of instantiation in VSpace is that of assigning Concentrations CN (a, b, c) on a single Voxel V (i, j, k). All subsequent methods or instantiations, although intuitively distinct between them, are compound-composite versions of this primary one.

- With **Distribution of Painted Properties** Voxels are instantiated locally through a gestural painting procedure or through a "pre-packaged" solid shape drawing method.
- With **Distribution of Pattern Primitives** any collection of Voxels is instantiated using a pattern that relates the relative position of each Voxel V(i,j,k) with a concentration CN (a,b,c).
- With **Distribution of Interpolated Properties** one or more regions/slices of Voxels are first instantiated either by painting or by importing "environmental" information and are then interpolated to create a 3dimensional distribution.

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[118] This inquiry started during my Master's Thesis. see Tsamis, Alexandros, *'Digital Graft. Towards a Non-Homogeneous Materiality'*, MSc Thesis, MIT 2004.

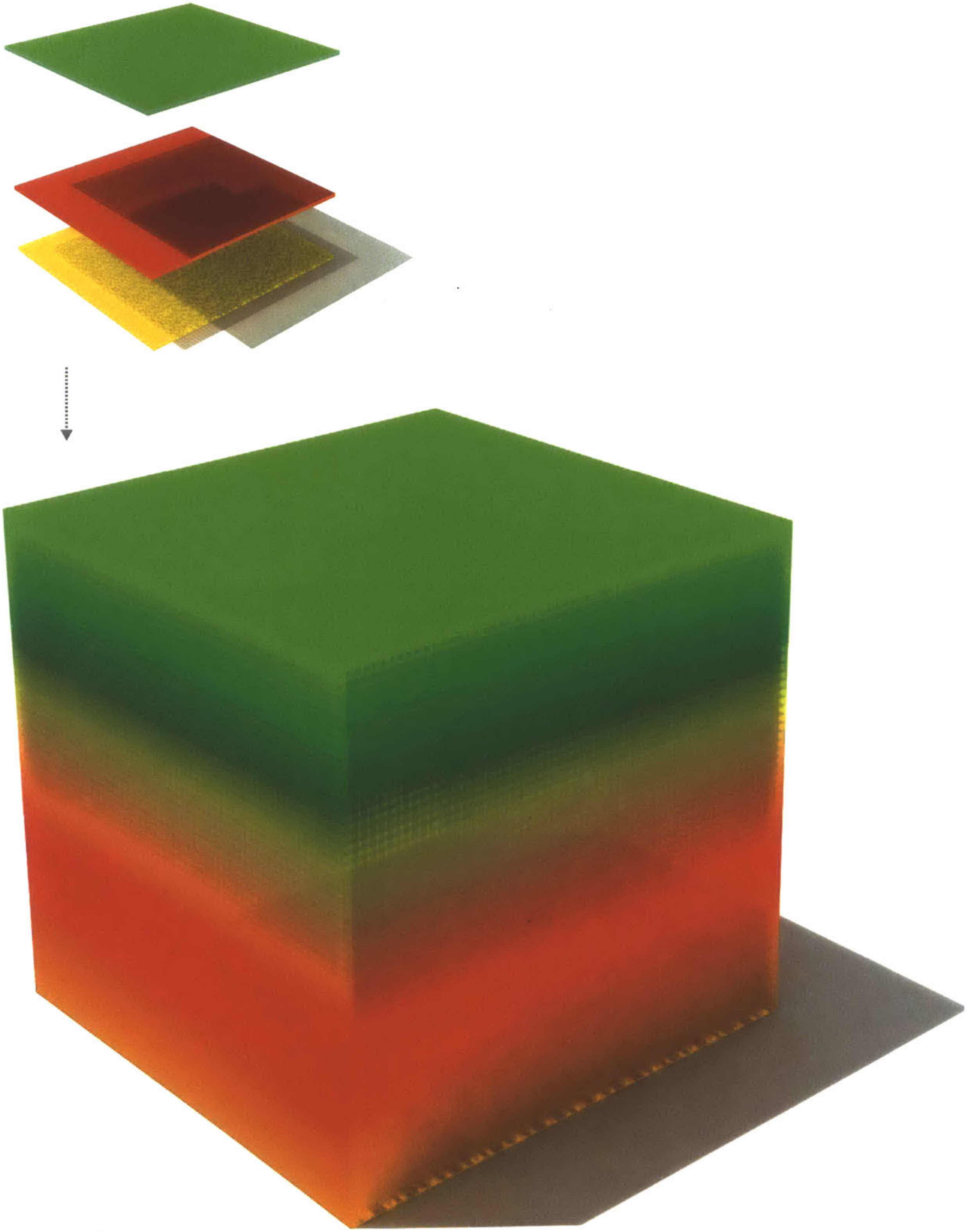

Figure 23: Interpolation Constant Fill. VSpace 3D

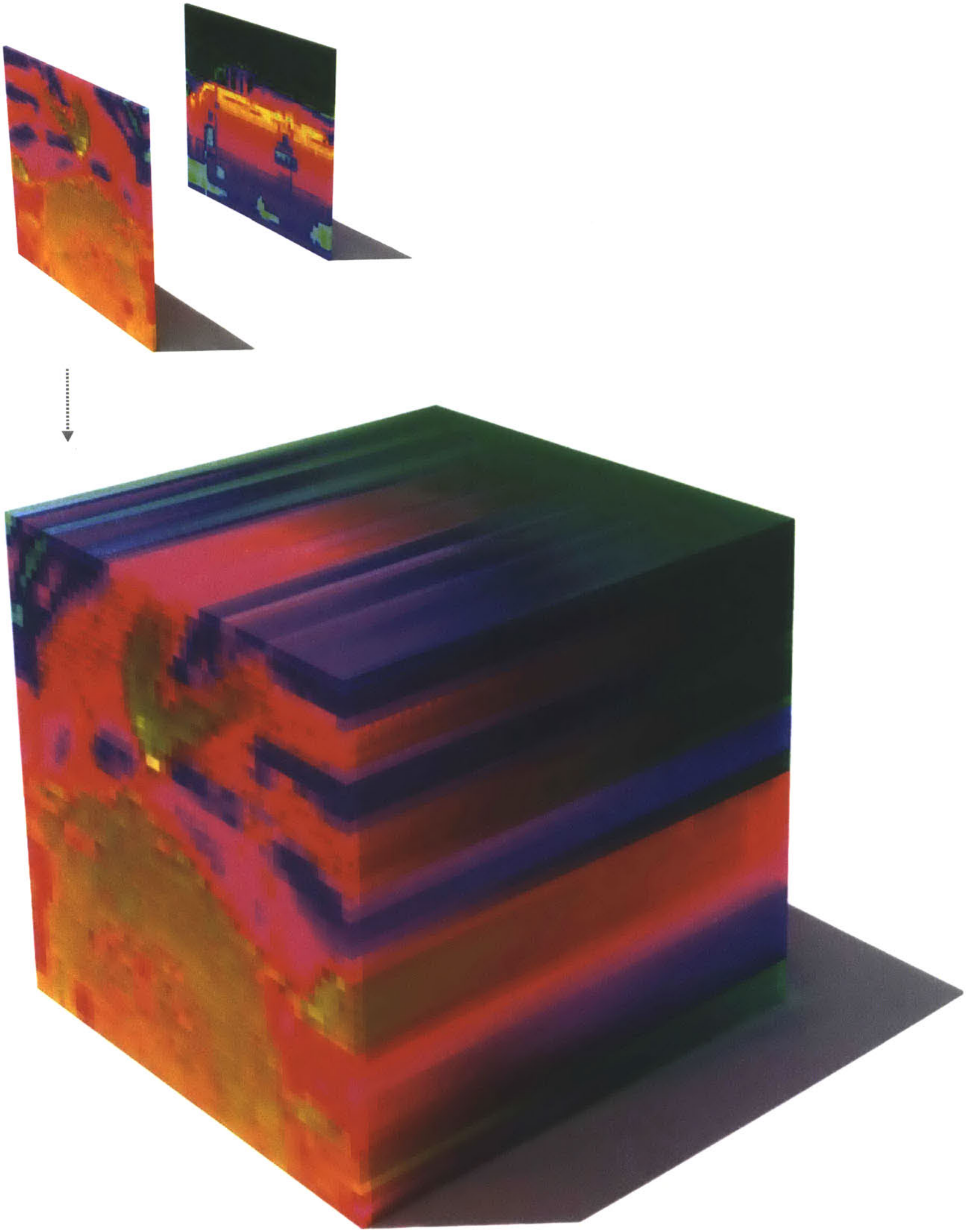

Figure 24: Interpolation Bitmap Fill. VSpace 3D

1.5.5 VSpace Transformation - Unary Property Transformation

In VSpace, following the instantiation of properties, the designer is allowed to perform operations that transform initial properties to new properties. Unary property transformations refer to transformations that occur on a single Property/Concentration. In B-Rep software, operations such as Translation, Rotation and Scaling are a few of the possible unary operations that transform a single boundary object to its new state. As William Mitchell puts it, for a given shape and a transformation operation we have:

Operation (shape 1) = shape 2

He goes on to explain that some transformations such as Translation or Uniform Scaling maintain the characteristics of the original shape while others, like unequal scaling or shearing can disrupt them.[119] In the case of VSpace two distinct methods of unary transformations have been implemented.

Unary Transformation - Paint_(Figure 25)

Painting with a brush cannot only be used to instantiate properties but also to transform them to new properties. Like in any bitmap editing software, by using a digital paint brush, the designer can access existing Voxel concentrations and paint new ones on top. As mentioned before the brush can have a color selected from a color palette, a size, affecting one or more Voxels at a time and an opacity that can add or subtract concentration values. For example, a given Voxel V (i, j, k) with existing concentration CN (a, b, c) and a brush with color R, G, B and opacity at K %, the new concentration CN (a_new, b_new, c_new) of Voxel V (i, j, k) is given by the formulas :

$$\mathbf{CNa\_new = Ca + R/255 * (K/100)} \quad \text{with } 0 < CNa\_new < 1$$
$$\mathbf{CNb\_new = Cb + G/255 * (K/100)} \quad \text{with } 0 < CNb\_new < 1$$
$$\mathbf{CNc\_nnew = Cc + B/255 * (K/100)} \quad \text{with } 0 < CNc\_new < 1$$

In the case that all 3 concentrations of a given Voxel scale up or down with equal values (visually that would mean that we get a darker or lighter shade of the same color), we have a uniform transformation, while in the case that the 3 concentrations scale up or down unequally (visually that would mean that we get a different color), we have a non uniform transformation.

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[119] Mitchell, William J., *'The Logic of Architecture'*, MIT Press, Cambridge Mass (1990), pp. 112-122

Unary Transformation - Automata

The 3 dimensional - ordered array - data structure of the *Voxel Constituent Space* allows designers to not only transform Concentration values directly on a Voxel but also gain computational access to concentrations of all of its neighboring Voxels. Therefore, in *VSpace,* in a Voxel space that is already propagated with Concentrations, the designer can describe rules of interaction between Voxels in a neighborhood in order to transform them to new ones. The discrete dynamical model that describes computations between cells and their neighbors generally falls under the umbrella of Cellular Automata.

One of their principal characteristics is that they can reproduce the behavior of a complex system using simple basic interaction rules. Like in the case of weather, Cellular automata constitute an ideal Computational platform for the reproduction of "environmental" phenomena.

Von Neumann began the study of his theory of automata at the same time that work began on his electronic computer project.[120] He "did not explicitly define 'automata,' but from his usage we can infer its application to any system that processes information as part of a self-regulating mechanism."[121] In 1970, cellular automata were widely introduced to the world through John Conway's "Game of Life." Within a two-dimensional grid, cells, through explicit rules of interaction, changed state, indicated by a change in color, and the computation behind automata was made visible.[122]

Among other things, Cellular Automata find practical application with the description of emergent phenomena, modeling biological formations and the reproduction of natural and artificial complex phenomena[123]. Before going into the technical characteristics of this Unary Property Transformation operation in VSpace, it is important to highlight the way it is understood and implemented here as a modality for design. While for some designers it could prove useful to be able to use "proven" interaction formulas to calculate or simulate anything from heat dissipation to urban sprawl, it is one of Stephen Wolframs observations that allows me to consider Cellular automata as a valid design operant.

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[120] Aspray, William, *'John Von Neumann and the Origins of Modern Computing'*, MIT Press, Cambridge Mass (1990), p. 189.

[121] Ibid.

[122] Rocker, Ingeborg M, *'When Code Matters'*, in Architectural Design (AD), vol. 76, issue 4, John Wiley & Sons Limited, London (10 Aug 2006), p. 21.

[123] For a thorough account of Cellular Automata their structure and applications see : Casti, John L. *'Alternate Realities: Mathematical Models of Nature and Man'*, Wiley, New York (1989).

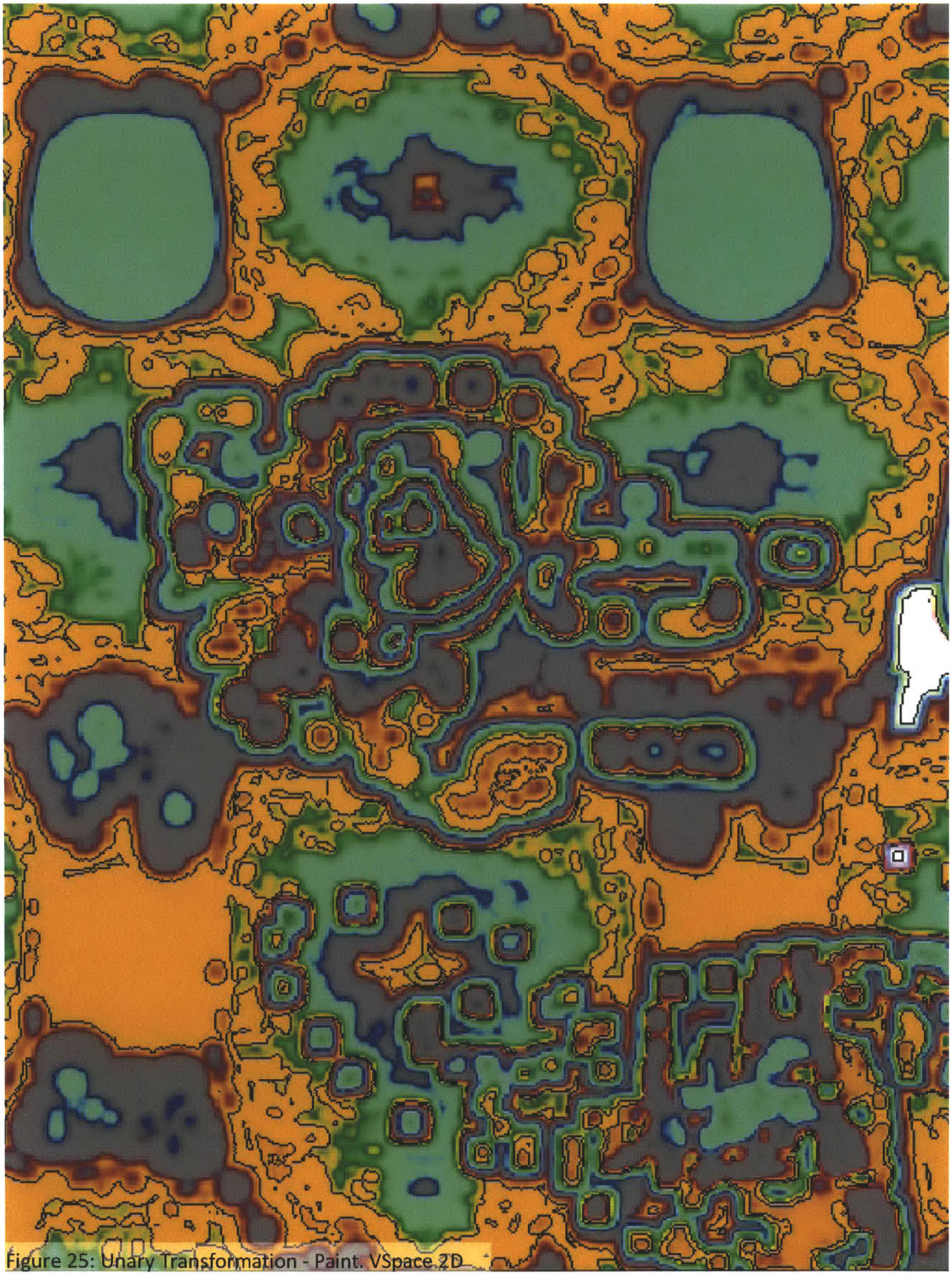

Figure 25: Unary Transformation - Paint. VSpace 2D

The fact that Wolfram's famous rule 30 produces a pattern that never repeats[124] is great but in my opinion of no particular significance to design practice. On the other hand, that fact that he verifies this, initially, through visual inspection is. In other words in this "New Kind of Science" he focuses our attention not on the validity or predictability of the rules themselves but instead on the ability we have to observe and therefore embed from outside a new rational.[125] This observation alone puts his work closer to design than any other scientific explanation of cellular automata.

The significance for VSpace, from a design standpoint, is that in dynamic systems like these an emergent distribution of properties becomes visual material, which is then examined for its characteristics. Furthermore, the model produced can be modified through painting or other transformation methods, cut in many different ways, while still maintaining a definition of constantly varying property.

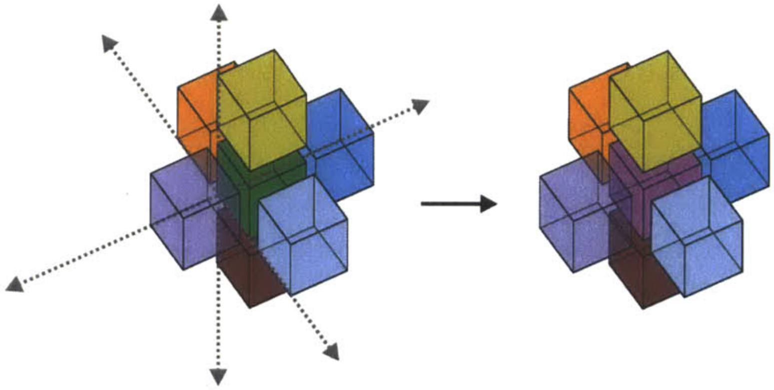

Figure 26: State change in a single step based on neighborhood concentration

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[124] Wolfram, Stephen, *'A New Kind of Science'*, Wolfram Media Inc., Champaign IL (2002), p. 27.

[125] This observation and critique of Wolfram's work was developed in a discussion with George Stiny

VSpace would ultimately allow the designer to describe any set of rules for interaction between the concentrations of Voxels in a neighborhood.[126] In the example demonstrated here the new concentration of each Voxel is evaluated based on the concentration of its neighbors (Figure 26). For a given Voxel V(i,j,k) with concentration C(a,b,c) and an average concentration of its neighbors C(a_n, b_n, c_n) the new concentrations are given by the formulas :

$$\mathbf{CNa\_new = Ca + K * (CNb\_n - CNc\_n)}\ \text{with}\quad 0 < \text{CNa\_new} < 1$$
$$\mathbf{CNb\_new = Cb + K * (CNc\_n - CNa\_n)}\ \text{with}\quad 0 < \text{CNb\_new} < 1$$
$$\mathbf{CNc\_new = Cc + K * (CNa\_n - CNb\_n)}\ \text{with}\quad 0 < \text{CNb\_new} < 1$$

K is a constant factor that determines the rate of diffusion of properties between states. When K becomes zero the concentrations for each Voxel remain unaltered (CN_new = CN) while as K increases the diffusion rate increases. From an intuitive perspective the smaller the K value is the slower the reaction-diffusion progresses and the more the colors blend. In VSpace, the K constant which controls the speed of the reaction, can be dynamically changed while the calculation runs.

The rules of interaction for this demonstration where not chosen by accident. They constitute an idealized Belouzov - Zabodinsky type reaction which was first implemented in a 2d cellular automaton by Greenberg and Hastings in 1978[127]. Starting with a random distribution of concentrations, the figures that follow (Figures 27 - 34), show an evolution of this reaction diffusion phenomenon over 16 iterations with the K value set to 1. Just as Alan Turing predicted, as properties interact with each other, gradient fields start to form and eventually three dimensional figurations emerge.

For visualization purposes an extra constraint is implemented. Voxels that contain concentration CNa > 0.35 are "trimmed". The white areas that appear as voids are simply the areas that would be occupied by Voxels with CNa > 0.35. Just like in any B-rep software one can trim a boundary object - let's say a line segment with a point along its length, in VSpace the designer can set a limit or limits for any single property between zero and one and trim it at a specific Value. In VSpace this value can be dynamically set (with a slider) for any property A, B or C at any time during the design process.

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[126] Neighborhoods are 3dimesional versions of either the Von Neumann neighborhood (6 Voxels) or the Moore neighborhood (27 Voxels)

[127] Ilachinski, Andrew, *'Cellular Automata: a Discrete Universe'*, World Scientific Publishing Company, Singapore (2001), p. 420.

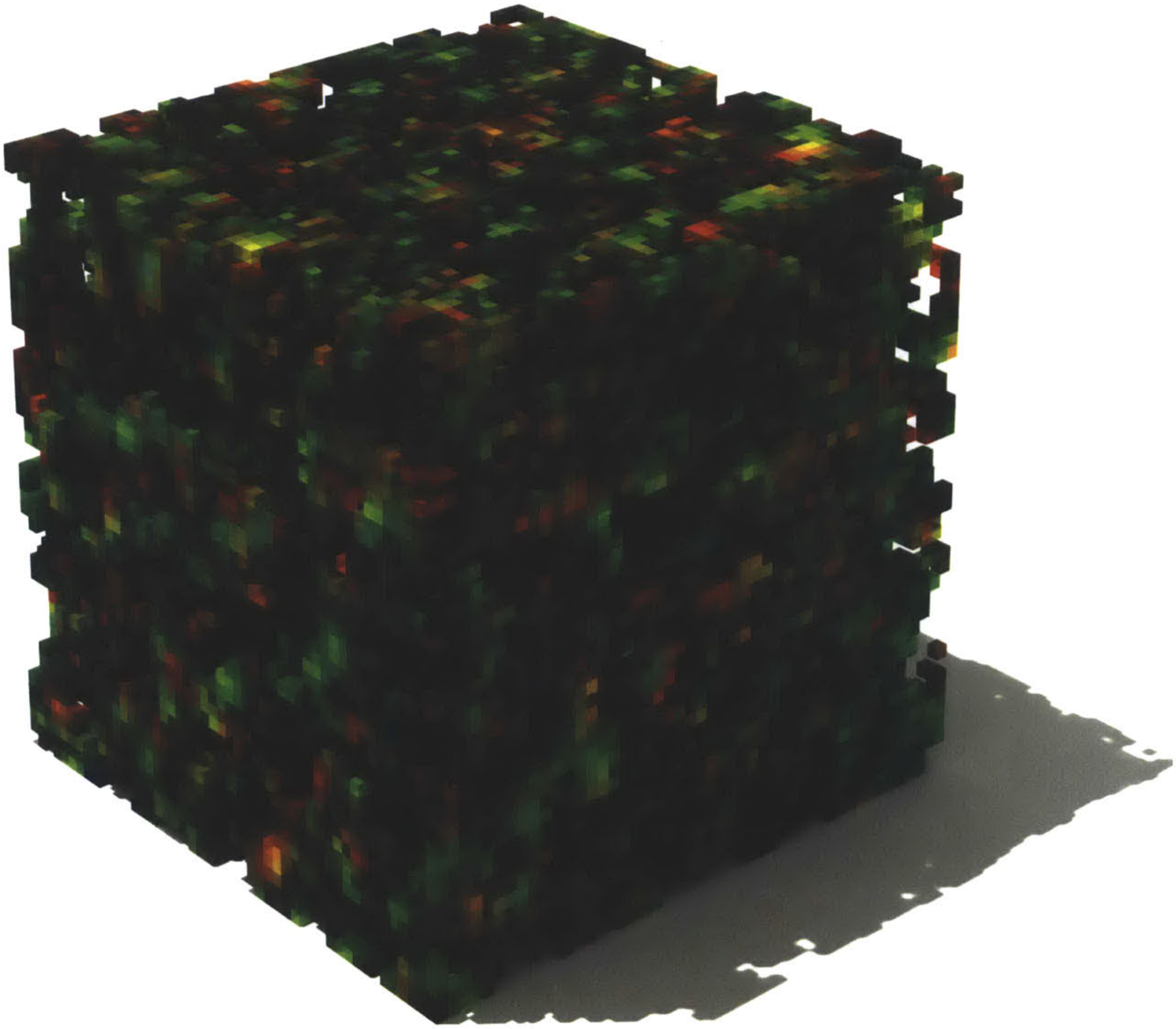

Figure 27: Unary Transformation - Automata Step 01. VSpace 3D

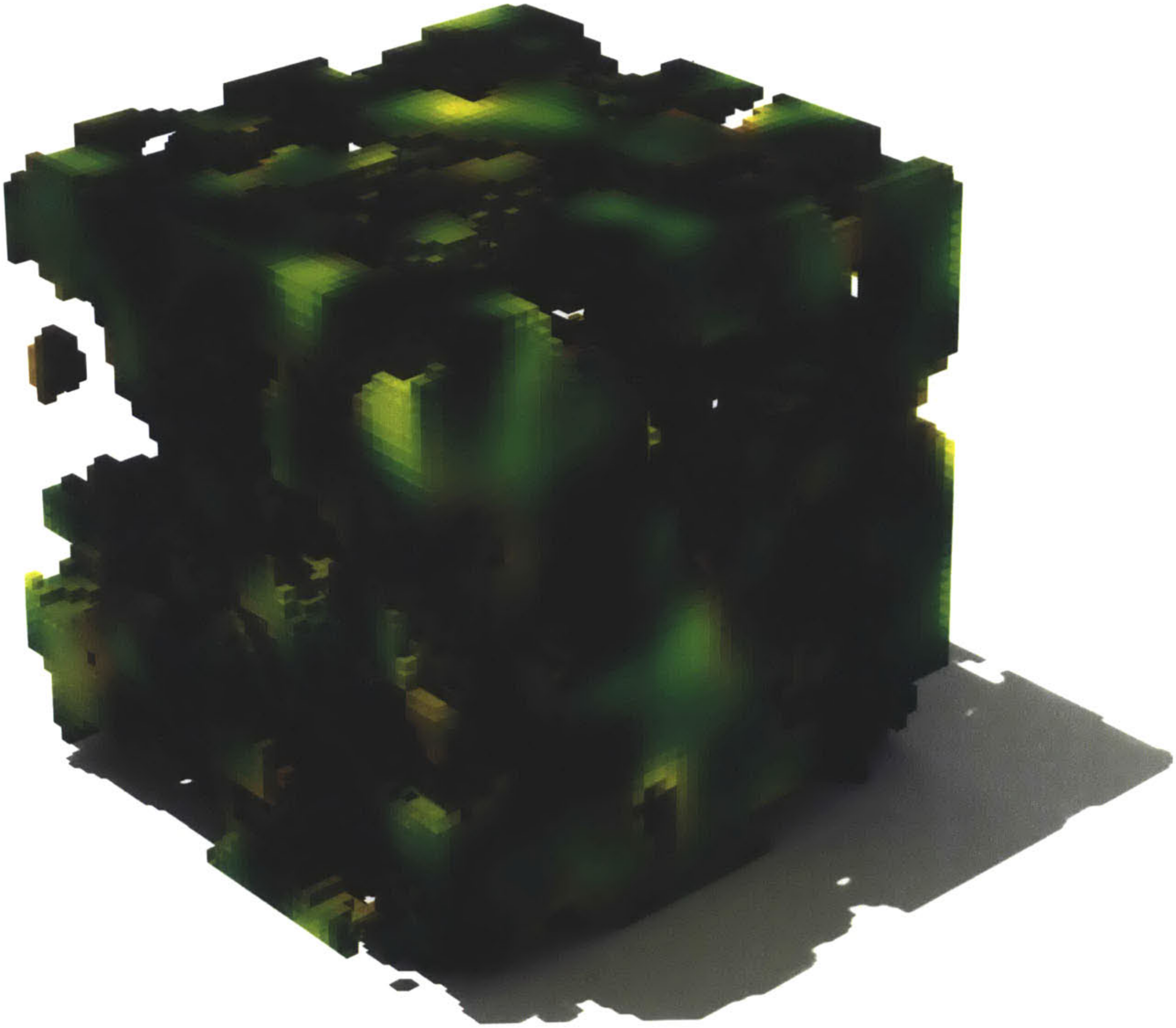

Figure 28: Unary Transformation - Automata Step 04. VSpace 3D

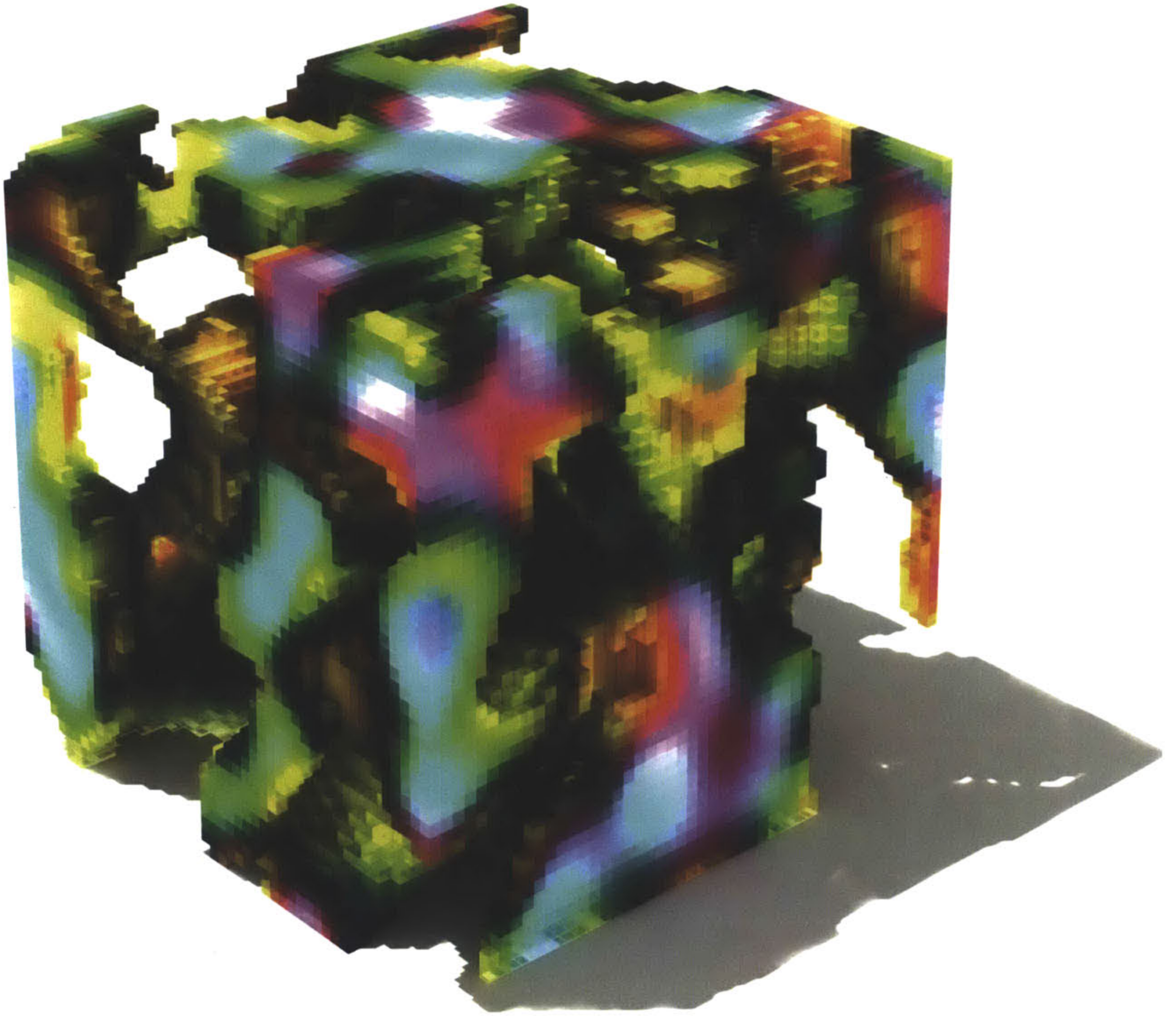

Figure 29: Unary Transformation - Automata Step 08. VSpace 3D

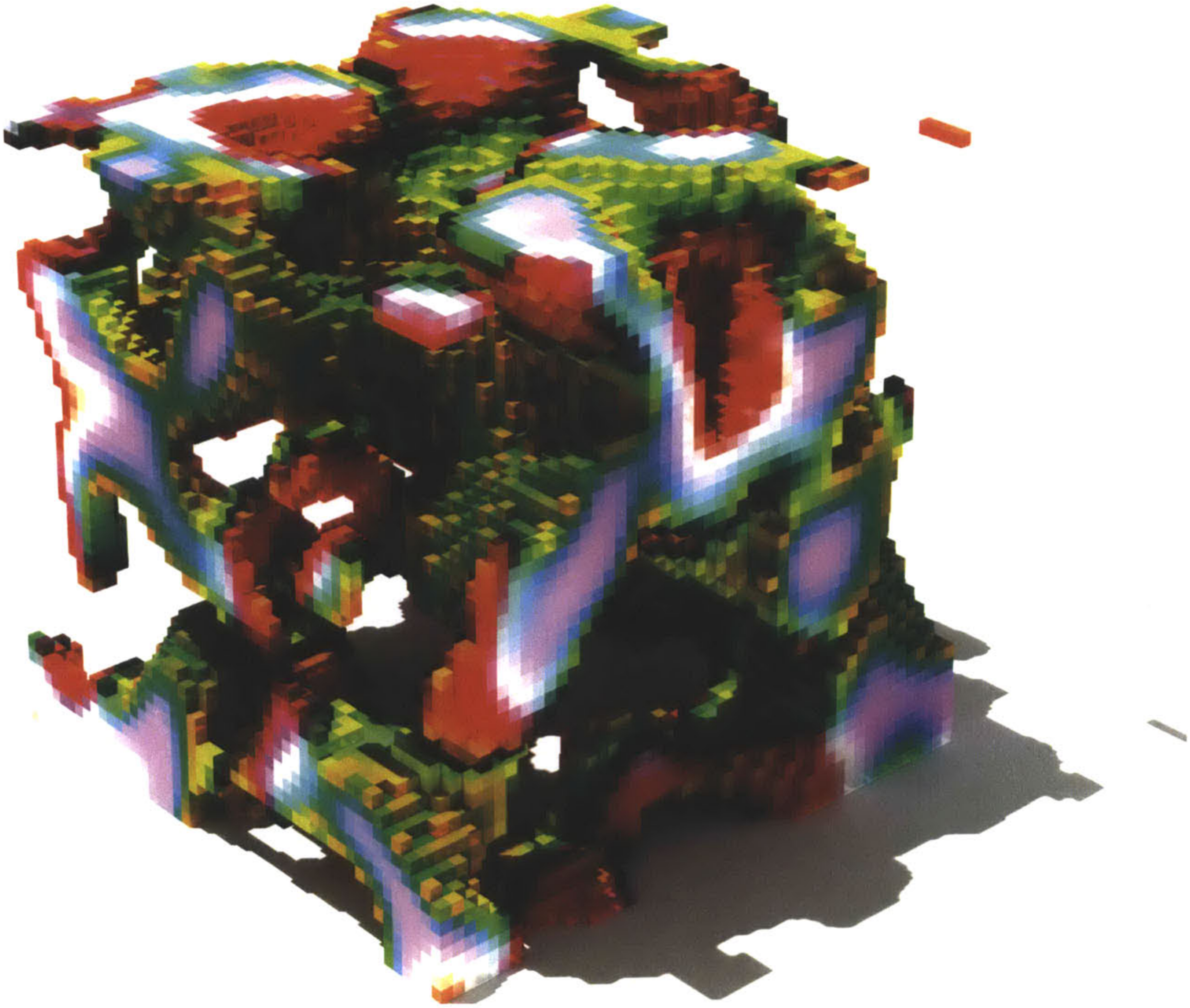

Figure 30: Unary Transformation - Automata Step 12. VSpace 3D

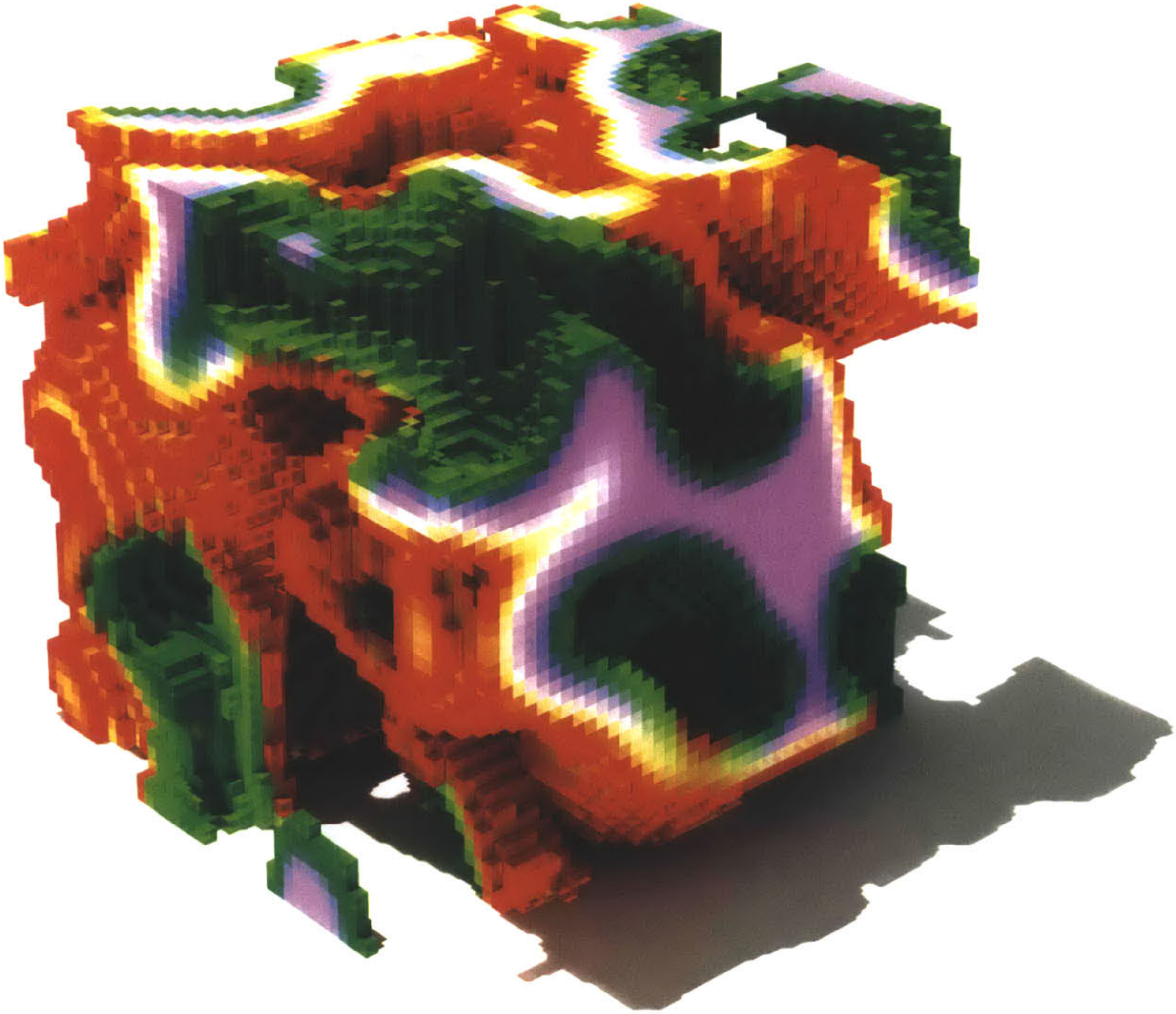

Figure 31: Unary Transformation - Automata Step 16. VSpace 3D

Figure 32: Unary Transformation - Automata Step 20. VSpace 3D

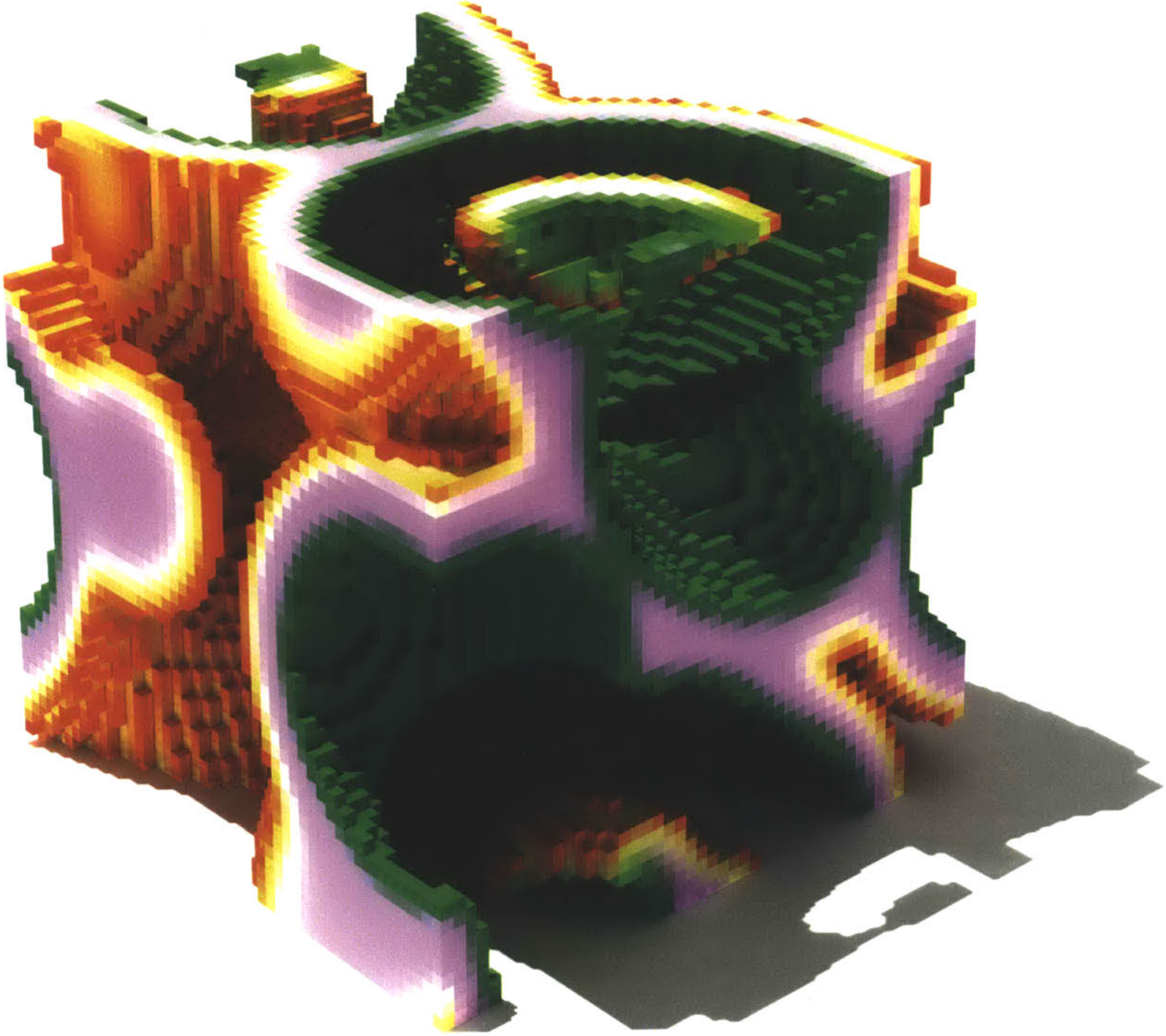

Figure 33: Unary Transformation - Automata Step 24. VSpace 3D

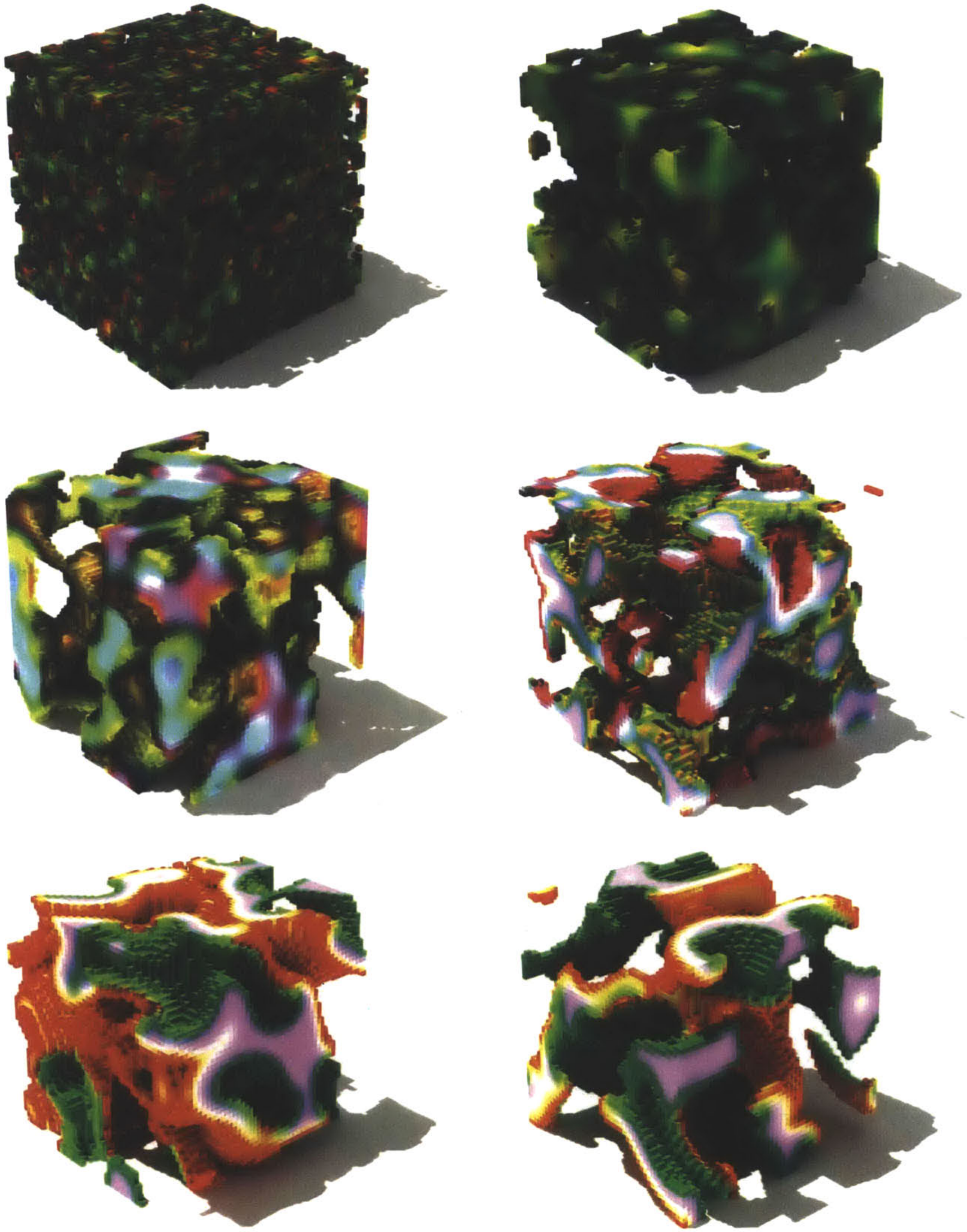

Figure 34: Unary Transformation - Automata Sequence. VSpace 3D

1.5.6 Vspace Transformation - Binary Property Transformation

In VSpace a designer can also perform operations that combine two or more properties together to derive new properties. In the examples we are using here, since all three properties A,B or C can occupy with a range of values the same Voxel in a Voxel space, one can perform Binary operations that derive new properties from their combination. In B-rep software these operations, also known as Boolean operations, determine whether or not a shape or part of is a sub-shape of another and derive new shapes from their combination[128]. But what is a shape in the case of P-Rep software?

So far, we have seen **Property Distributions** and how any given property in a *Voxel space*, in its most general definition, can have concentrations CN (represented by color) which range for 0 to 1. **A PROPERTY SHAPE (PS) is any sub set of a given Property Distribution that is defined by an upper and a lower concentration limit.** For example a Property Shape PS(Property, Lower Limit, Upper Limit) of Property Distribution A could be PSa (A, 0 , 0.46). This property shape consists of all Voxels in a Voxel space that satisfy $0 < Ca < 0.46$. Property shapes can include the empty shape when the Upper Limit is equal to the Lower Limit, for example PSa (A, 0.36, 0.36) as well as the "Full" shape when The Lower limit = 0 and the upper Limit = 1. In the case of PSa(A,0,1) the Property Shape coincides with the Property Distribution (Figure 35).

Property shapes, eco Lionel Marchs' sets in that they too are derived as subsets of a voxel grid using boolean algebras. In the case of this 60x60x60 the total amount of possible sub sets are $2^{216,000}$, and although they are a lot, they are still countable. The difference here is that they are not meant to describe objects. Instead, they allow the designer to find within a property distribution where in space a property has a specific concentration value. If we consider that one can "paint" at any given stage a property in order to transform it to a new one, property shapes allow access in 3 dimensions to specific conditions. In other words, Property Shapes "cut" a property distribution in ways that can be designed, and allow access for further manipulations. The process of selection happens here with properties in mind, which in my opinion from a designer's-practitioner's perspective is somewhat qualitatively different than the space of combinations that Lionel March proposes.

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[128] Mitchell, William J., *'The Logic of Architecture'*, MIT Press, Cambridge Mass (1990), p. 122.

In *VSpace*, in order to execute boolean operations between properties, we need to define Property Shapes and consequently determine if a property shape intersects and how with another. For the boolean Union, boolean Difference and boolean Intersection transformations and for two property shapes PSa(A, 0, 0.65) and PSb(B, 0, 0.35) (Figure 36) we have :

1. Transformation - Boolean Union is the property distribution subset that contains all Voxels that have $0 < CNa < 0.65$ **OR** $0 < CNb < 0.65$ (Figure 37) . **New Property Shape = A + B - A*B**

2. Transformation - Boolean Difference is the property distribution subset that contains all Voxels that have $0 < CNa < 0.65$ **AND NOT** $0 < CNb < 0.65$ (Figure 38). **New Property Shape = A - B**

3. Transformation - Boolean Intersection is the property distribution subset that contains all Voxels that have $0 < CNa < 0.65$ **AND** $0 < CNb < 0.65$ (Figure 39). **New Property Shape = A * B**

In an even more general fashion[129] in order to exhaust all possible $2^{216{,}000}$ subsets, any condition that can be expressed as a relationship between properties can be also used to isolate Property Shapes. For example since $0 < CNa < 1$, $0 < CNb < 1$ and $0 < CNc < 1$ a mathematical expression such as this one: $0 < CNa + 2*CNb - CNc^2 < 2$ also has known limits and can be used derive a New Property Shape[130].

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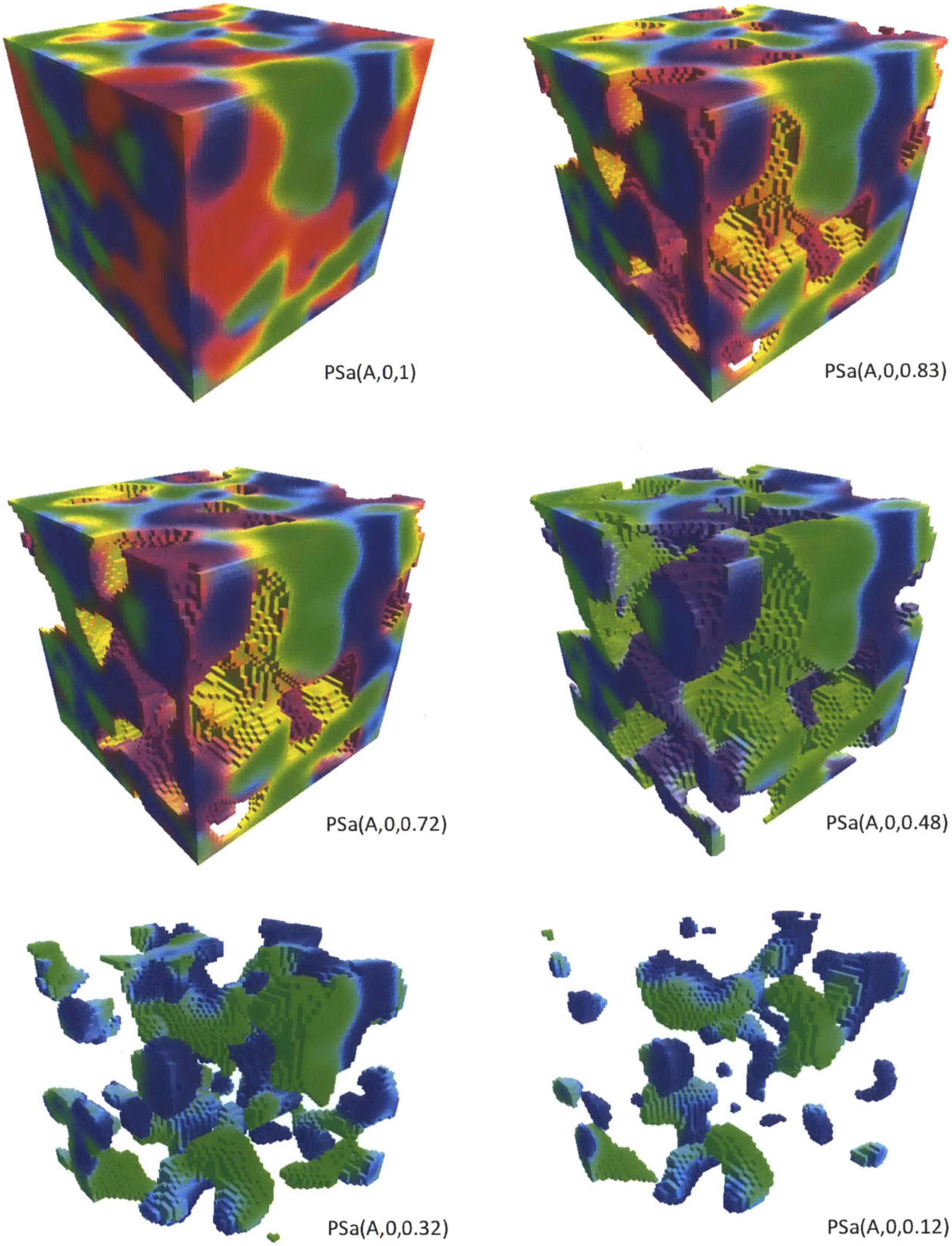
[129] not implemented yet in VSpace

[130] This mathematical expression would only make sense for a specific designer with a specific design goal in mind.



PSa(A,0,1)

PSa(A,0,0.83)

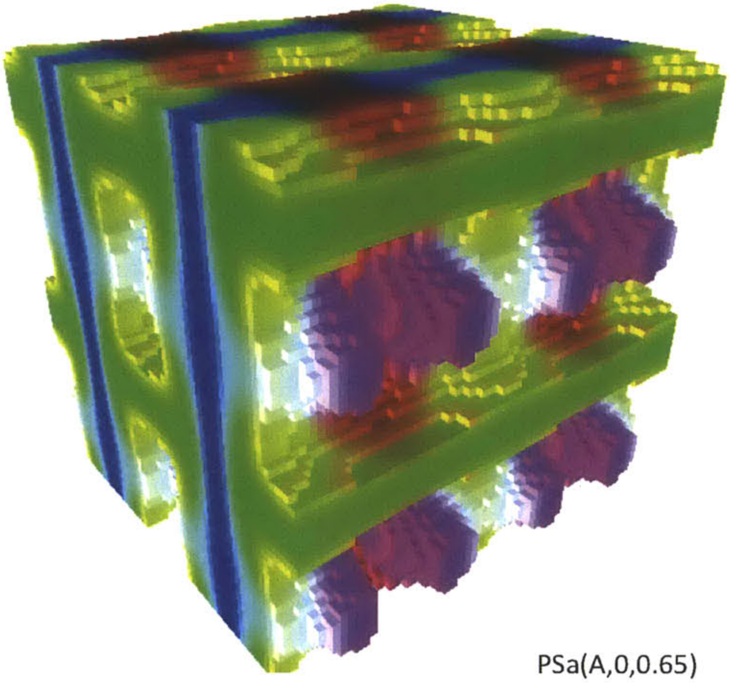
PSa(A,0,0.72)

PSa(A,0,0.48)

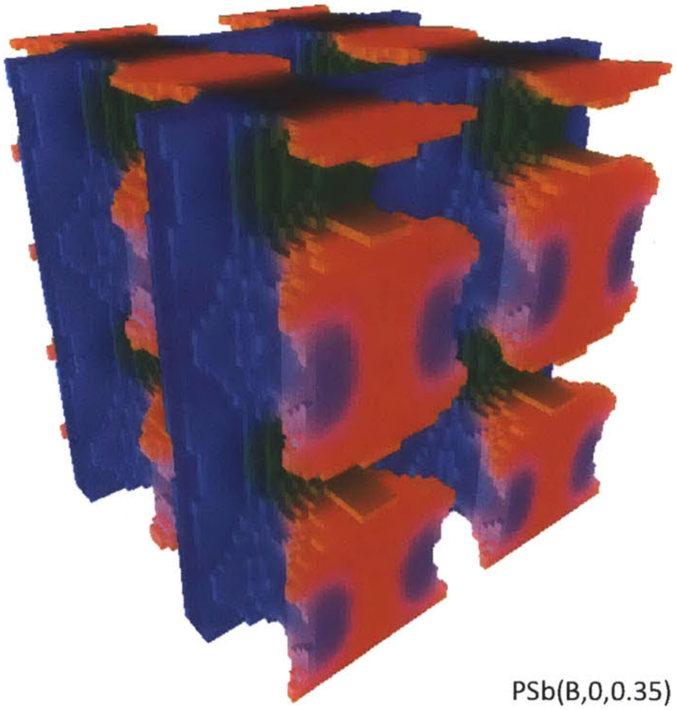
PSa(A,0,0.32)

PSa(A,0,0.12)

Figure 35: Property Shapes PS at Various Limits. VSpace 3D (screen shots from VSpace)



PSa(A,0,0.65)



PSb(B,0,0.35)

Figure 36: Property Shapes. PSa(A,0,0.65) and PSb(B,0,0.35). VSpace 3D (screen shots from VSpace)

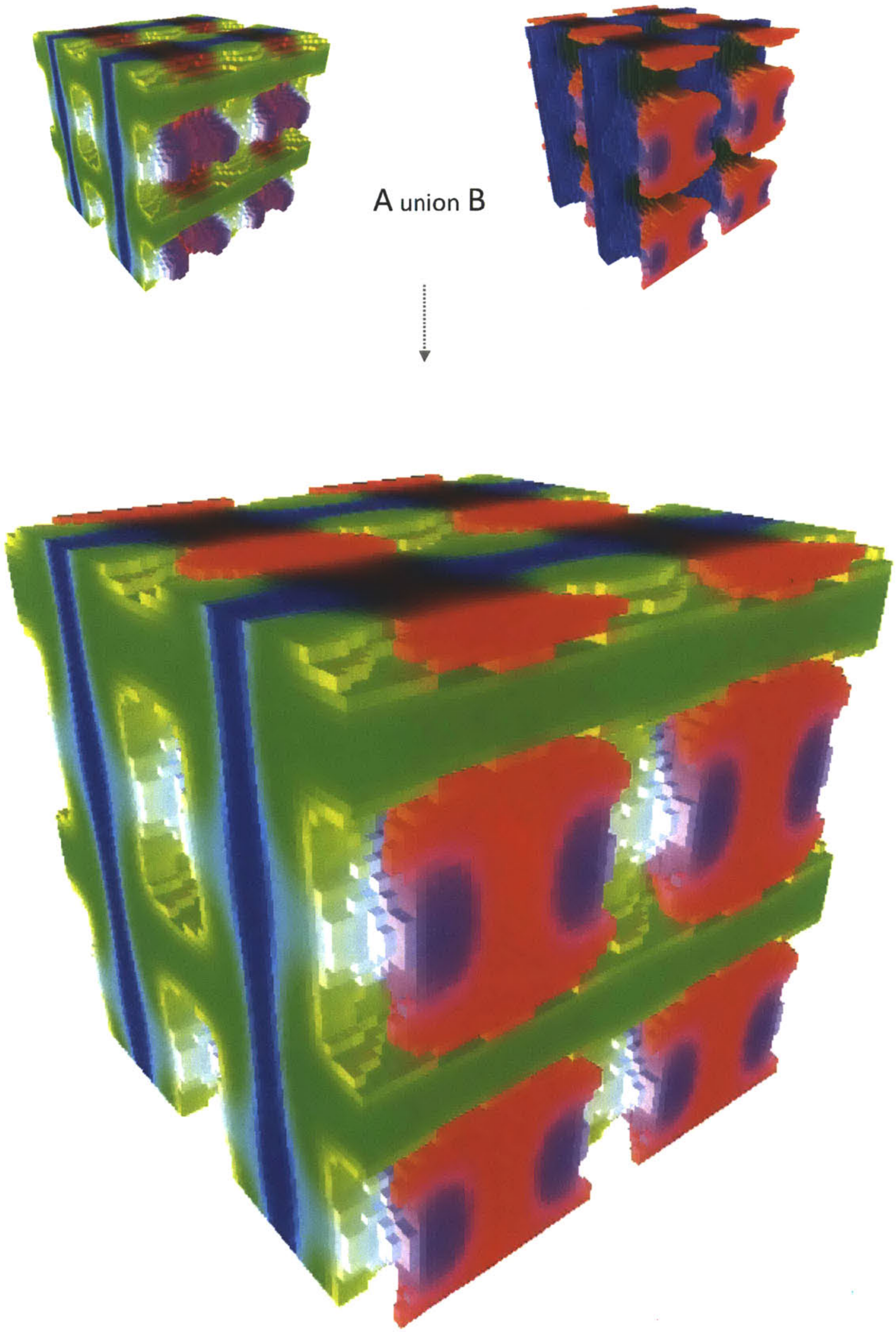


Figure 37: Property Shapes. Tranformation - Boolean Union. VSpace 3D (screen shots from VSpace)

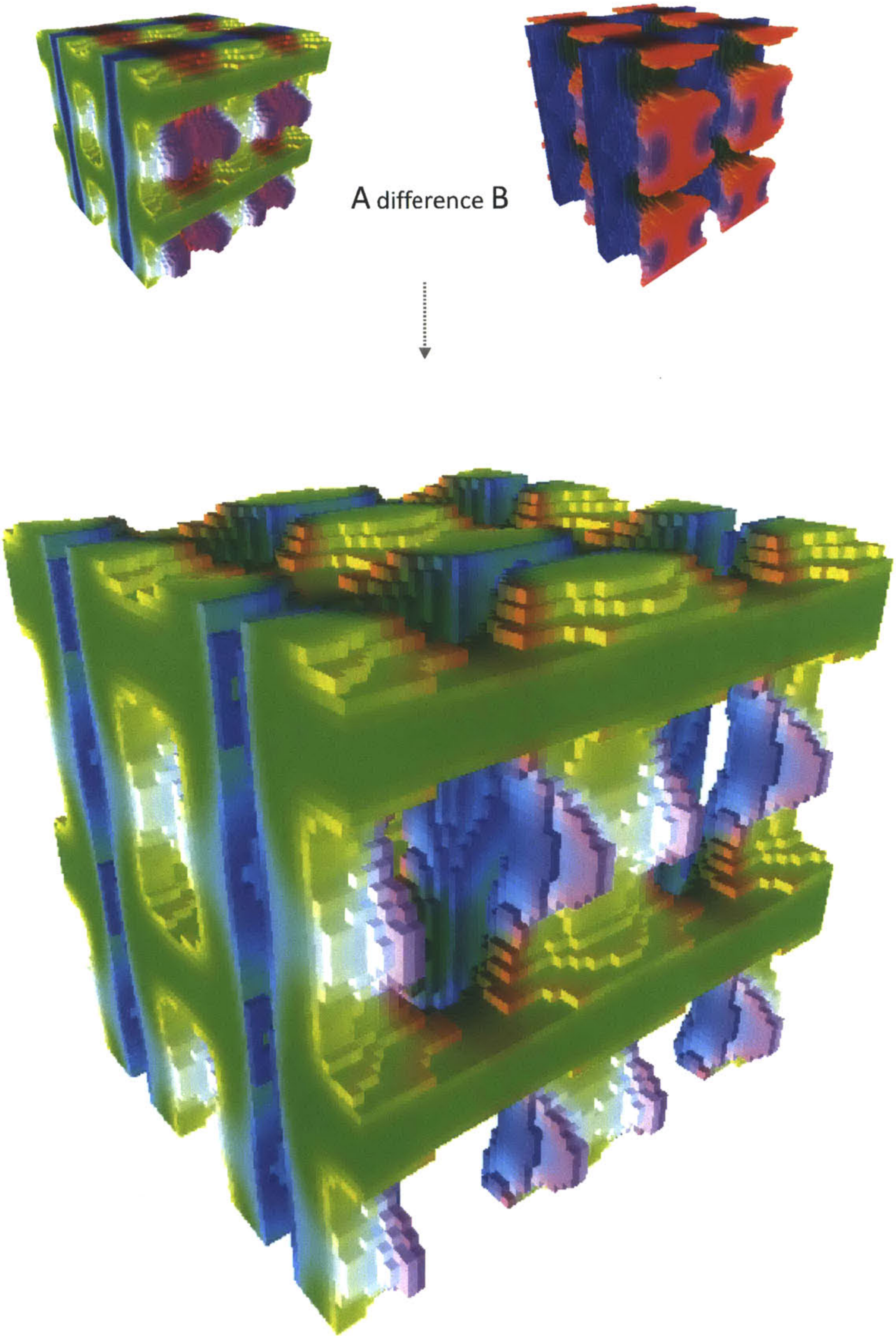


Figure 38: Property Shapes. Tranformation - Boolean Diffrerence. VSpace 3D (screen shots from VSpace)

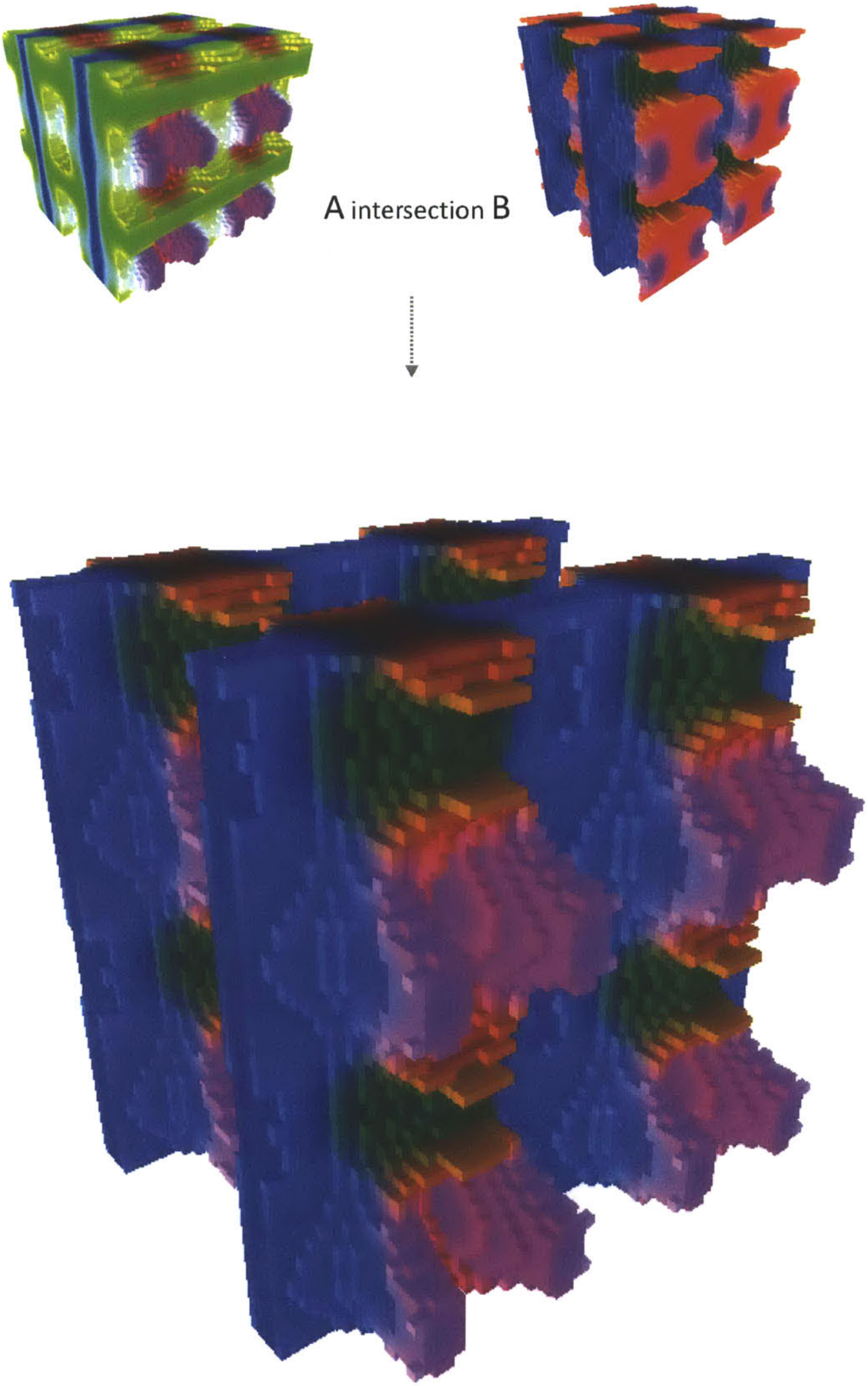


Figure 39: Property Shapes. Tranformation - Boolean Intersection. VSpace 3D (screen shots from VSpace)

1.5.7 VSpace - Boundaries

With the "boolean description of a class of built form"[131], Lionel March extends his previous work with voxels/cubelets. He critiques that his previous descriptive method was limited to forms made from adding rectangular forms together.[132] In this new extension, he describes rectangular and non rectangular forms by using cells as "scaffolds" upon which planes can be drawn using the vertices of a given grid[133]. He shows how for a given 2dimesional cell, there are multiple combinations of planes lines and points that can be drawn (Figure 40).

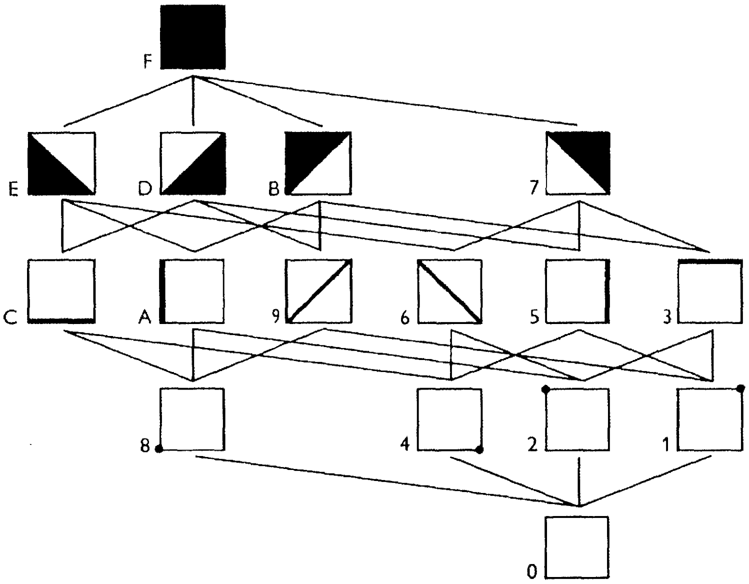


Figure 40: Lionel March, boundaries drawn from grid cells

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[131] March, Lionel, *'The Architecture of Form'*, Cambridge University Press, (1976), p. 60

[132] Ibid

[133] Ibid p.66

He goes on to demonstrate how this boolean algebra can be used to describe Mies' Seagram Building in 3dimensions (Figure 41 left) or even a "beveled" version of it by using the cube diagonals (Figure 41 right).

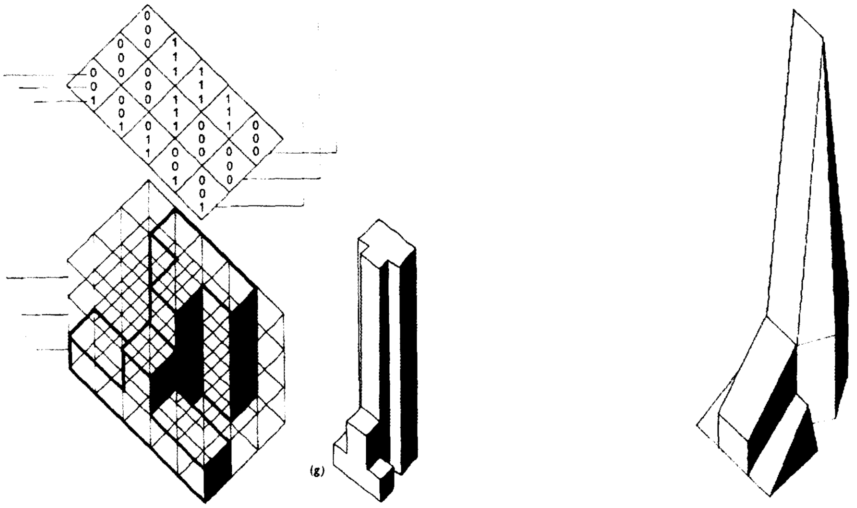

Figure 41. Lionel March: Mies' Seagram Building and its beveled version

When March compares the two distinct approaches of description, he associates the first one with a sculptor's additive, modeling approach to form while he associates the second one with a subtractive, carving approach.[134] Furthermore, since any given cell has a countable set of possible boundary objects and any grid of cells also contains a countable amount of sub sets, their combination is still countable. Extending further March's second approach VSpace uses the voxel space as a "scaffold" upon which boundary objects can be drawn, while still maintaining the boundary - property reversal.

As stated in the introduction, the *VSpace* project demonstrates a reverse hierarchy between Boundaries and Properties. So far we have seen how properties are defined and how design operations can be used for their instantiation and their transformation. We have also seen how a Property Shape (PS) is a sub set of a property distribution defined by an upper and a lower limit.

In VSpace, **Boundaries** are defined as exactly those limits of a property shape. In our example, if the Concentration values of any given property A, B or C range from 0 to 1, any specific concentration (i.e. CNa=0.35) including the limits 0 and 1 constitutes a boundary for that property.

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[134] Ibid p.71

Boundaries are visualized by employing what is known as the Marching Cube algorithm. It was first published in the 1987 SIGGRAPH proceedings by William E. Lorensen and Harvey E. Cline[135] and was initially targeted to the medical imaging industry for the visualization of data taken from CT and MRI scans. It was basically developed in order to reconstruct 3dimensional surfaces out of Voxel data and is used today extensively among other fields in the medical imaging and 3d graphics industries. The difference between the Lionel March approach and the Marching Cube algorithm is that boundary objects are not derived by combining the vertices of a cubelet but instead a continuous approach is used. Here the centroids of 8 voxels in a neighborhood define a new "median" voxel that has different concentrations stored in its vertices[136] (Figure 42).

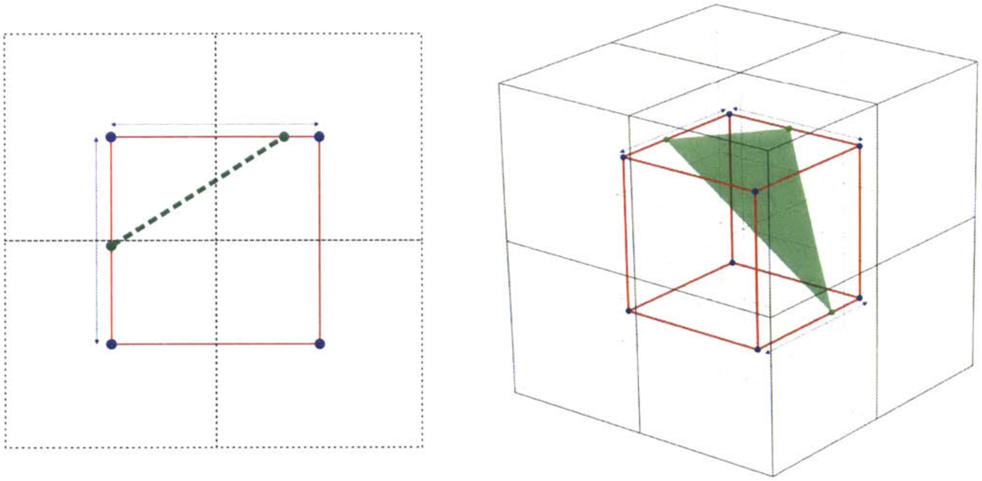

Figure 42 : The marching cube in 2 and 3 dimensions. Green points can slide between the blue

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[135] Lorensen, William E. and Cline, Harvey E., *'Marching Cubes: A high resolution 3D surface construction algorithm.* In: *Computer Graphics'*, Vol. 21, Nr. 4, July 1987.

[136] The concentrations correspond to the respective original voxels.

A line in 2 dimensions or a plane in 3 dimensions can be defined by points that can slide along the edges of this new "median" voxel. Unlike Lionel Marches countable subsets, here boundaries are infinite but nevertheless bound[137] by the unit[138]. In order to make the algorithm more efficient[139], Lorensen and Harvey encoded in text form a set o possible boundary derivations (Figure 43).

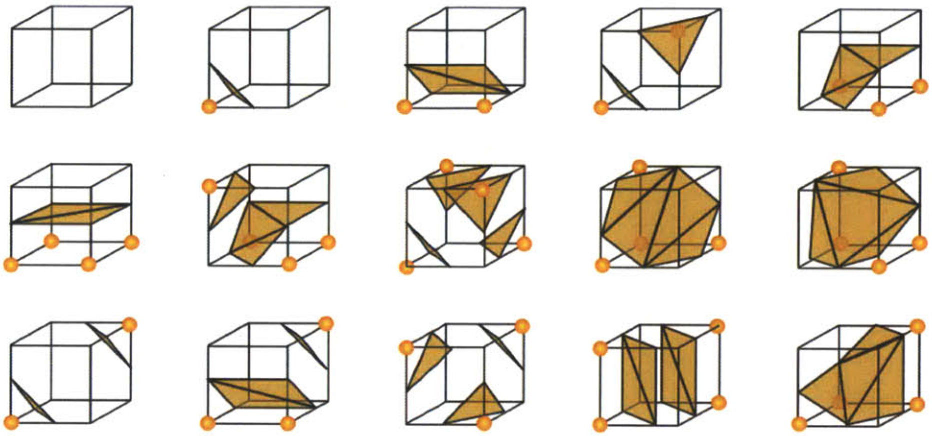

Figure 43 : 15 cube configurations. William E. Lorensen, Harvey E. Cline.

Simply put, in VSpace the application of the Marching Cube algorithm answers with boundary the following question: **Where in space does property A, B or C (or any combination) have Concentration CN = X?** (lower limit < X < upper limit). For example with a Property Shape PSa (A, 0 , 0.46) a boundary can be drawn at CNa=0.55. (Figures 44 - 47). From a design perspective this question is quite fundamental as it allows us to derive a **Boundary object from a Property distribution**. If in B-Rep software the intuitive action is to first define a boundary object and then attach properties to it[140], in VSpace we instantiate or transform properties first and then derive boundaries from them. The following examples will demonstrate how boundaries are derived from different Property Distributions and will examine their characteristics based on methods of property instantiation and transformation.

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[137] an easy analogy here is that if all integer numbers are infinite, even integer numbers are infinite but bound by their "evenness" while all integers from 1 to 10 are countable.

[138] In the ideal case that we could at any point during the design process be able to redefine the unit subdivision - like in the case of the "ice rays" we would be able to achieve unbound definitions of boundary objects.

[139] Calculations with voxels in a digital computer are already very memory intensive.

[140] Consider applying a color to an object or a material for rendering or even more accurate physical characteristics like density or transparency.

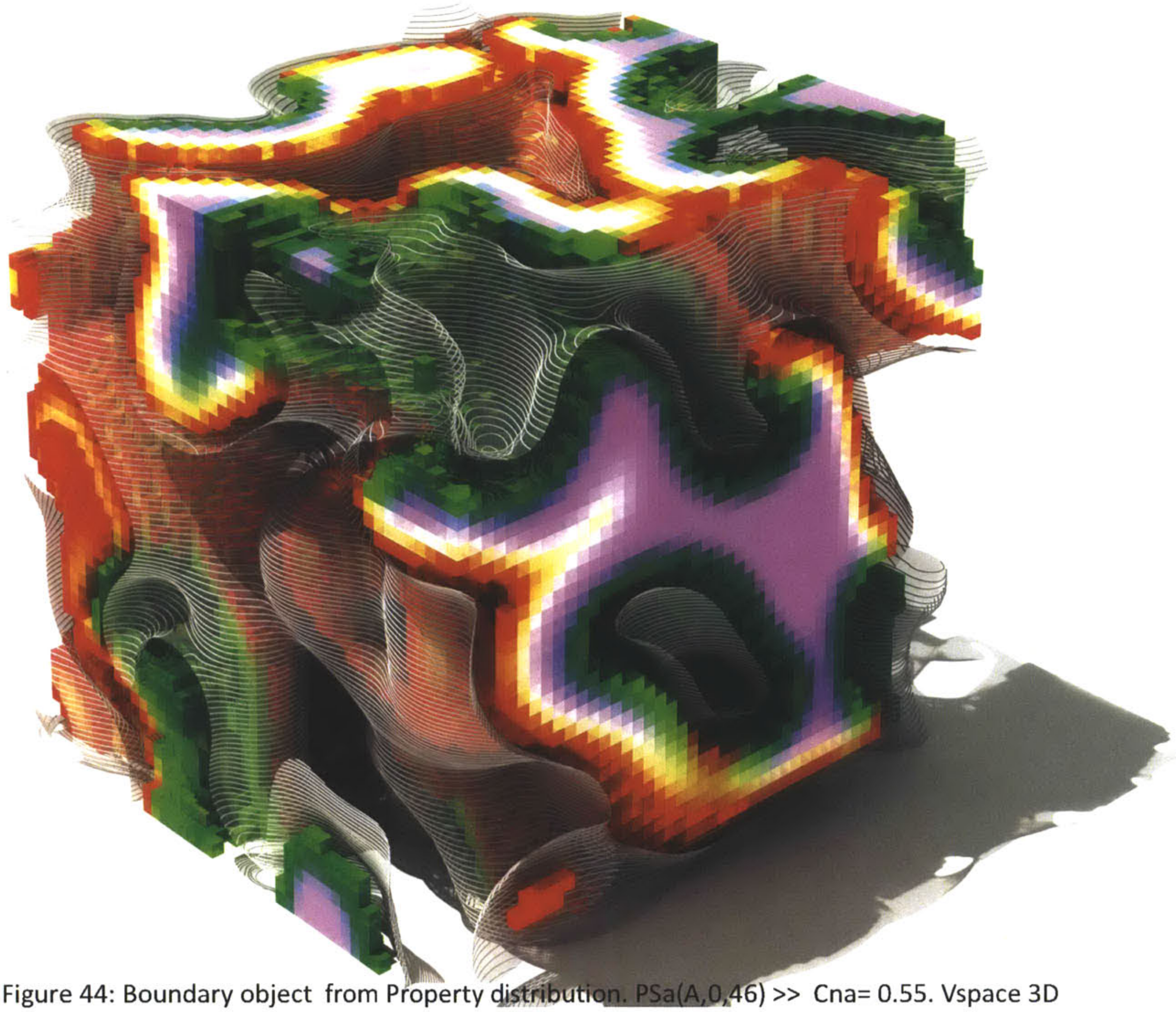

Figure 44: Boundary object from Property distribution. PSa(A,0,46) >> Cna= 0.55. Vspace 3D

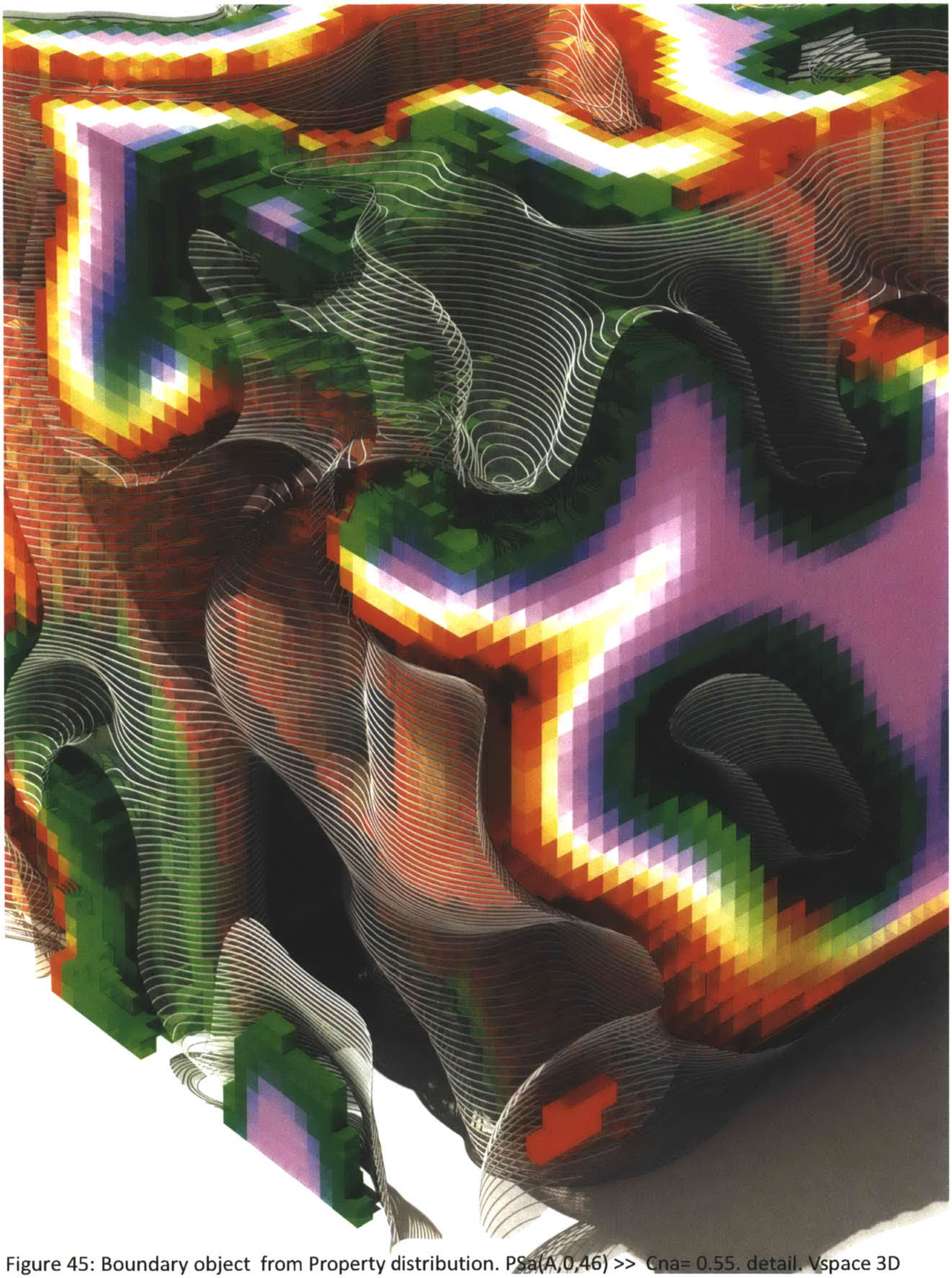

Figure 45: Boundary object from Property distribution. PSa(A,0,46) >> Cna= 0.55. detail. Vspace 3D

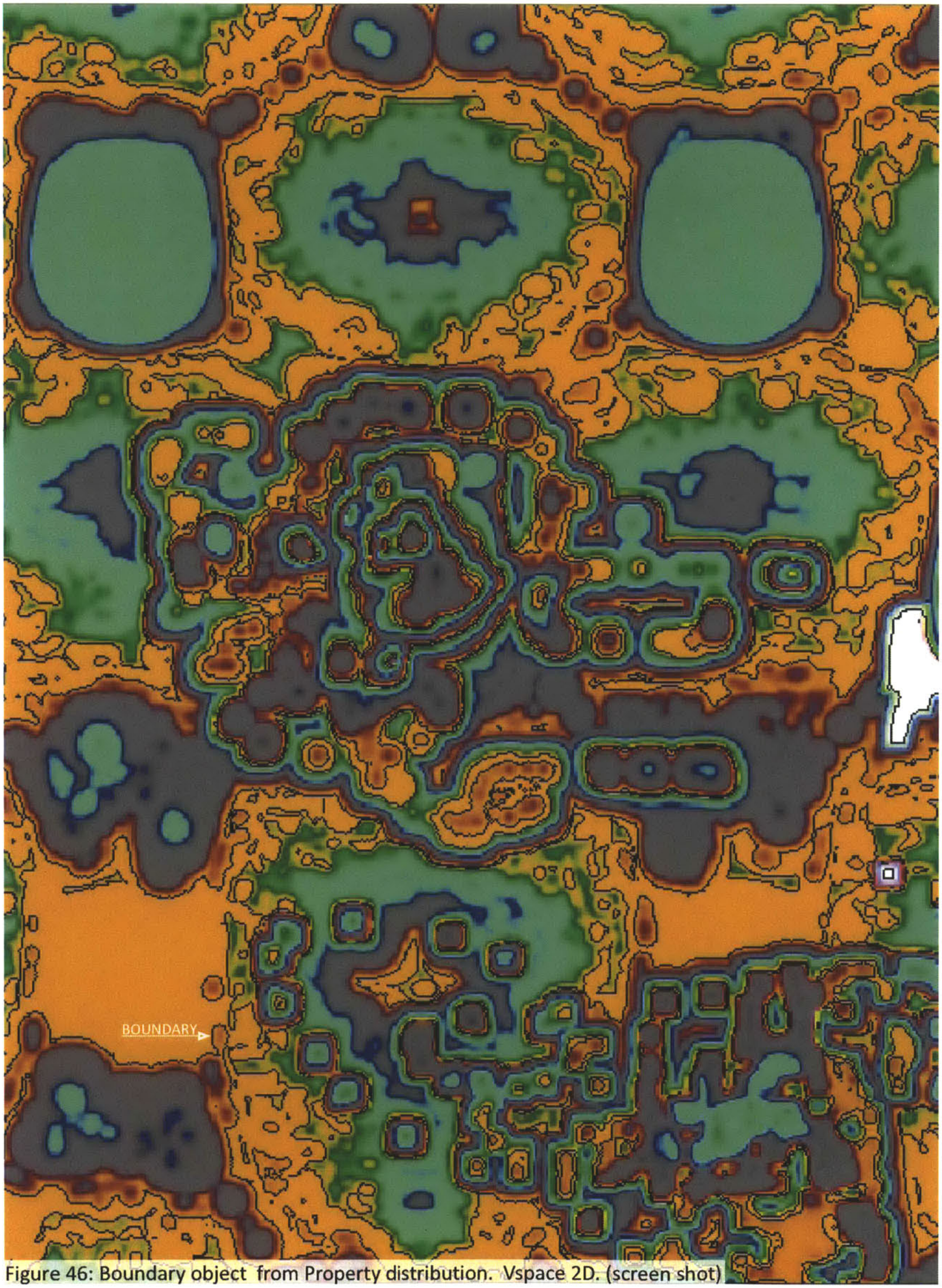

Figure 46: Boundary object from Property distribution. Vspace 2D. (screen shot)

Figure 47: Boundary object from Property distribution. Vspace 2D. (Multiple Boundaries. Vector drawing)

1.5.8 Instantiation- Boundary

Boundary Instantiation. Primitives

Primitive - Constant Fill

Since the marching cube uses interpolation between concentration values in a Voxel Space in order to compute surface boundaries[141], a homogeneously filled Voxel space **does not** produce boundaries. In this example, all Voxels in the 60x60x60 Voxel Space are filled with concentration CN (a, b, c) = (0.26, 0.32, 0.17), therefore, no boundaries are drawn. On the other hand, if we keep the distribution fixed and extend the Voxel space to at least 61x61x61 filling the remainder Voxels with C(a, b, c)=(255, 255, 255) and apply the marching cube for MC@CNa=0.26 we get a boundary surface (a cube) 60x60x60 in all three directions (Figure 48).

note: In VSpace the application of the marching cube is intuitively achieved. By enabling the algorithm and using a slider (0-1) one can query properties for their boundaries. In other words you don't have to know the concentrations values in order to derive boundaries. Once you see the boundary then you can find out the concentration value that it corresponds to.

Primitive - Slice Fill

In the slice fill example in a pattern of multiples of 3, the Voxels in each slice are filled with either (CNa=1, CNb=0, CNc=0) or (CNa=0, CNb=1, CNc=0) or (CNa=0, CNb=0, CNc=1). For instance if we apply the marching cube for CNc=1 (MC@CNc=1) *(the intuitive question here is: where in space is color blue equal to 255)* we get 5 parallel planes in the direction of the pattern (Figure 49). The planes are only drawn where the blue Voxels are next to either green or red ones. For MC@CNb= 1 and MC@CNa=1 we get planes parallel to the first ones albeit in locations is space that correspond to their respective boundaries.

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[141] This is a fundamental characteristic of the Marching Cube. For further clarification please see the original paper Lorensen, William E. and Cline, Harvey E., *'Marching Cubes: A high resolution 3D surface construction algorithm.* In: *Computer Graphics'*, Vol. 21, Nr. 4, July 1987.

Primitive - Grid Fill (Figures 50 - 52)

In these examples, where the instantiation method fills Voxels in a grid pattern, boundaries also reproduce the grid characteristics but vary between them depending on the specific distributions. For the 3x3x3 grid which is symmetrically filled with either (CNa=1, CNb=0, CNc=0) or (CNa=0, CNb=1, CNc=0) or (CNa=0, CNb=0, CNc=1) a Boundary MC@CNa=1 appears symmetrical with 90 degree shifts from the horizontal to the vertical following the edges of property change (Figure 50). When the 3x3x3 grid is filled asymmetrically with varying concentrations a boundary MC@CNc=0.8 appears asymmetrical but still maintains the 90 degree angle shifts (Figure 51). In the case of a random distribution on each Voxel in the Voxel space, a boundary MC@CNb=0.5 also appears asymmetrical but this time the angle of shift between the horizontal and the vertical appears also equally random (Figure 52).

Primitive - Equation Fill (Figure 53)

When looking at the distribution of the Wave Function, a boundary MC@CNa=0.32 produces parallel planes at intervals that correspond to the period of the wave function. Unlike the Slice Fill example (Figure 49), where all three properties produce boundaries parallel to each other, here if we also draw a boundary MC@CNb=0.48 and MC@CNc=0.50 we get sets of parallel planes on all three directions. In Slice Fill all properties diffuse along the same direction while here each property A, B and C diffuse in directions perpendicular to each other.

Boundary Instantiation. Interpolation (Figures 54 - 55)

Interpolate - Constant Fill

A constant fill interpolated instantiation produces a unidirectional linear gradient of properties. A Boundary MC@CNa=0.8 is a single horizontal plane perpendicular to the direction of the gradient. Unlike the examples in Figures 49 and 53 in which the same concentration value appeared more than once in the same Voxel distribution here Ca= 0.8 exists only in a single slice (Figure 54).

Interpolate - Bitmap Fill

When using two distinct bitmaps for the property distribution a Boundary MC@CNa=0.5 traces the same property as it linearly blends between the two limits (Figure 55).

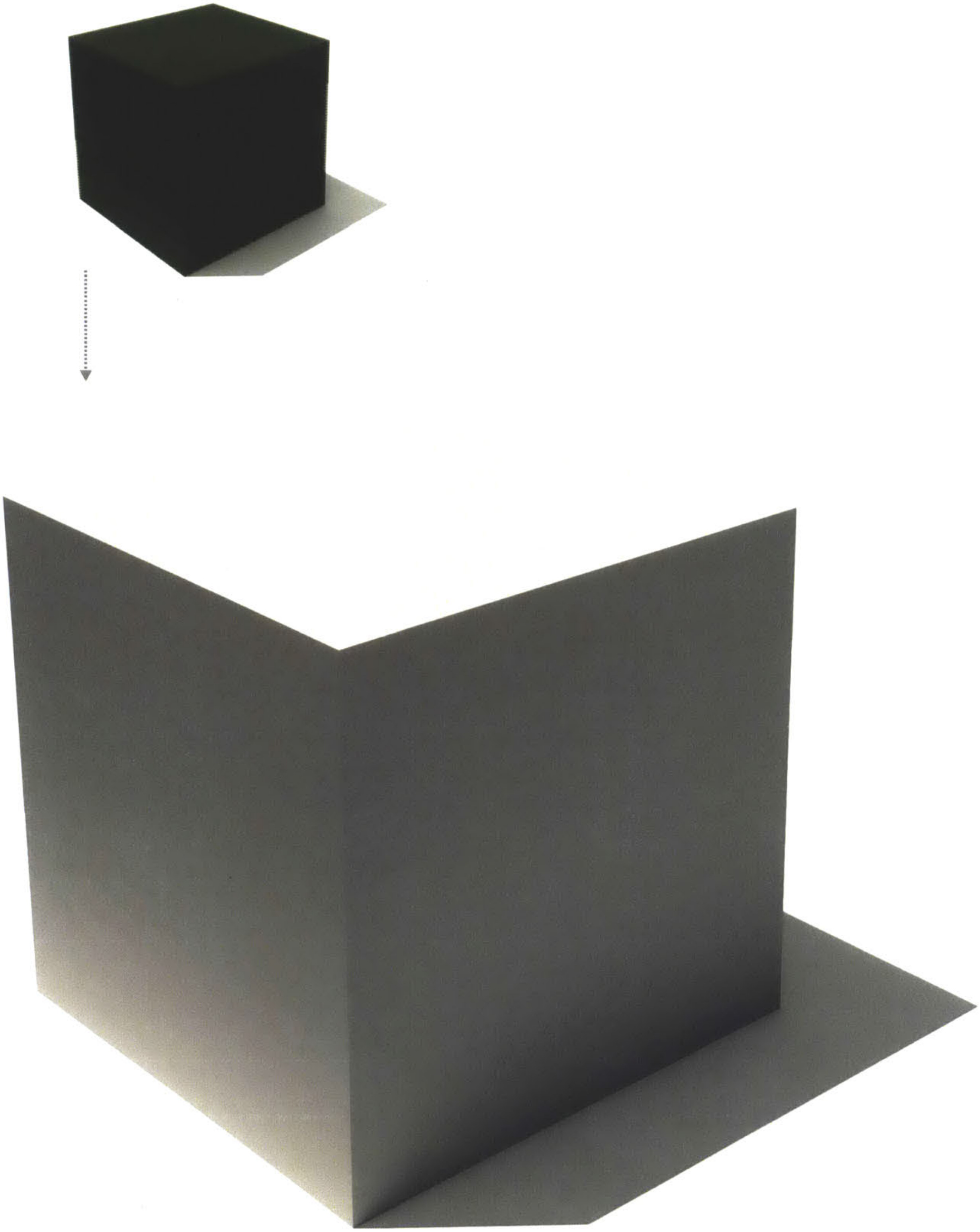


Figure 48: Boundary Instantiation. Primitive - Constant Fill. CNa=0.26. Vspace 3D.

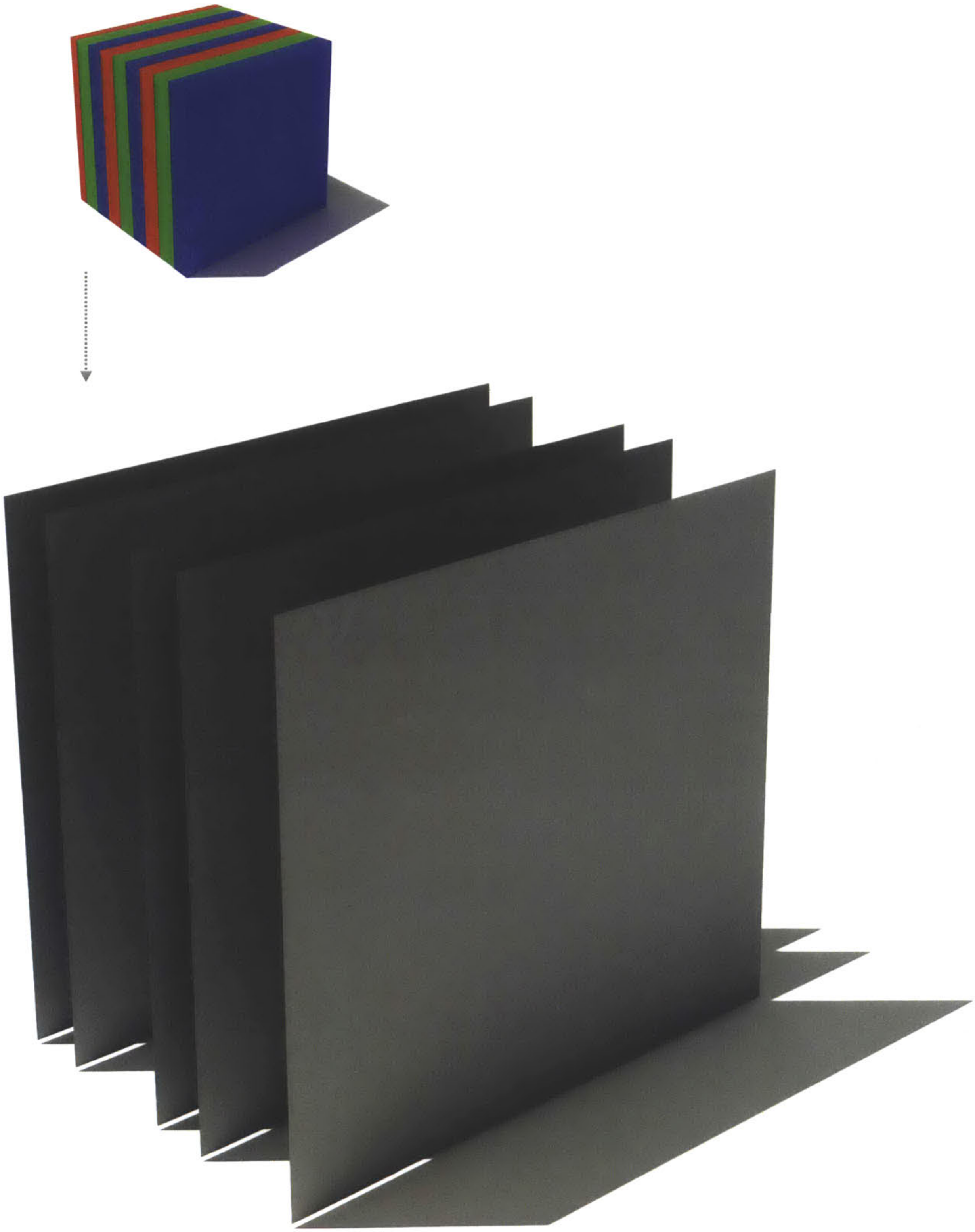


Figure 49: Boundary Instantiation. Primitive - Slice Fill. MC@CNa=0.26. Vspace 3D.

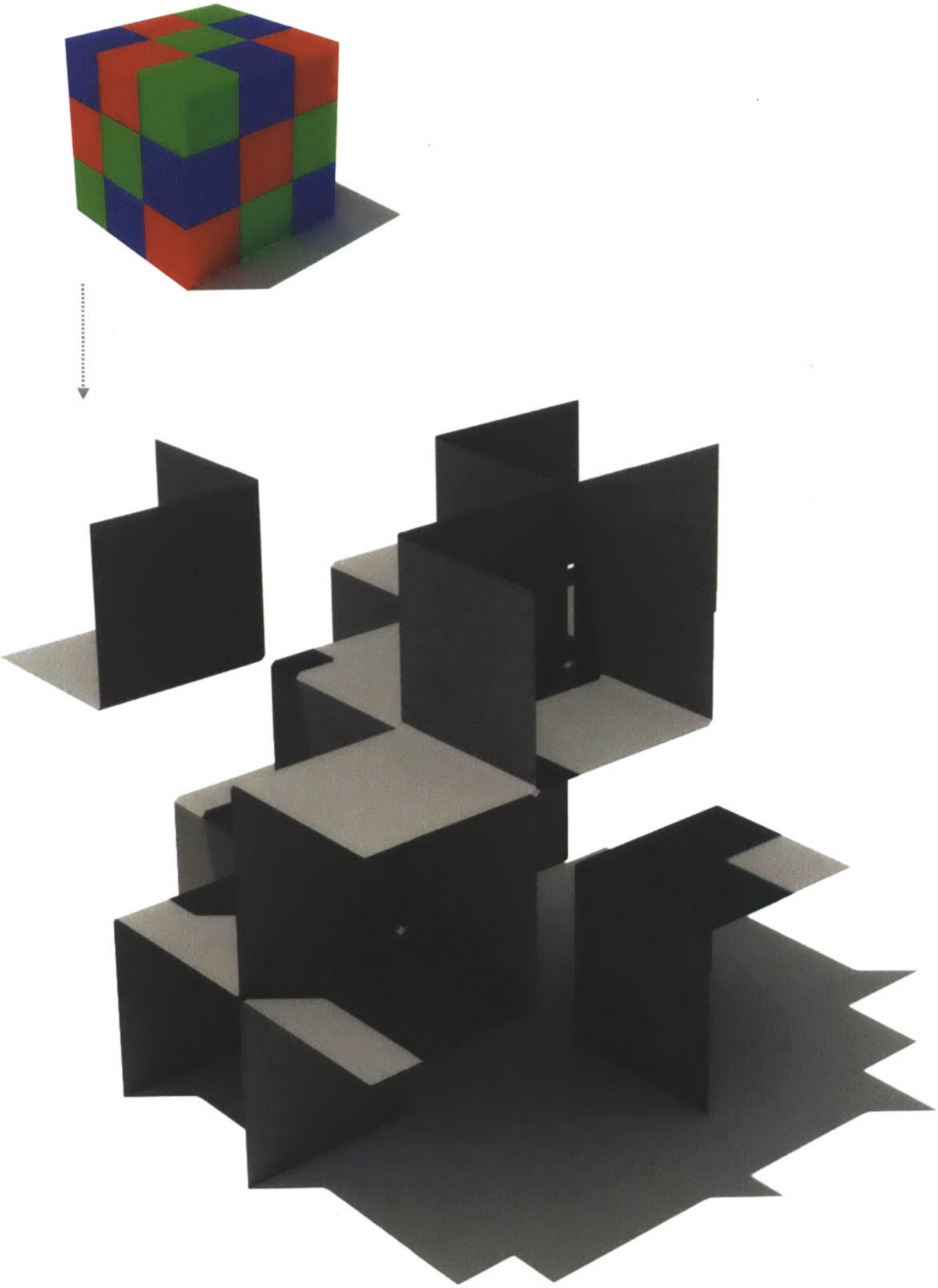


Figure 50: Boundary Instantiation. Primitive - Grid Fill 1. MC@CNa=1. Vspace 3D.

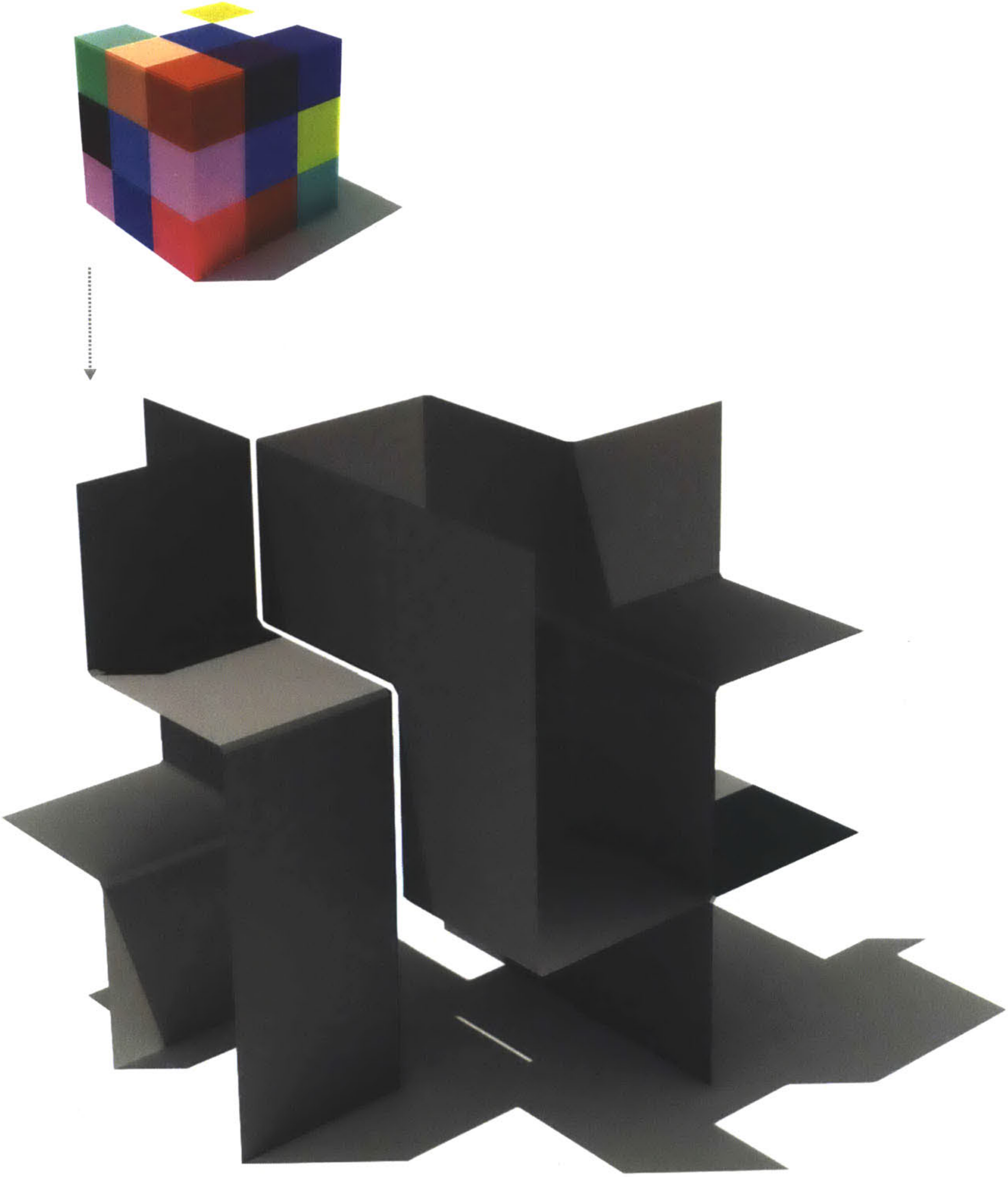


Figure 51: Boundary Instantiation. Primitive - Grid Fill 2. MC@CNa=0.8. Vspace 3D.

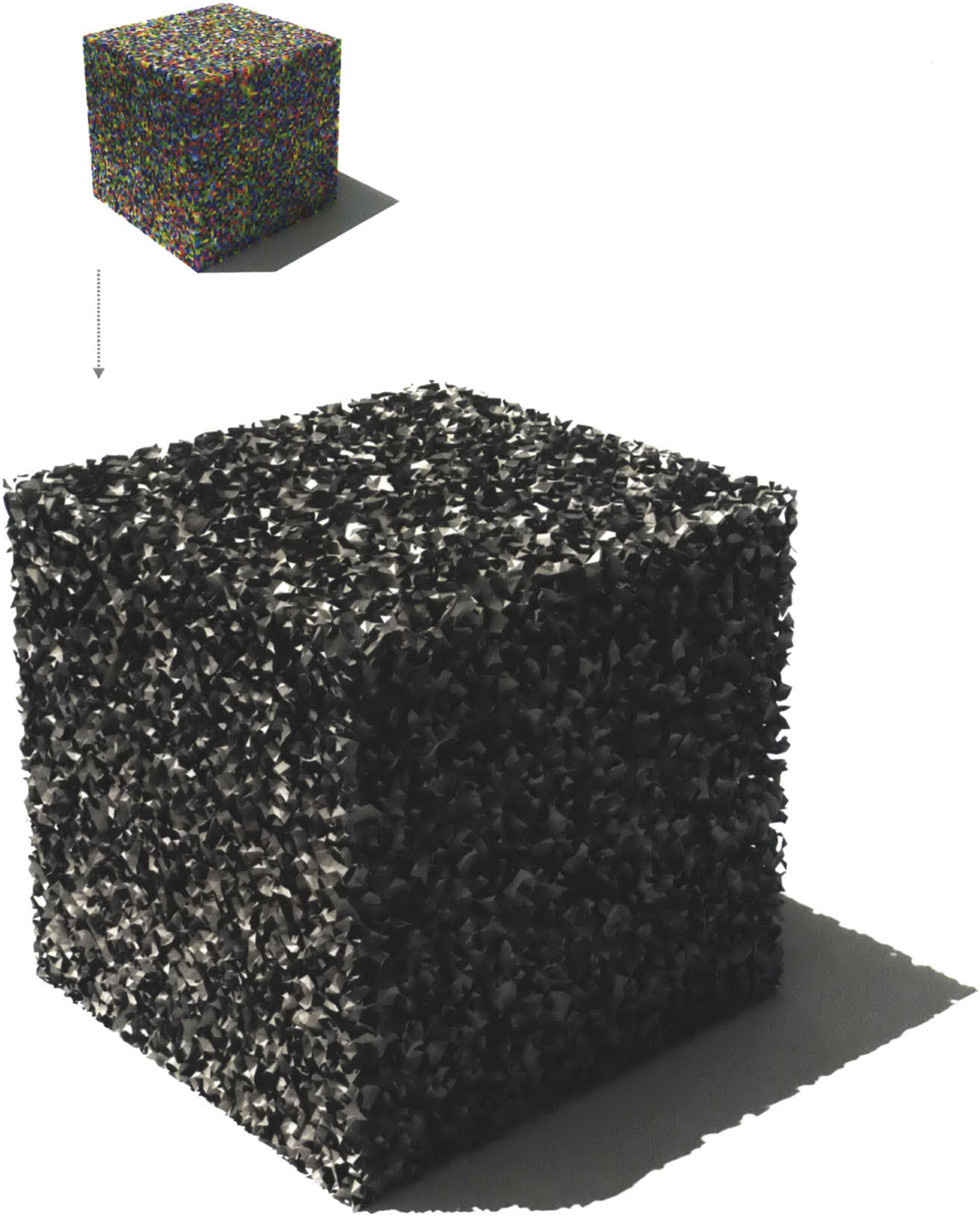
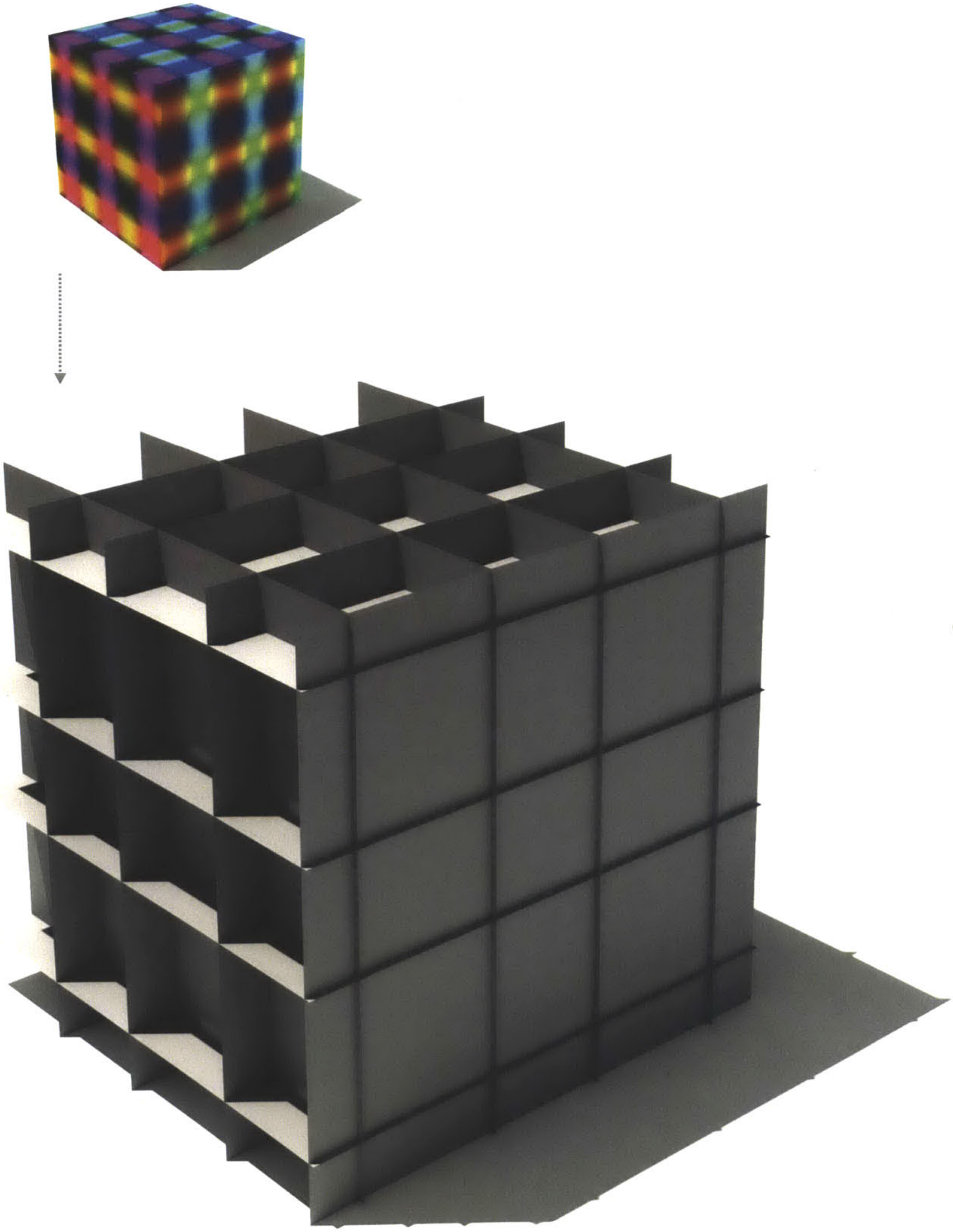


Figure 52: Boundary Instantiation. Primitive - Grid Fill 3. MC@CNa=0.5. Vspace 3D.



MC@CNa=0.32
+
MC@CNb=0.48
+
Figure 53: Boundary Instantiation. Primitive - Equation Fill. MC@CNc=0.50. Vspace 3D.

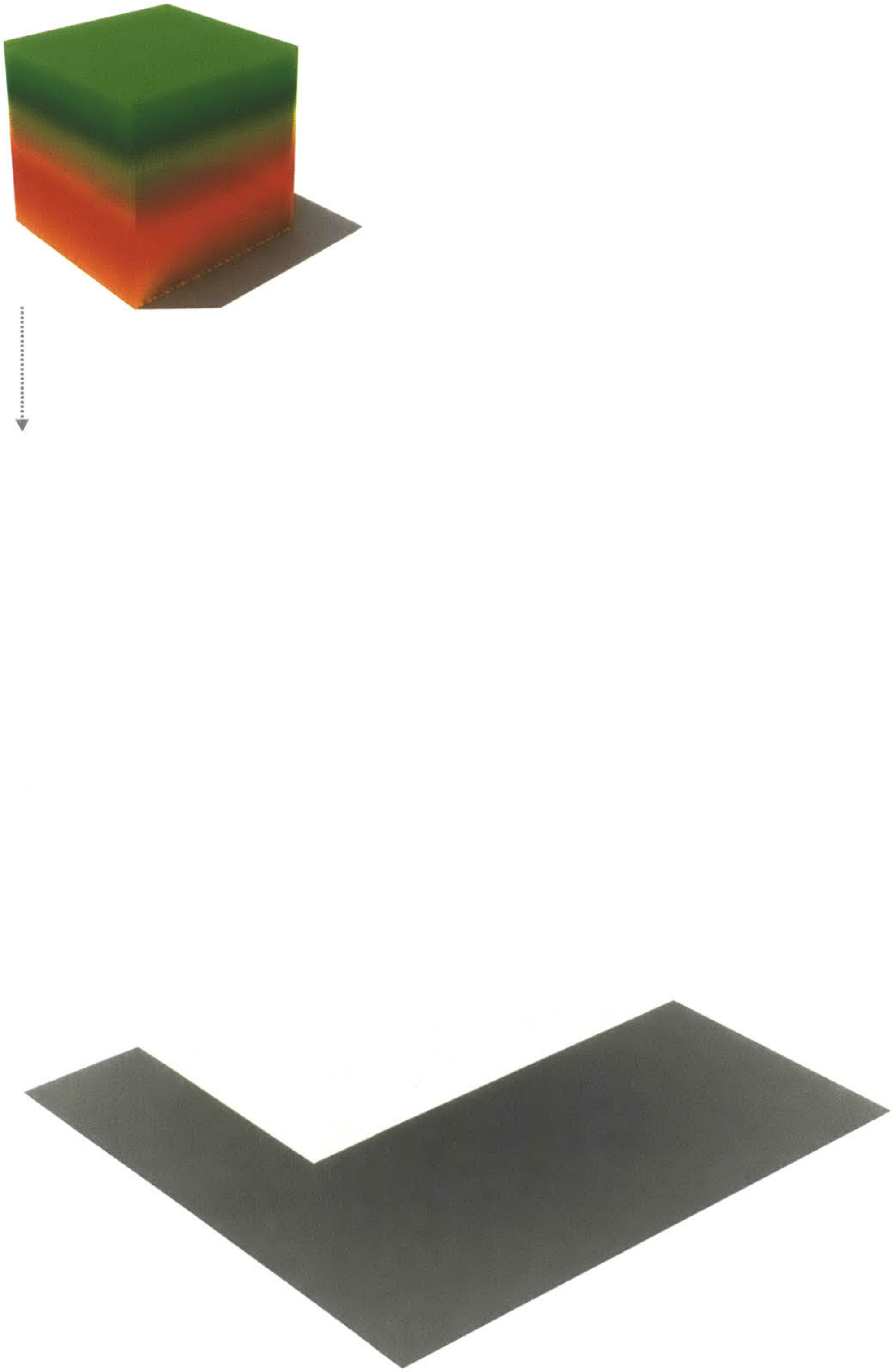


Figure 54: Boundary Instantiation. Interpolate - Constant Fill. MC@CNa=0.8. Vspace 3D.

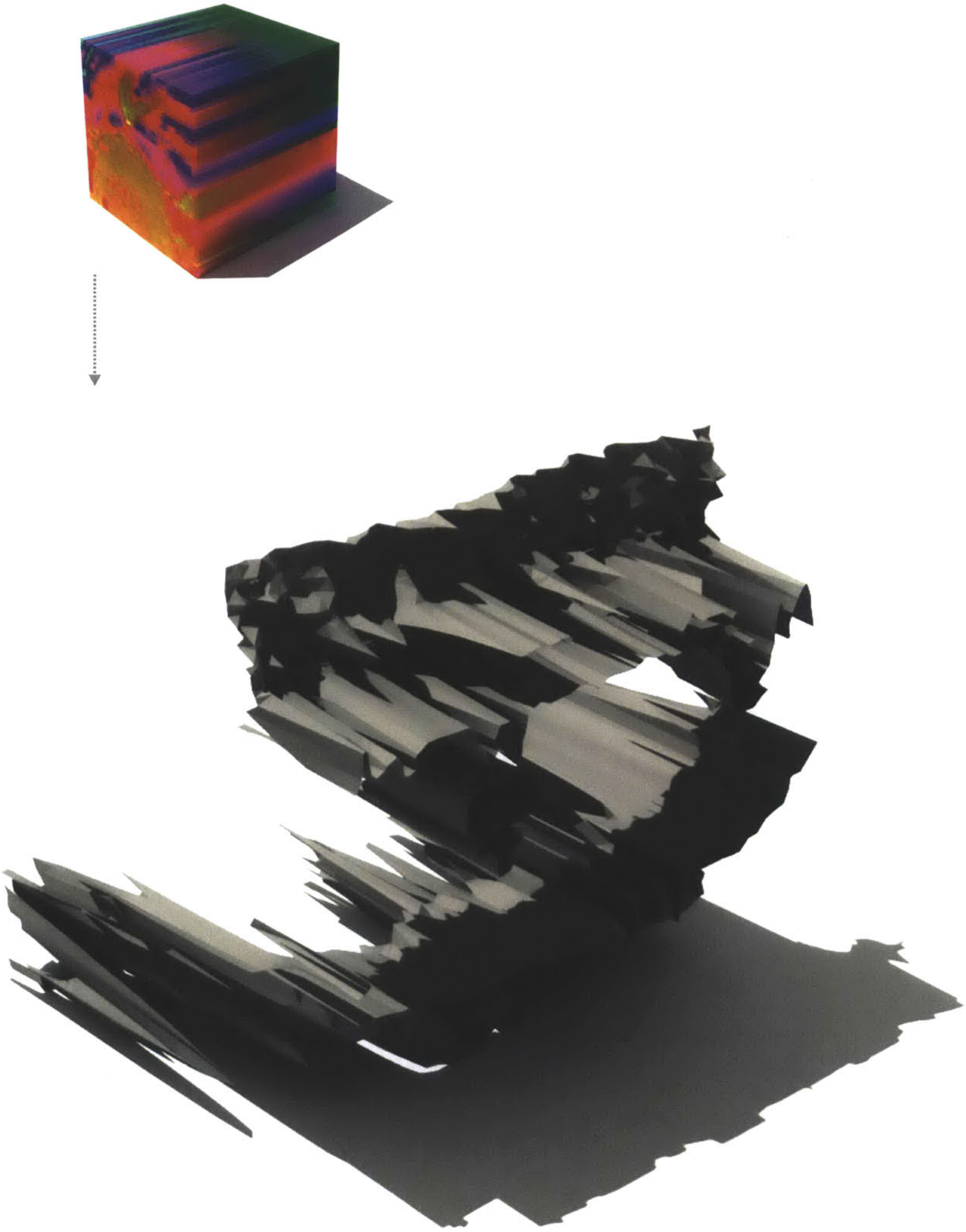


Figure 55: Boundary Instantiation. Interpolate - Bitmap Fill. MC@CNa=0.5. Vspace 3D.

Boundary Instantiation. Paint.

VSpace has a "property mode" in which a designer can instantiate properties and a "boundary mode" in which the designer can query properties for their boundaries. Those distinct modes of representation can be enabled independently or in parallel. When the "boundary mode" is on the Marching Cube is set to a specific property A, B or C and a Specific Concentration value CN (example MC@CNa = 0.47). In a Voxel space (here implemented in 2D) filled with concentrations CN (a,b,c)=(0,0,0) the designer can select the digital paint brush with color from a palette, size, opacity and hardness. Predetermined boundaries like cubes, spheres, ellipsoids and so on can be drawn using the predetermined property solid functions (see 1.2) from the menu. Boundaries can also be drawn as freehand objects in a gestural manner (see 1.1). In all cases the corresponding boundary is updated while properties are being distributed (Figure 56).

Notes:

1. Boundaries are not drawn directly. Instead they are traces of Property Shape Limits. All instantiations happen at the property level and are only reflected on Boundaries. In VSpace a boundary cannot exist without a property that goes along with it.
2. Boundaries are defined as vectors while properties as Voxels (or pixels). Boundaries can for instance be exported as .dxf files to be further manipulated in B-Rep software, while properties can be exported as 2 or 3 dimensional images or text files.

1.5.9 Transformation - Boundaries

Since boundaries can always be dynamically drawn as Property Shape limits, any operation that would transform a property concentration or a property limit would directly transform Boundaries as well.

Transformation – Painted Boundaries

With painting in VSpace, a designer can transform existing boundaries to new ones. It is easy to imagine that a paint brush that transforms a concentration value CN of a Voxel V (I, j, k) simultaneously transforms a corresponding boundary. Let's assume that the marching cube is set to MC@CNa=1. When painting with a brush with red color (property A) and opacity 50%, any Voxel with concentration CNa=0.5 will transform to CNa=1[142] and in consequence add a boundary. If the brush is set to color blue any Voxel with CNa=1 will transform to CNa=0[143] thus removing a boundary (Figure 57).

An apparent conclusion here is that in VSpace **boundary objects are not bound by geometric topological constraints**. In geometrical topology - popularly known in the design community as the geometry of the elastic sheet[144] – topological definitions of boundaries come with constraints. For example, in B-Rep software, a topologically defined torus, while it can transform into the shape of a drinking cup it cannot transform into a sphere. And the reason is simple. The torus and the cup both have one hole while the sphere has none.

In VSpace, topological constraints also exist but at the level of property[145]. Although the marching cube is already a kind of topology, boundaries can be transformed, pushed and pulled, cut and expanded without any geometrical constraint. Certainly this observation does not constitute a proof; nevertheless, an initial visual inspection of a number of different boundary transformations point to this direction.

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[142] Calculations follow the general formula : CNa_new = Ca + R/255 * (K/100)

[143] Calculations follow the general formula : CNa_new = Ca + R/255 * (K/100)

[144] Di Christina, Giuseppa, *'The Topological Tendency in Architecture'* in *Architectural Design: Architecture and Science*, (ed) Giuseppa Di Christina, Willey Academy, Great Britain, (2001), p. 7.

[145] There is always an underlying structure in any digital CAD software. Nevertheless, topological constraints although not absent are here limited to the ones described in the introduction of VSpace.

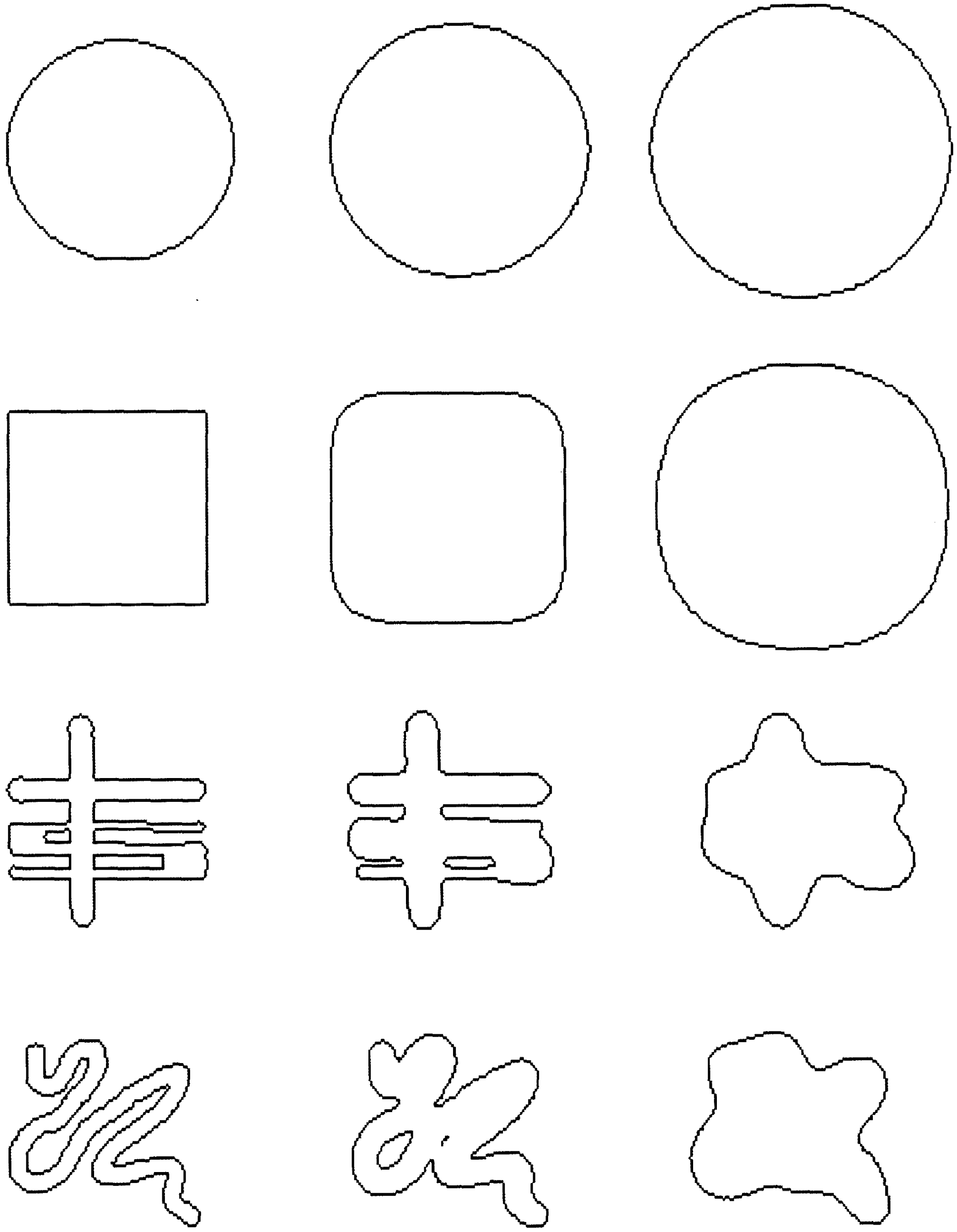


Figure 56: Boundary Instantiation. Paint Vspace 2D.(screen capture, Vspace 2D)

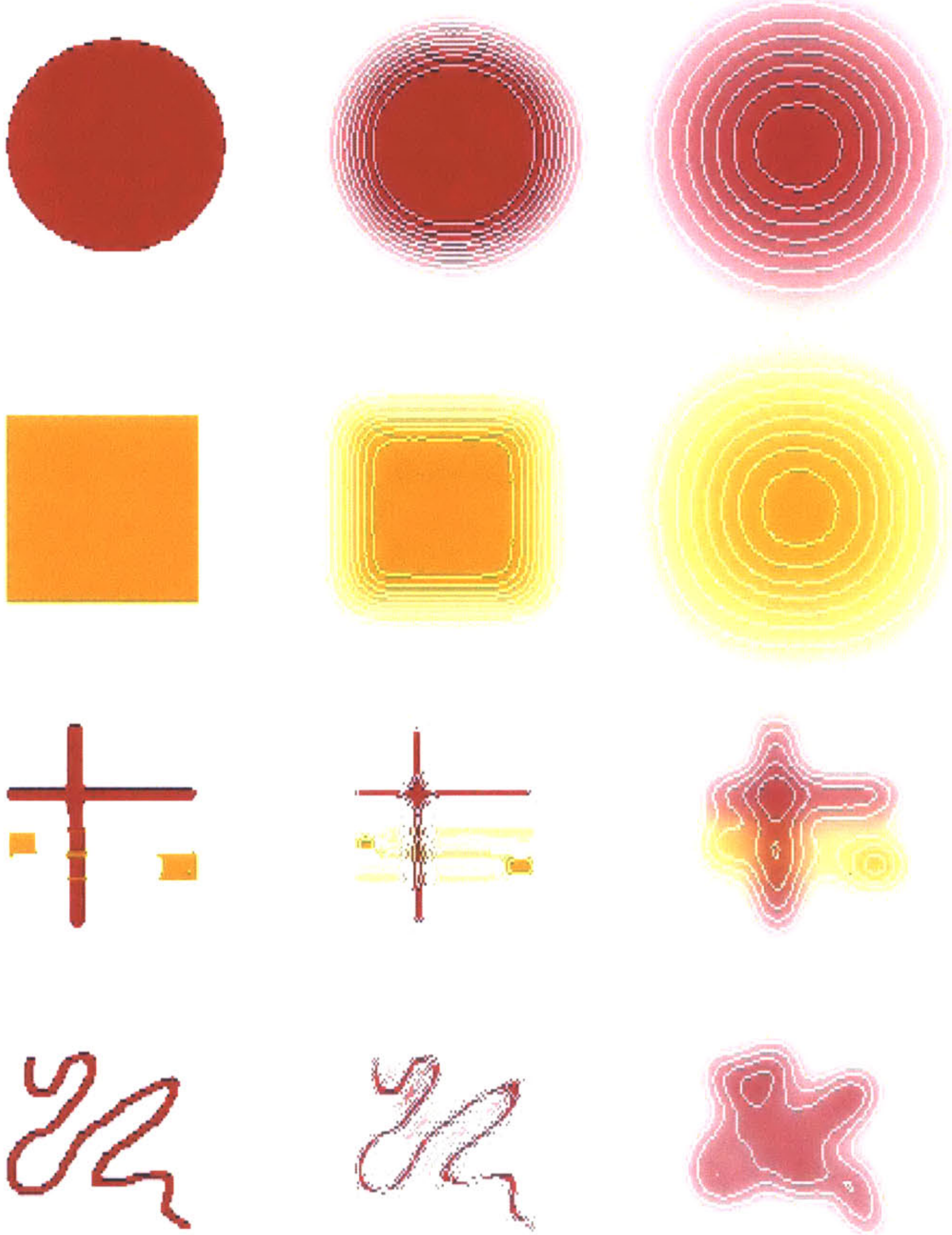


Figure 57: Boundary Transformation. Paint Vspace 2D. (screen capture, Vspace 2D)

Transformation – Boundaries with Automata

With automata in VSpace, when rules of interaction between properties are set in motion, boundaries dynamically follow the transformation of properties into new properties; thus transforming boundaries into new boundaries. The Figures that follow demonstrate 3 such examples.

In Figures 58-64 the initial state for the Automaton is a random distribution.
In Figures 65-69 the initial state for the Automaton is an equation fill distribution.
In Figures 70-79 the initial state for the Automaton is a a-periodic grid distribution.
In Figures 80-87 the initial state for the Automaton is a periodic grid distribution.

When visually inspected, the four examples, also demonstrate that boundaries in VSpace do not have geometric topological constraints. Although the property topology and the marching cube topology are always there, the resultant boundary objects differ between steps in terms of their geometric topology.

However, there is a second observation that is particular to Automata. While in all three examples the same rules of interaction have been used (idealized Belouzov – Zabodinsky), the geometric characteristics of the boundary objects that emerge vary drastically between them. This allows me to conjecture that the characteristics of the property distributions (the initial states) play a more important role in defining boundaries than the rules of interaction themselves. Flat horizontal and vertical surfaces, surfaces with chamfered or filleted edges and minimal surfaces, have more to do with their corresponding property distributions than the rules of their transformation. Although it would be difficult to claim control over the outcome of such a method of transformation (after all predictability is a major concern in the theory of automata), a visual inspection shows the direct relationship between a property distribution and its formal outcome.

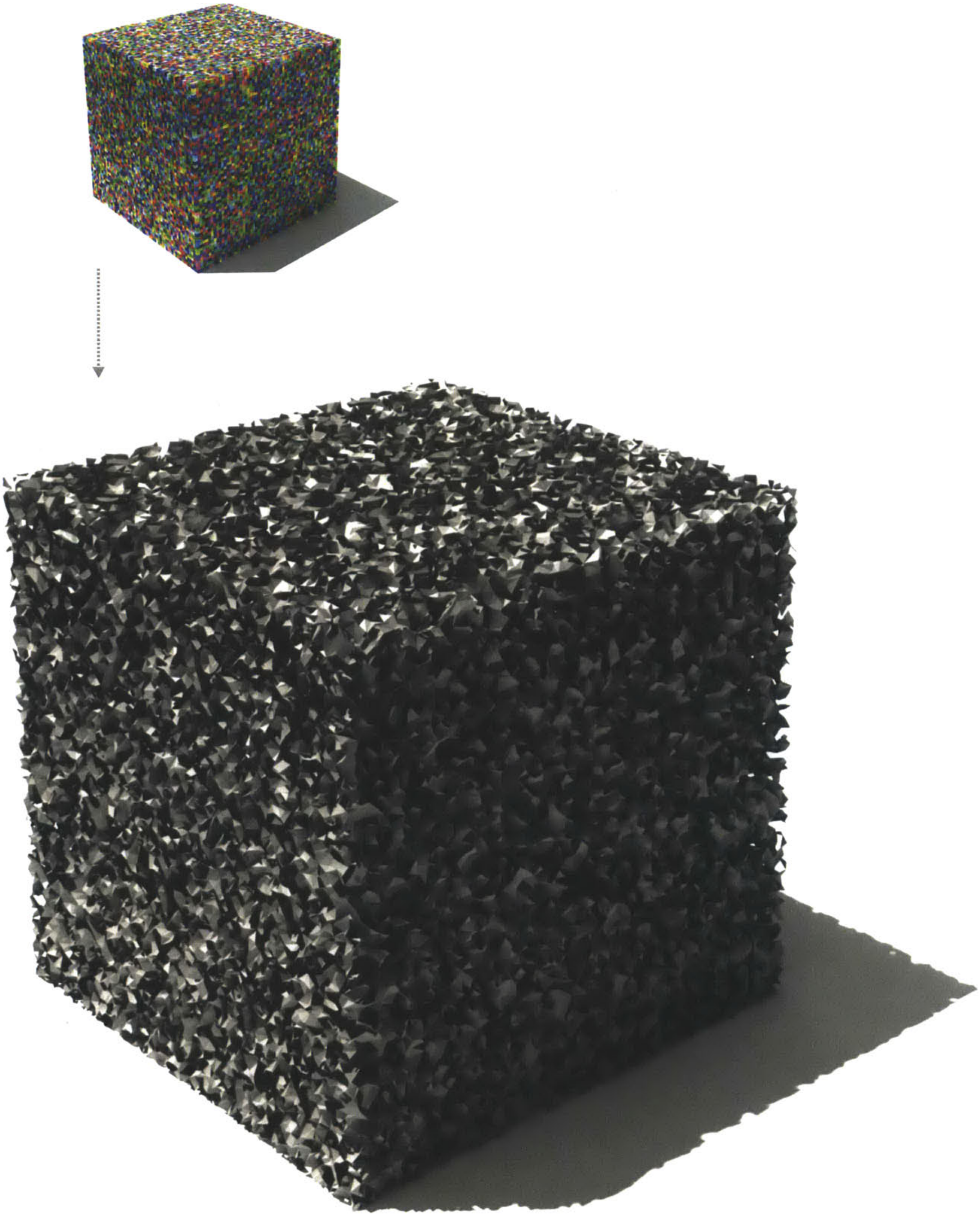


Figure 58: Boundary Transformation. Initial State. MC@CNa=0.5. Vspace 3D.

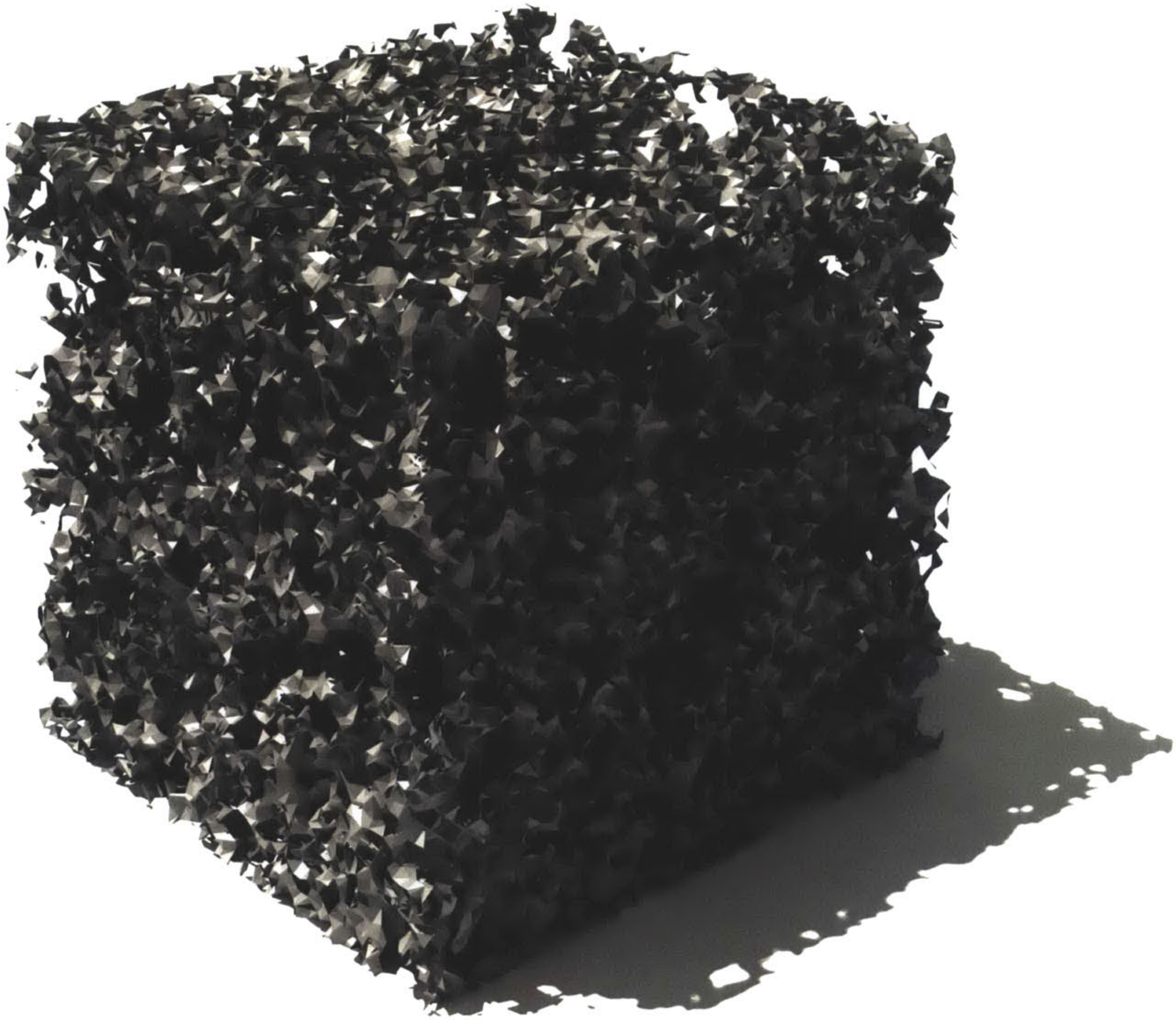


Figure 59: Boundary Transformation. Step 1. MC@CNa=0.5. Vspace 3D.

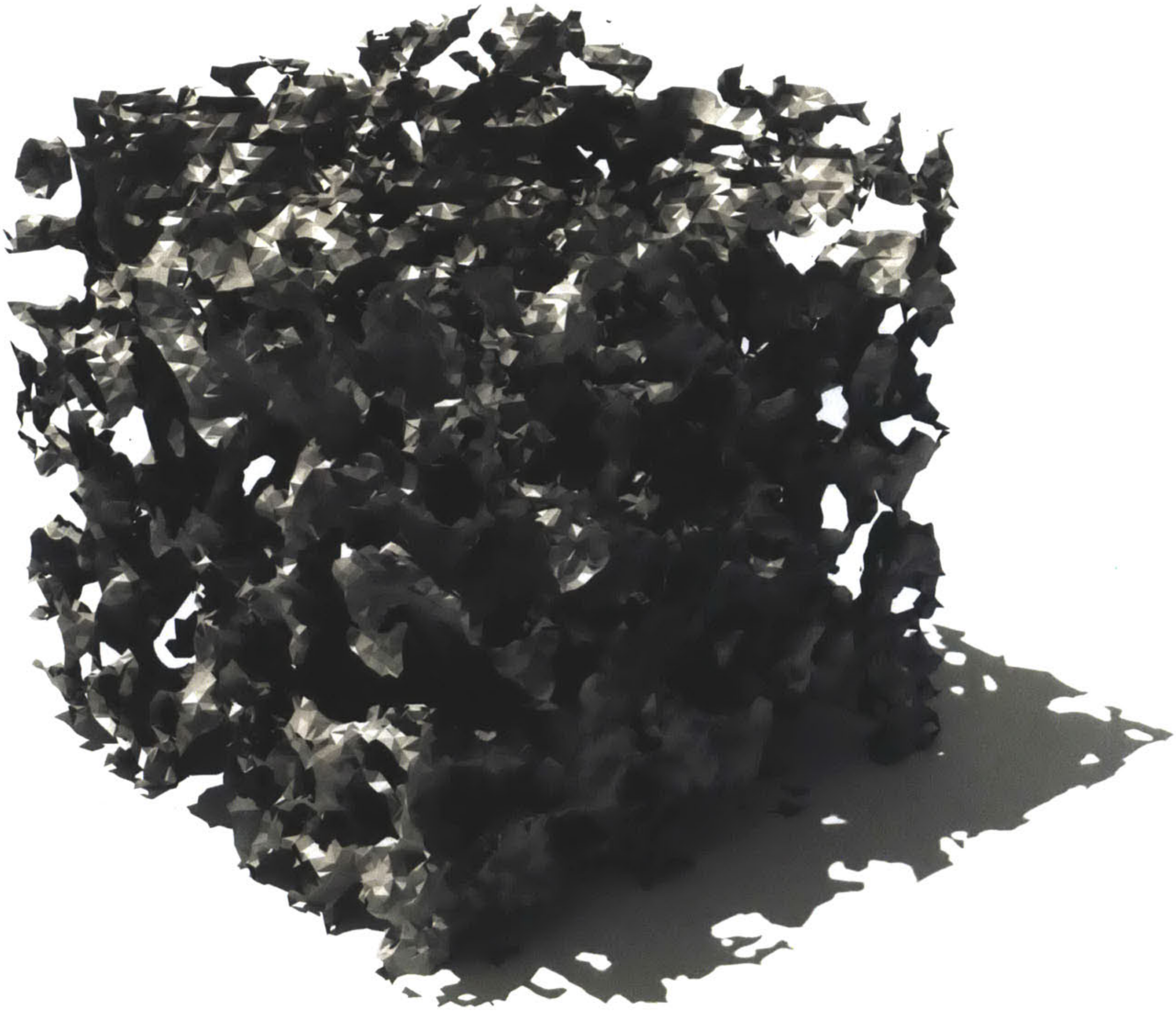


Figure 60: Boundary Transformation. Step 4. MC@CNa=0.5. Vspace 3D.

Figure 61: Boundary Transformation. Step 8. MC@CNa=0.5. Vspace 3D.

Figure 62: Boundary Transformation. Step 12. MC@CNa=0.5. Vspace 3D.

Figure 63: Boundary Transformation. Step 16. MC@CNa=0.5. Vspace 3D.

BZ Automata Rules
+
Figure 64: view of "Surrogate House" (Tsamis 2010). Initial state : Random Distribution

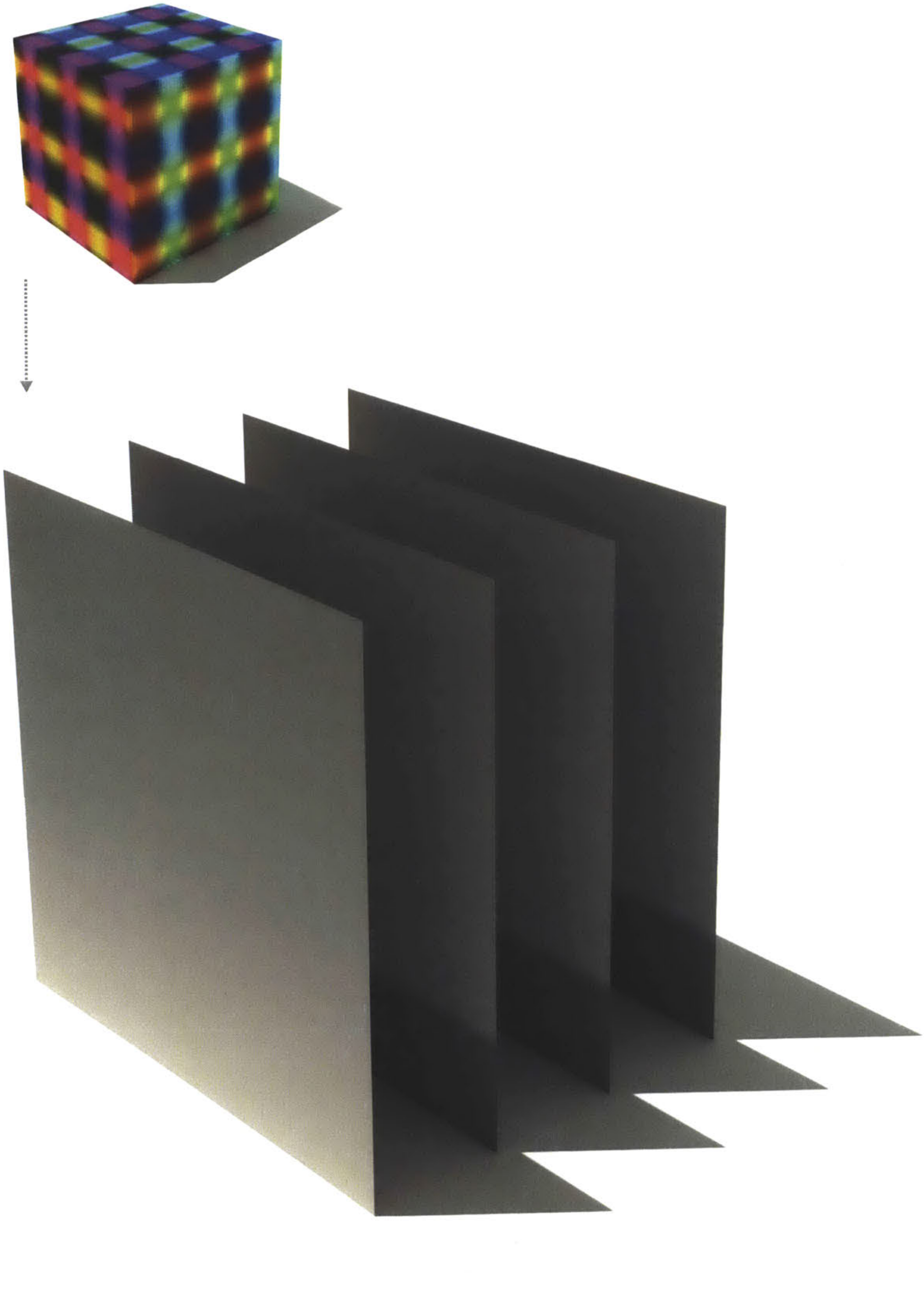


Figure 65: Boundary Transformation. Initial State. Equation. MC@CNa=0.5. Vspace 3D.

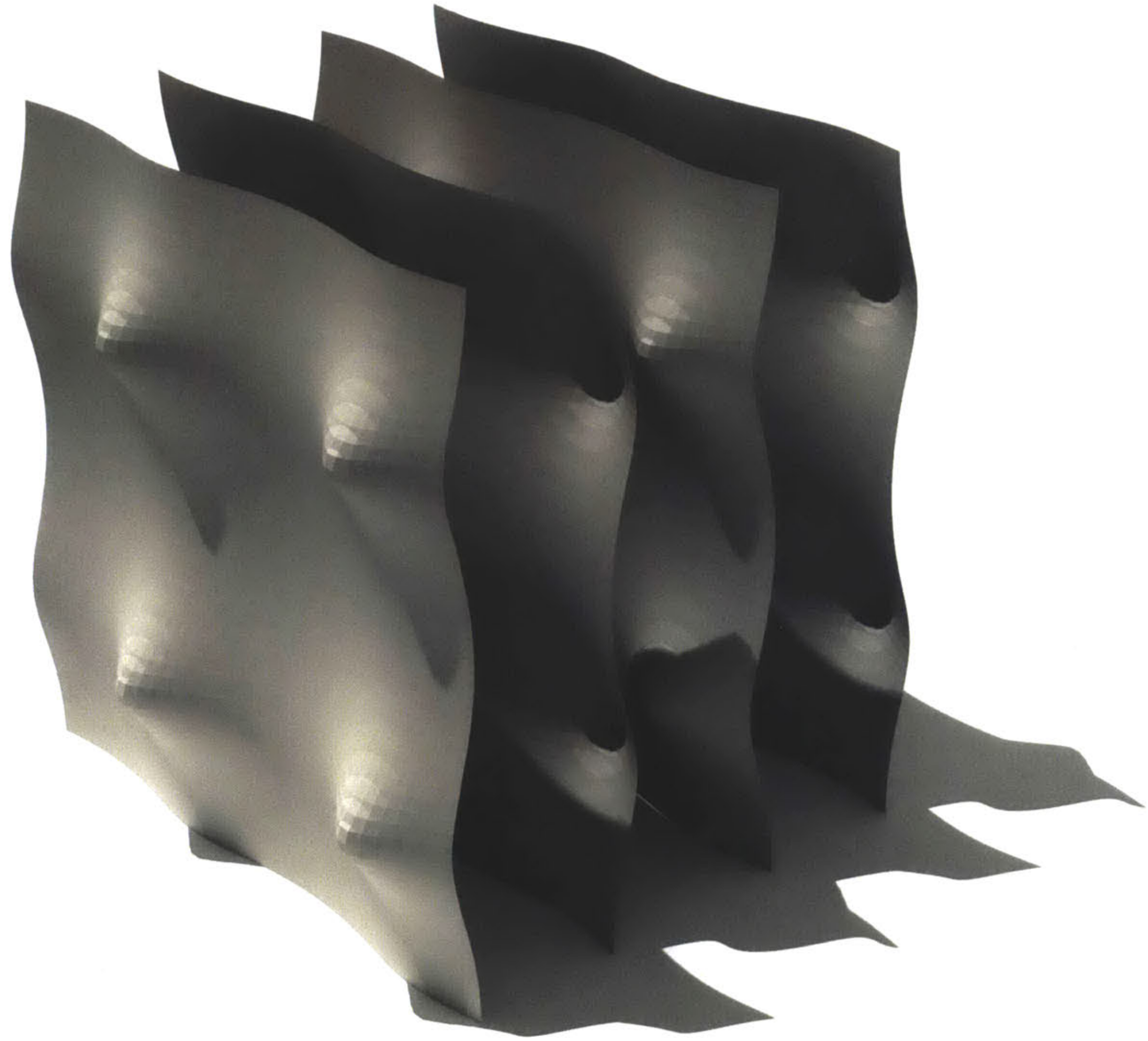


Figure 66: Boundary Transformation. Step 1. Equation. MC@CNa=0.5. Vspace 3D.

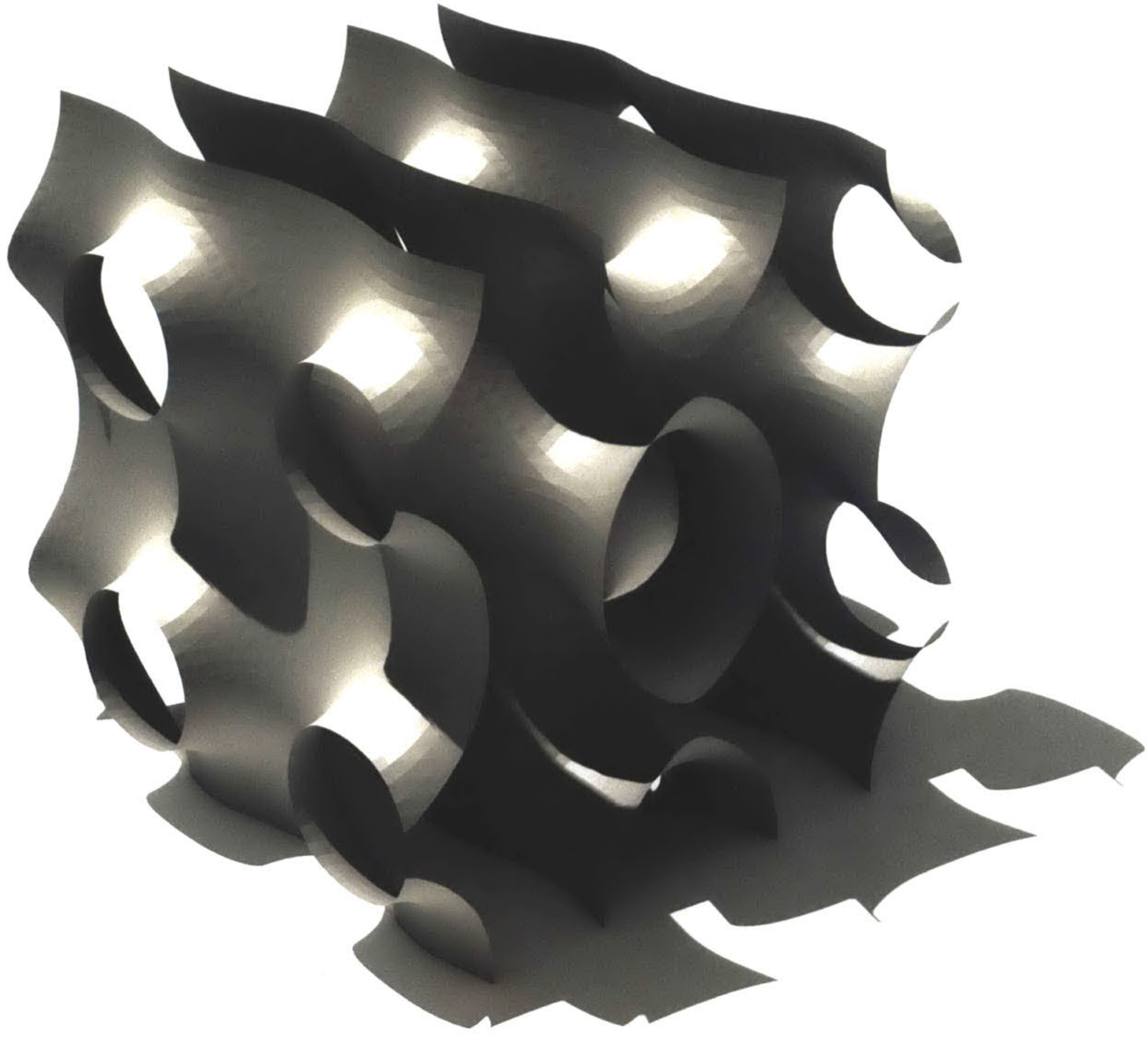


Figure 67: Boundary Transformation. Step 4. Equation. MC@CNa=0.5. Vspace 3D.

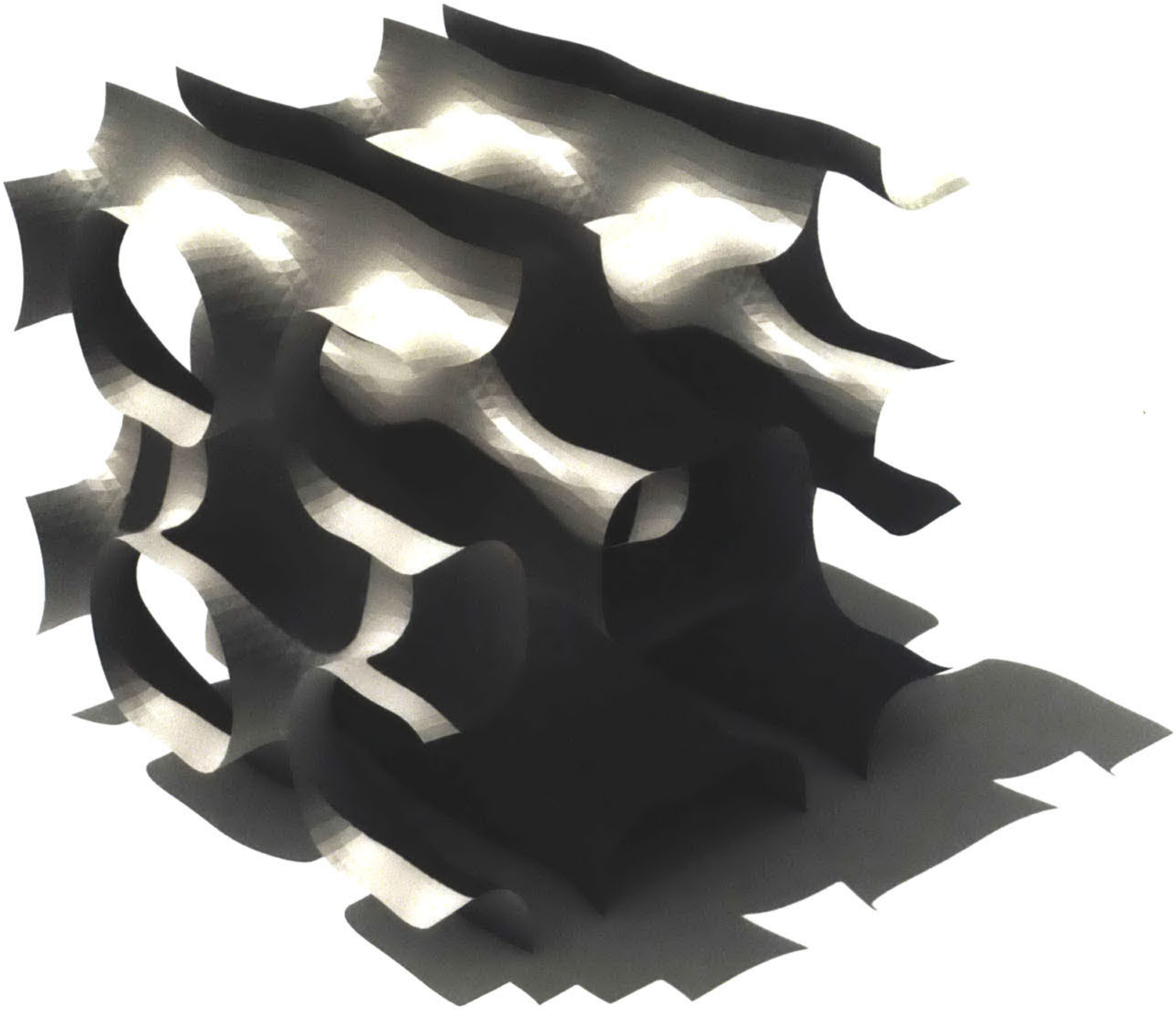


Figure 68: Boundary Transformation. Step 8. Equation. MC@CNa=0.5. Vspace 3D.

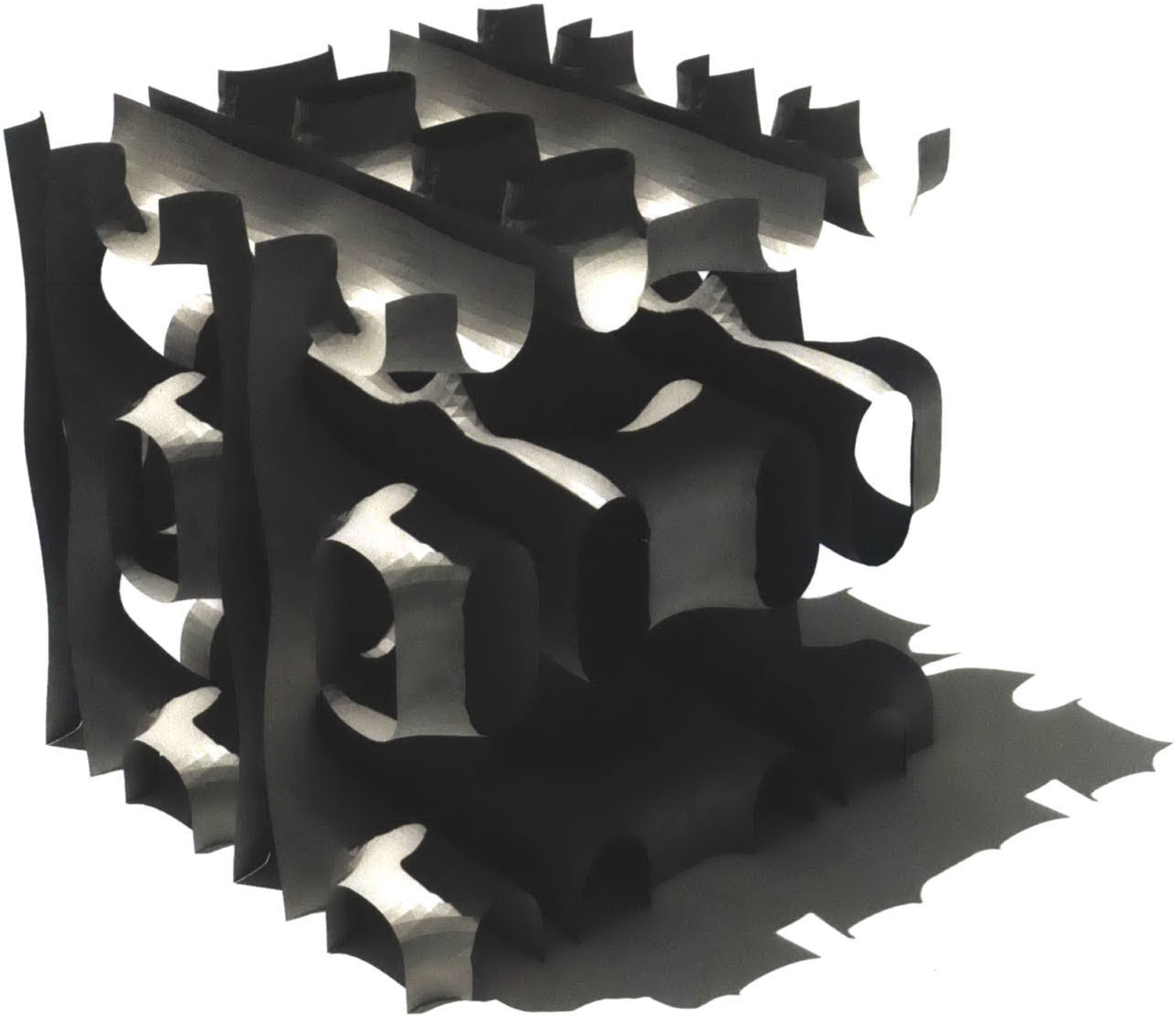


Figure 69: Boundary Transformation. Step 12. Equation. MC@CNa=0.5. Vspace 3D.

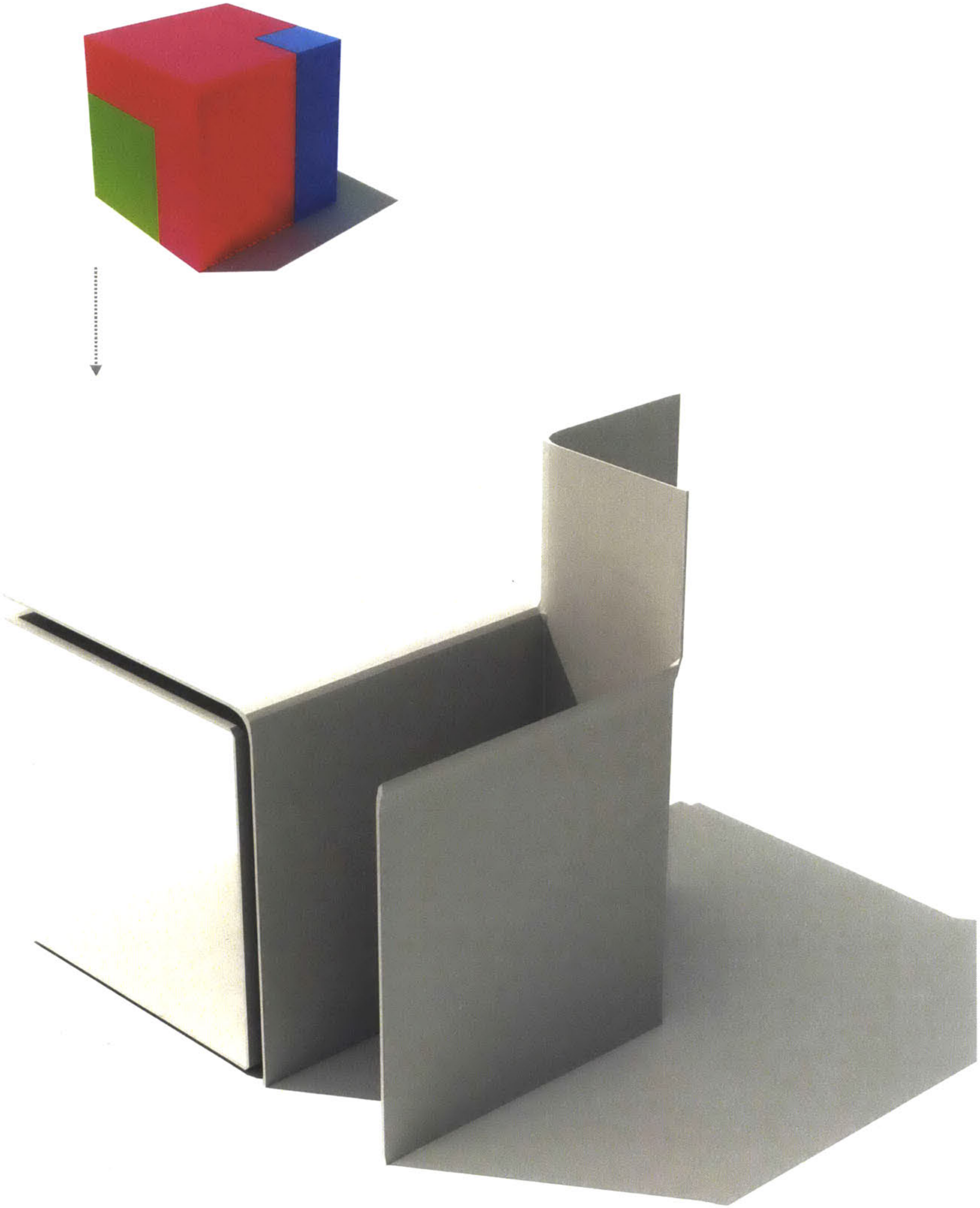


Figure 70: Boundary Transformation. Initial State. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

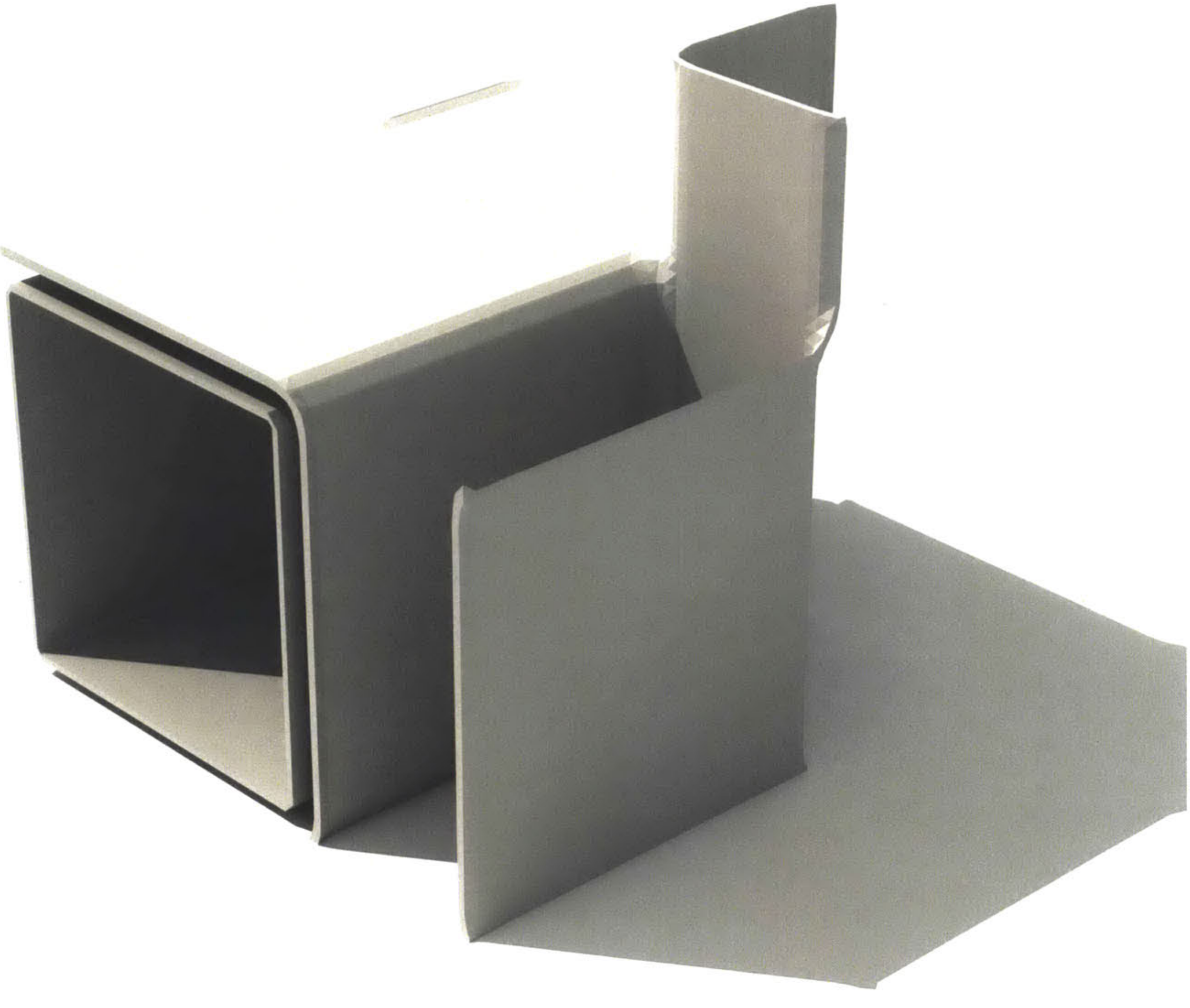


Figure 71: Boundary Transformation. Step 01. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

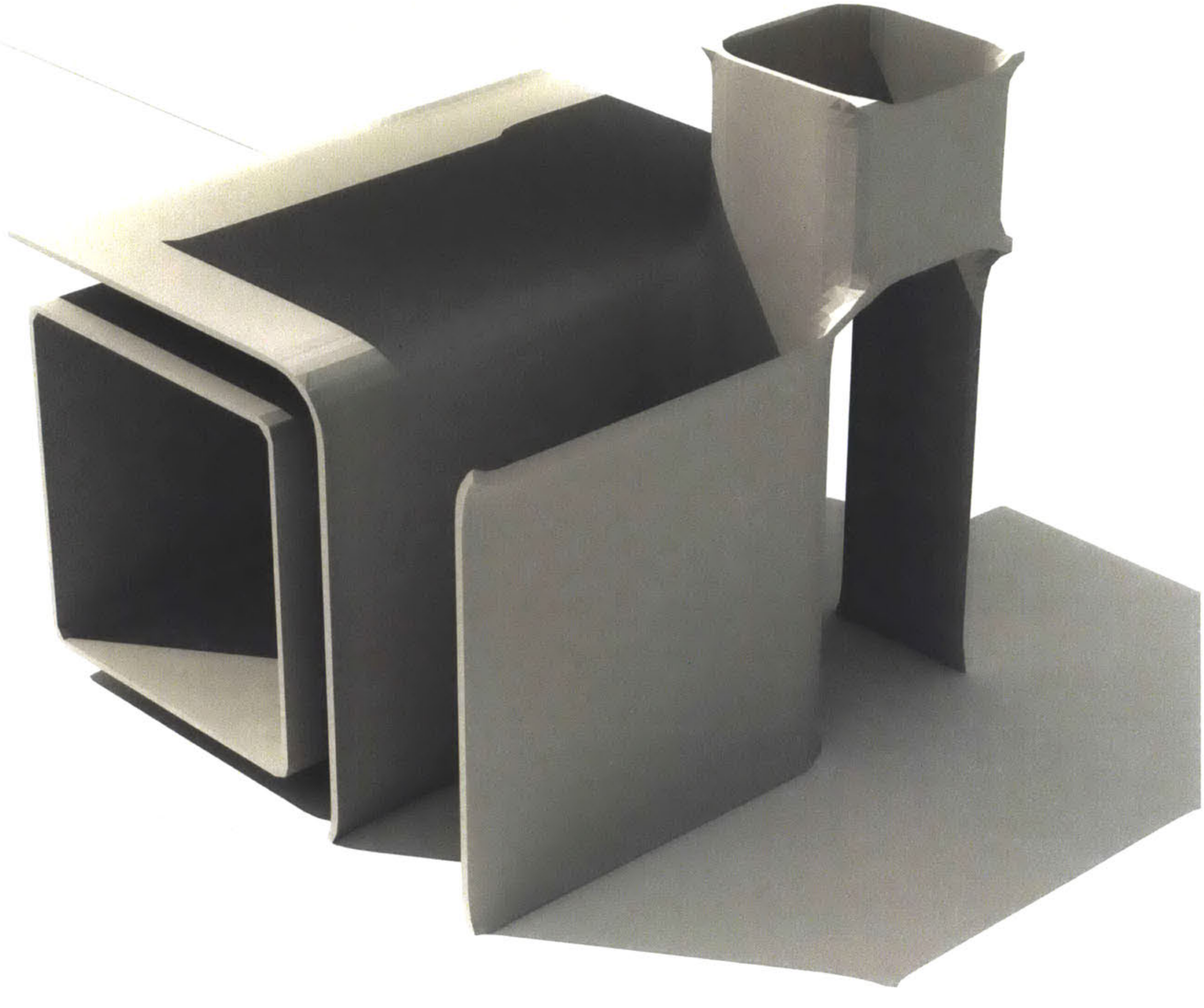


Figure 72: Boundary Transformation. Step 04. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

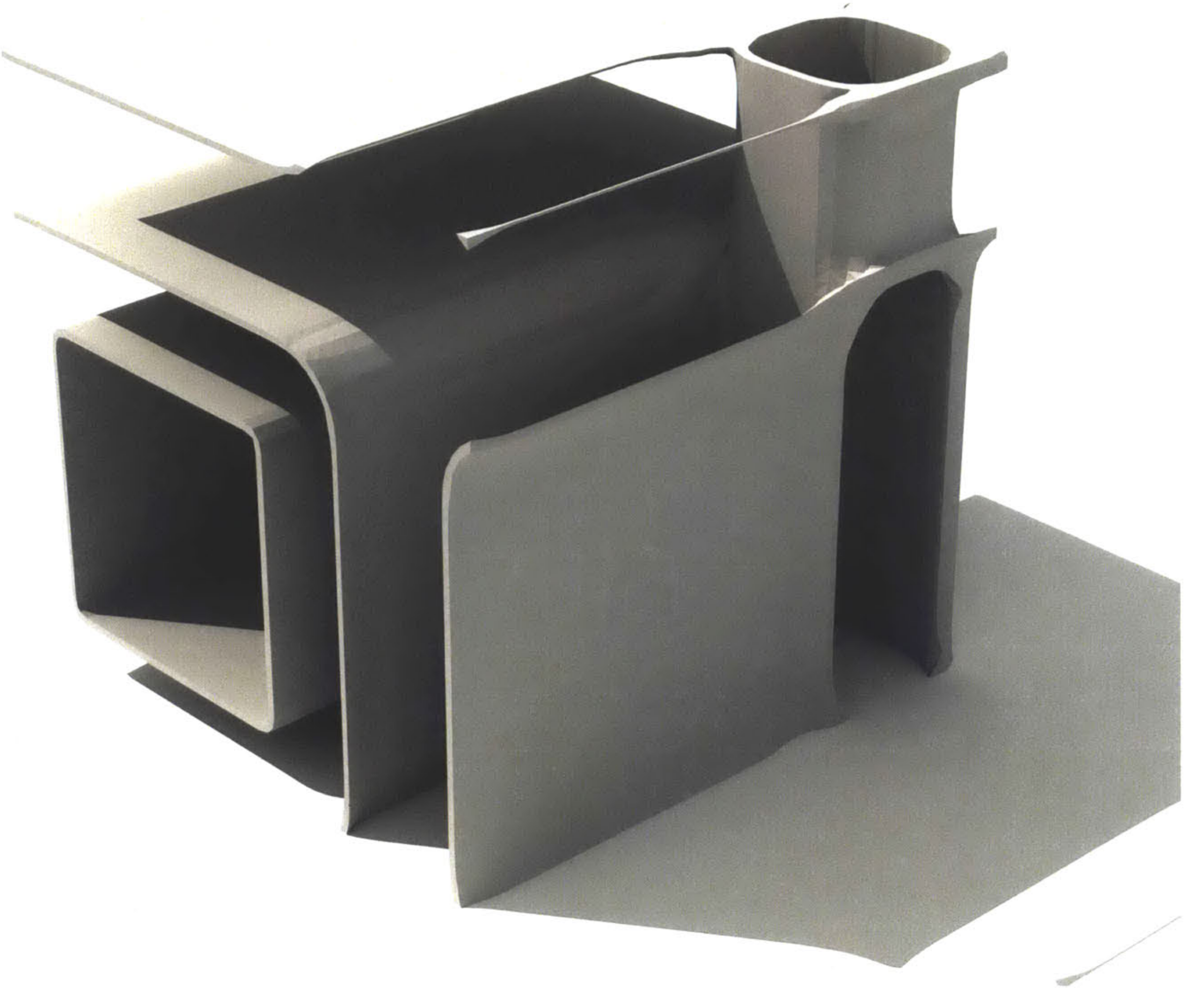


Figure 73: Boundary Transformation. Step 06. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

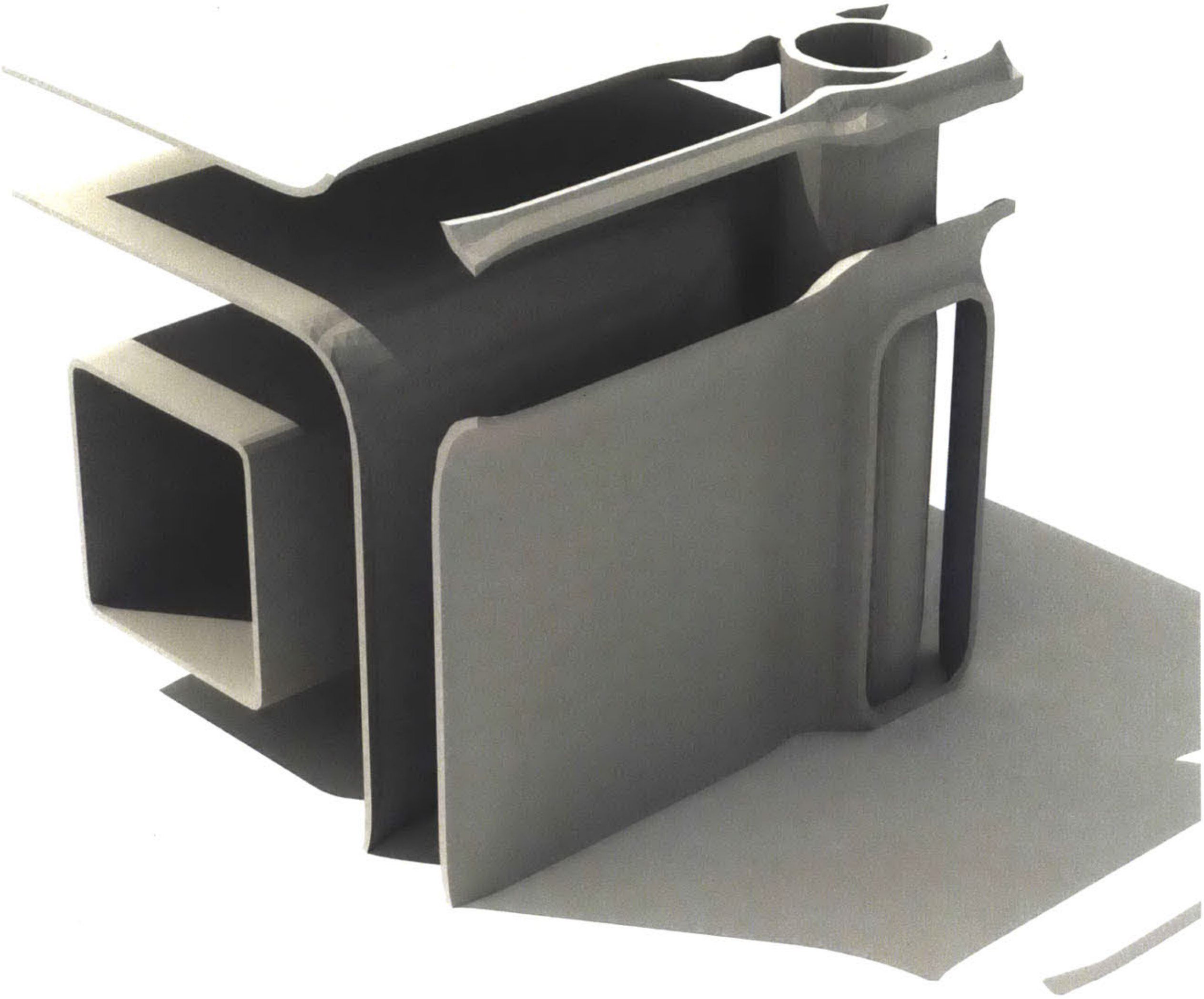


Figure 74: Boundary Transformation. Step 08. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

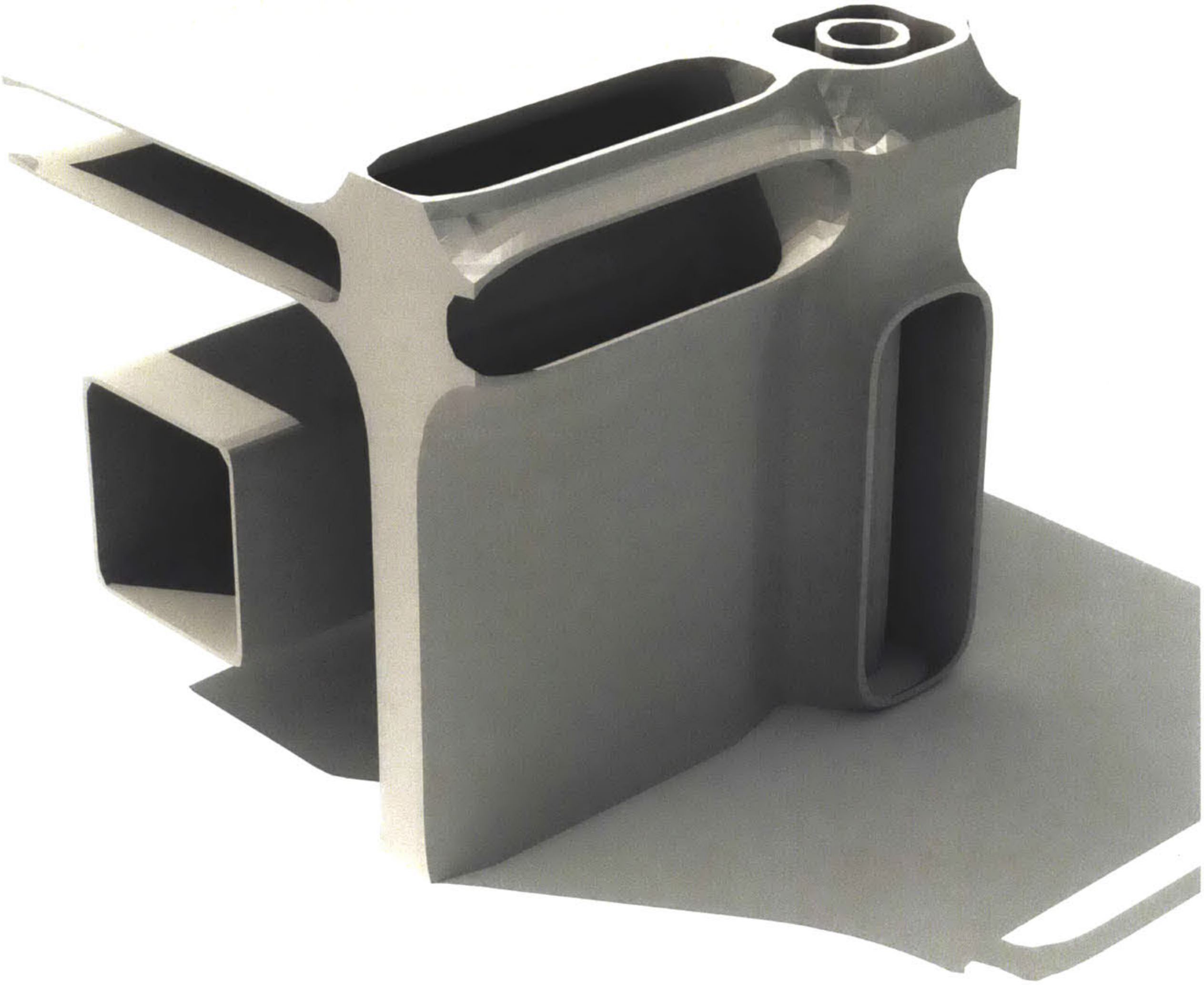


Figure 75: Boundary Transformation. Step 10. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

Figure 76: Boundary Transformation. Step 12. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

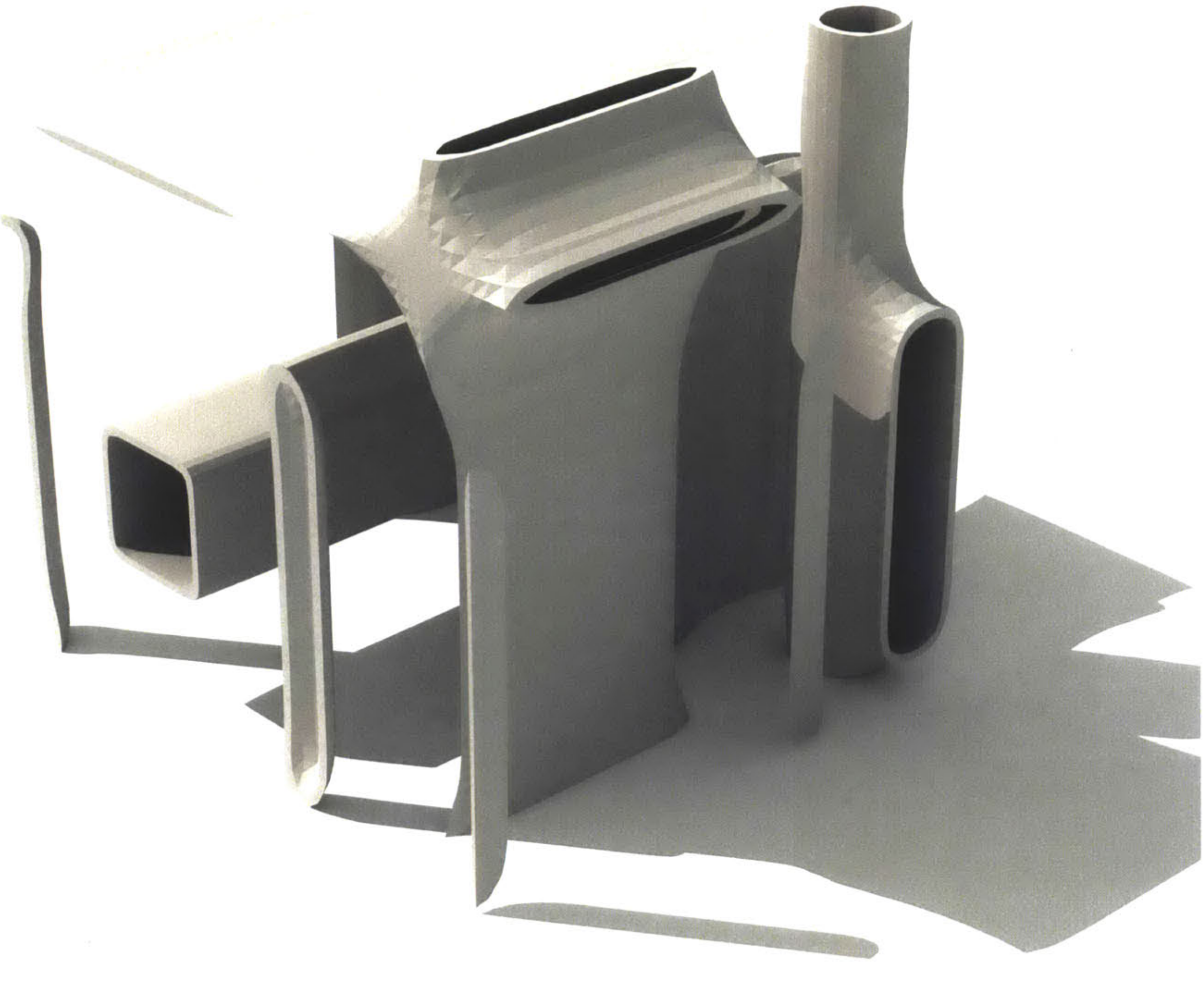


Figure 77: Boundary Transformation. Step 14. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

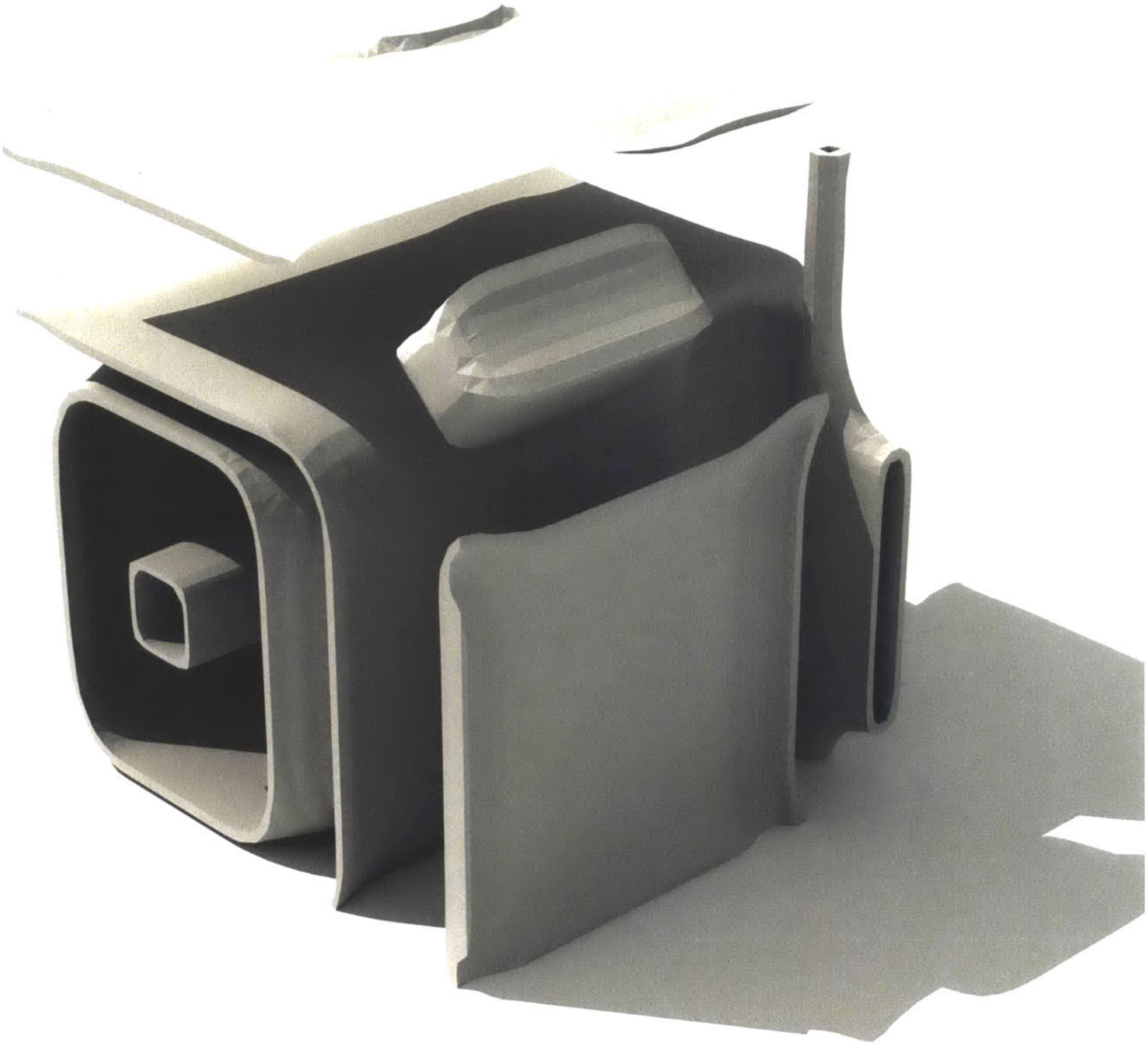


Figure 78: Boundary Transformation. Step 16. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

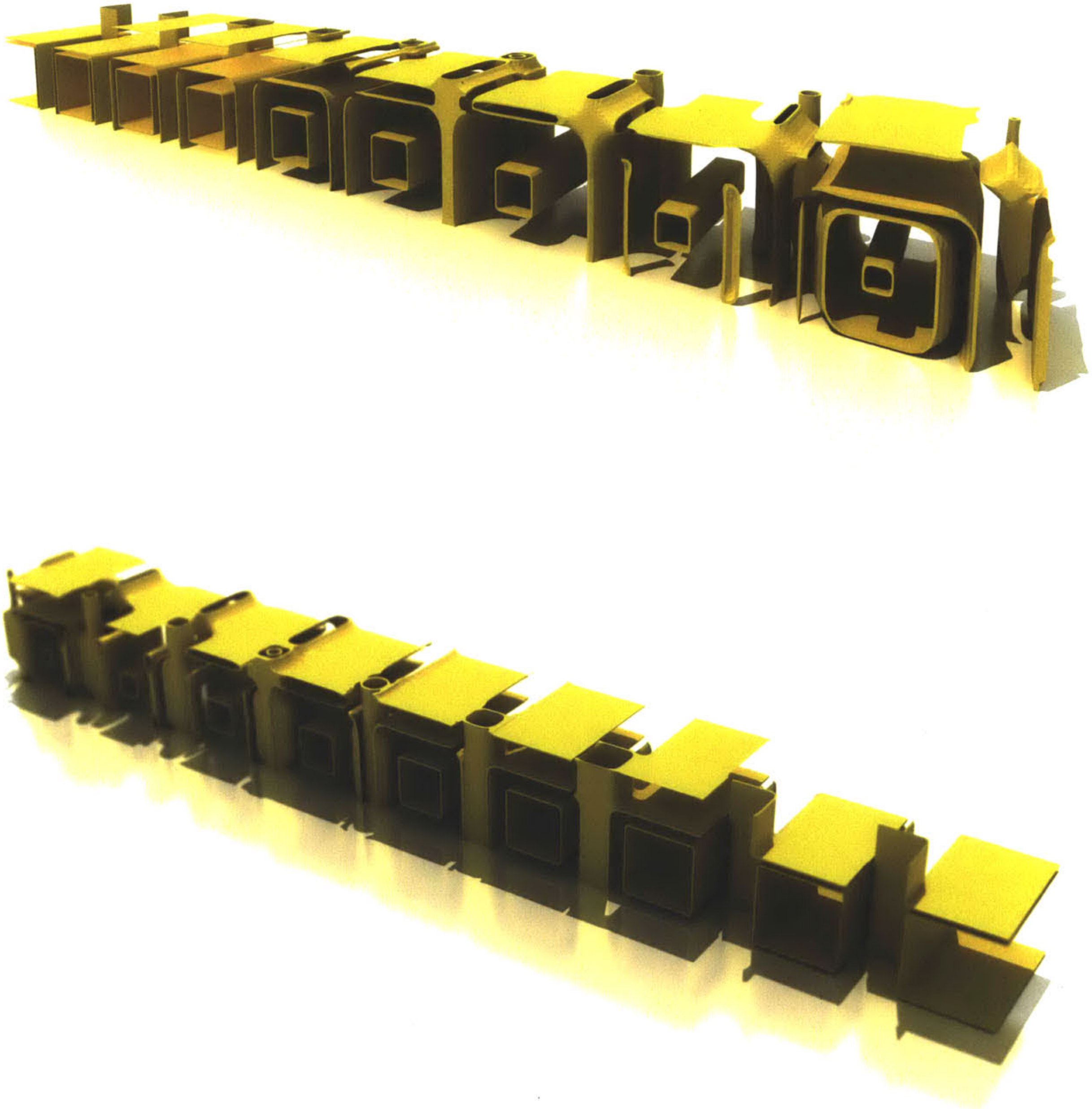


Figure 79: Boundary Transformation. Sequence. Aperiodic Grid. MC@CNa=0.5. Vspace 3D.

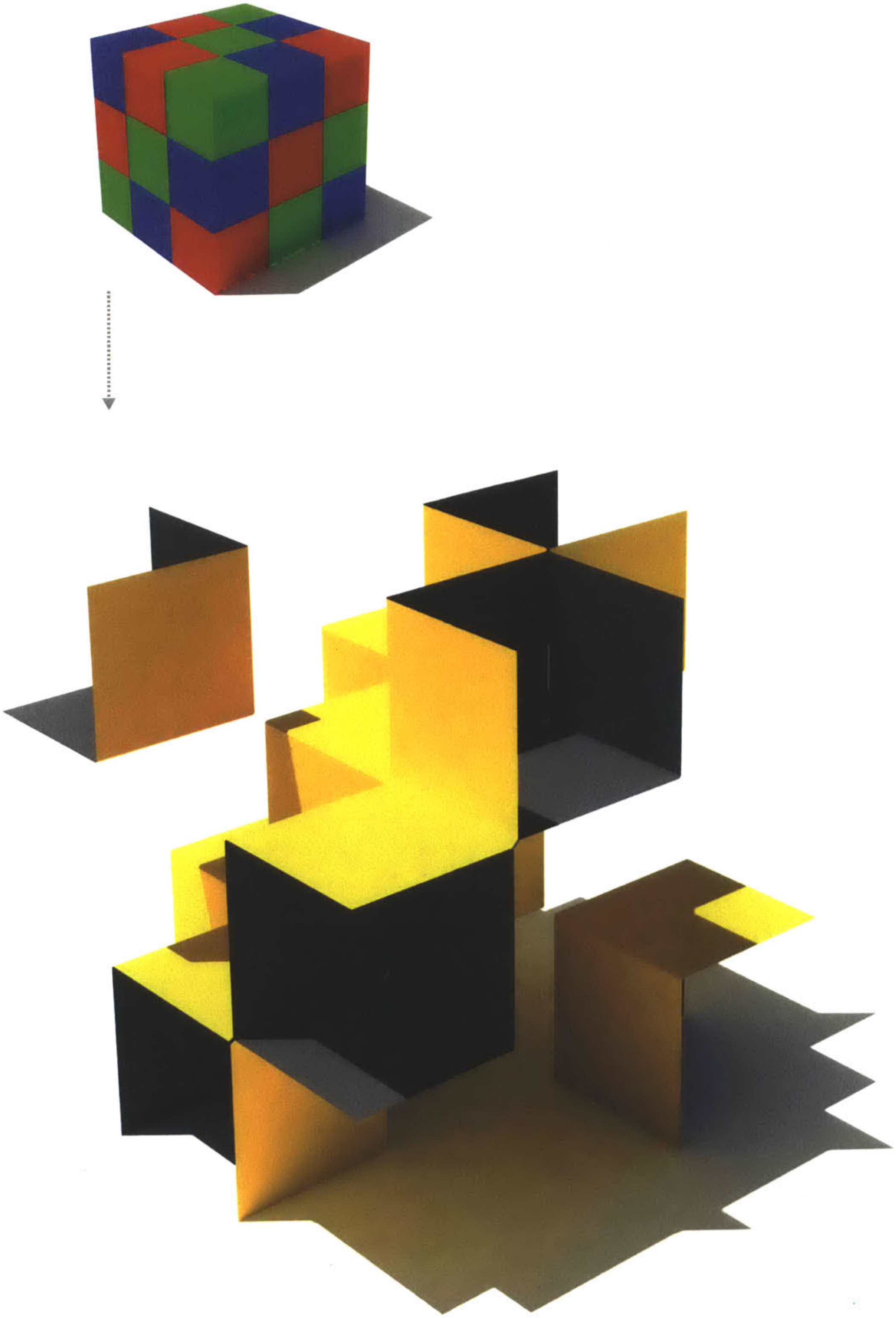


Figure 80: Boundary Transformation. Initial State 16. Periodic Grid. MC@CNa=0.5. Vspace 3D.

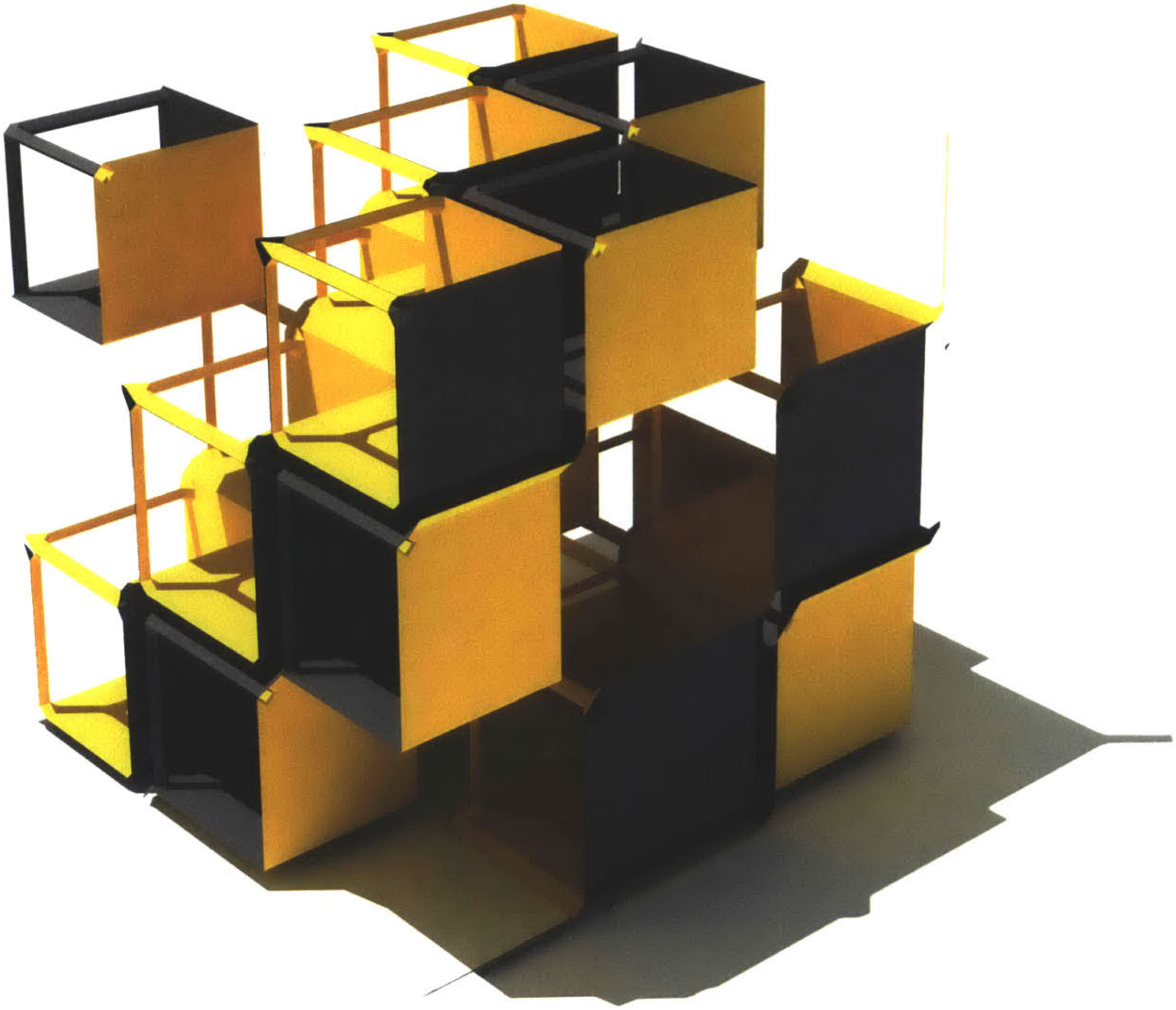


Figure 81 : Boundary Transformation. Step 01. Periodic Grid. MC@CNa=0.5. Vspace 3D.

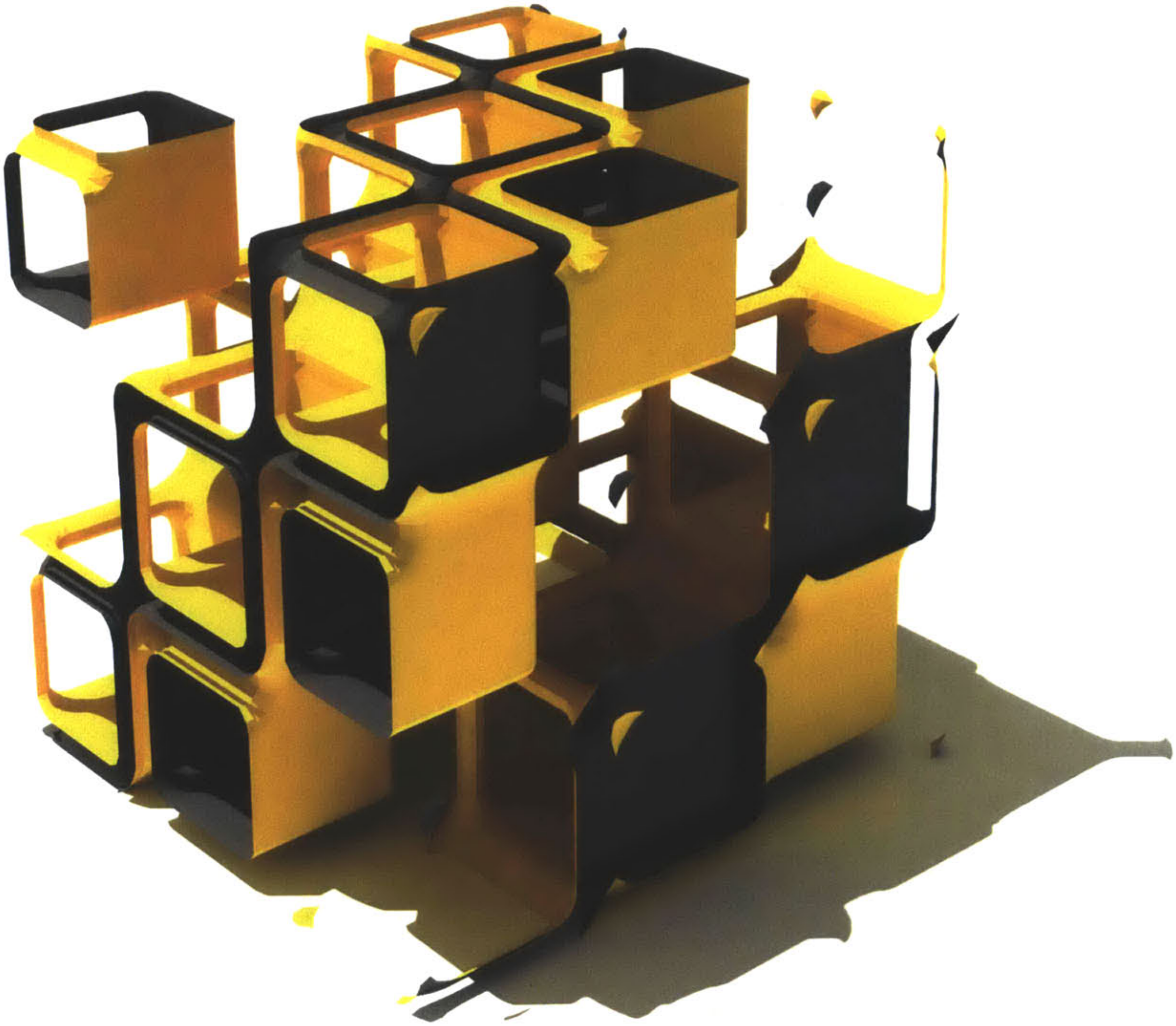


Figure 82: Boundary Transformation. Step 04. Periodic Grid. MC@CNa=0.5. Vspace 3D.

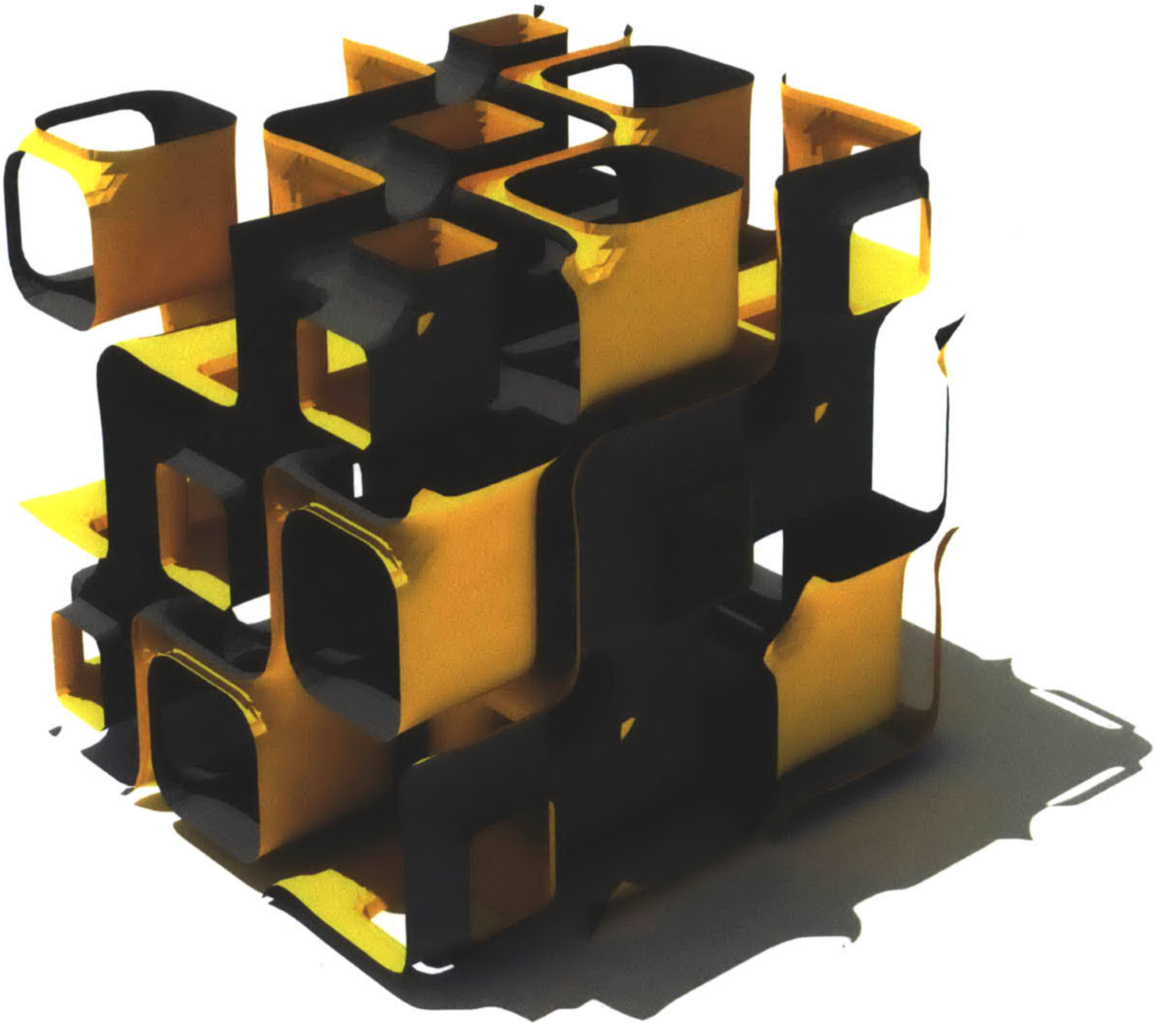


Figure 83: Boundary Transformation. Step 08. Periodic Grid. MC@CNa=0.5. Vspace 3D.

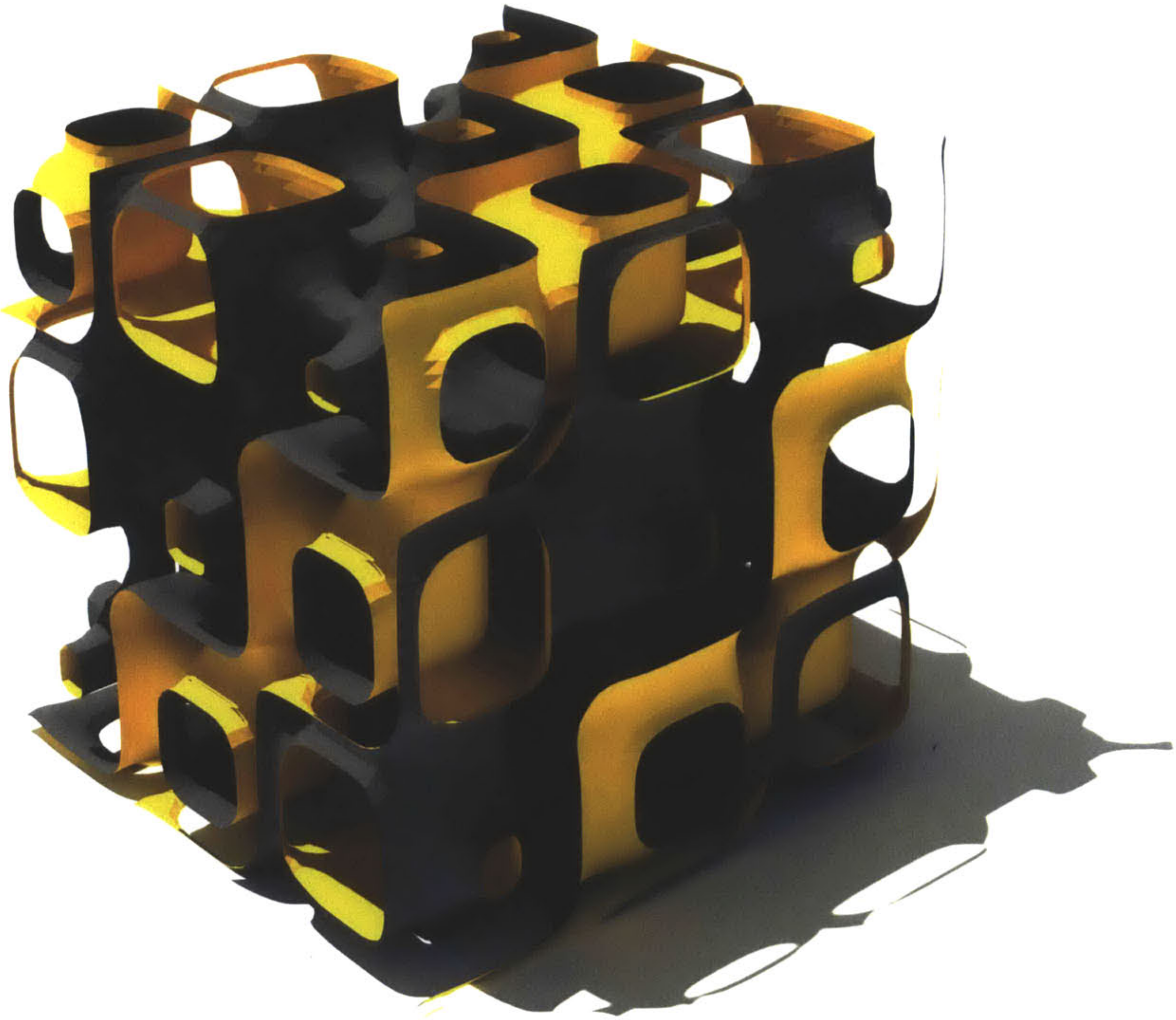


Figure 84: Boundary Transformation. Step 12. Periodic Grid. MC@CNa=0.5. Vspace 3D.

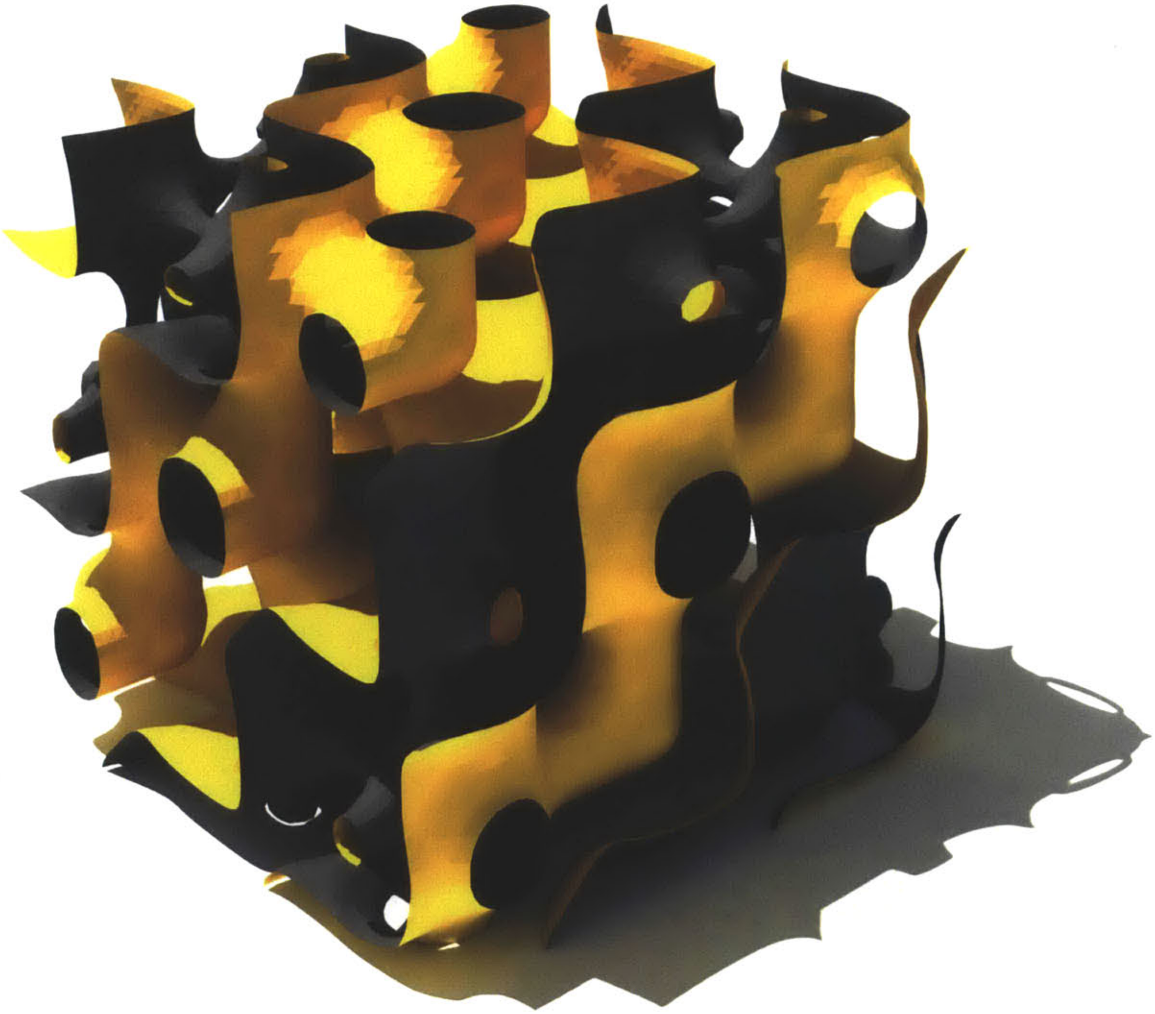
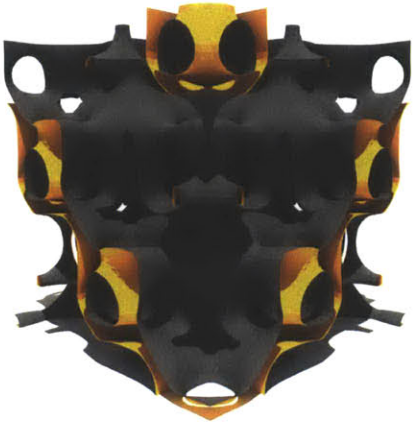


Figure 85: Boundary Transformation. Step 16. Periodic Grid. MC@CNa=0.5. Vspace 3D.



Happy Martian in Sauna Suit

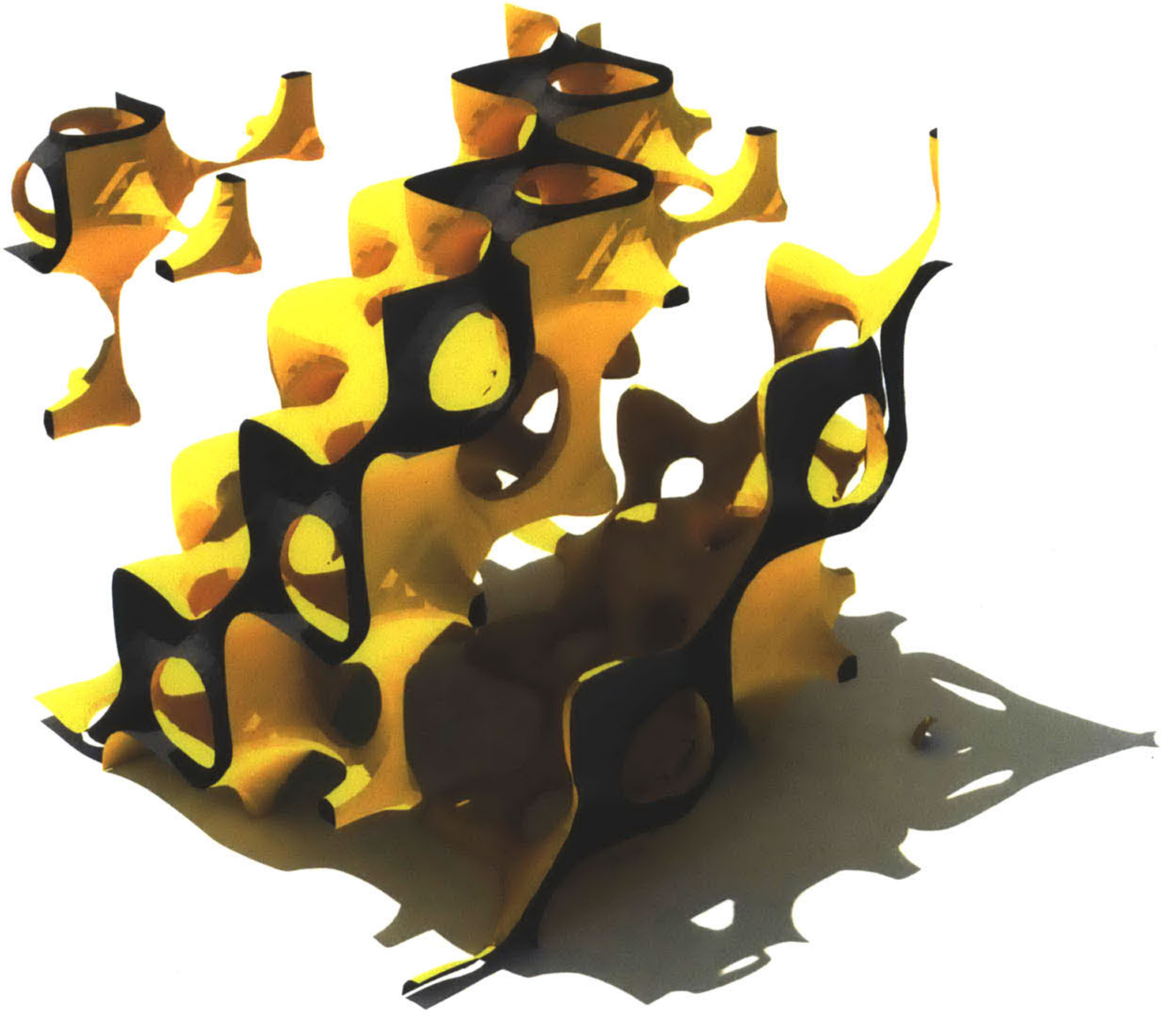


Figure 86: Boundary Transformation. Step 20. Periodic Grid. MC@CNa=0.5. Vspace 3D.

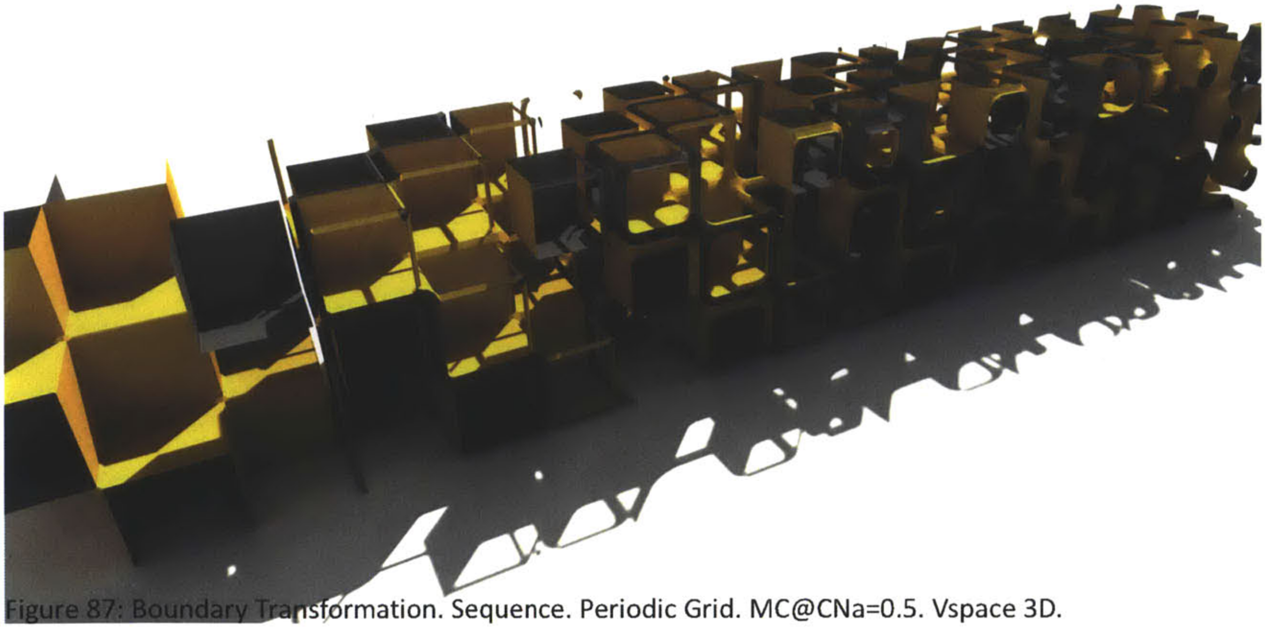


Figure 87: Boundary Transformation. Sequence. Periodic Grid. MC@CNa=0.5. Vspace 3D.

Transformation – Boundary Offset (Figures 88 - 89)

VSpace allows the designer to offset a boundary relative to an already-defined boundary. Like in any B-Rep software one can derive a boundary parallel to an original at a fixed distance, in VSpace an offset boundary can be derived by querying an "offset" property. In Figure 88 for a given property distribution ten offset boundaries of property A are produced at concentrations CNa = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0. Since two different concentration values of the same property can never occupy the same location in space, offset boundaries can never intersect.

The boundaries shown here are "equidistant". Only in VSpace the distance is measured in property distance and not geometric distance. Two consecutive boundaries are parallel in property space and not necessarily parallel in geometry space. Although in this example the property distance is always 0.1, the geometric distance can vary depending on the diffusion rate of the given property in space (Figure 89). If the diffusion rate of a given property is constant within a distribution then the resulting offset boundaries would also be geometrically parallel.

Diffusion Rate

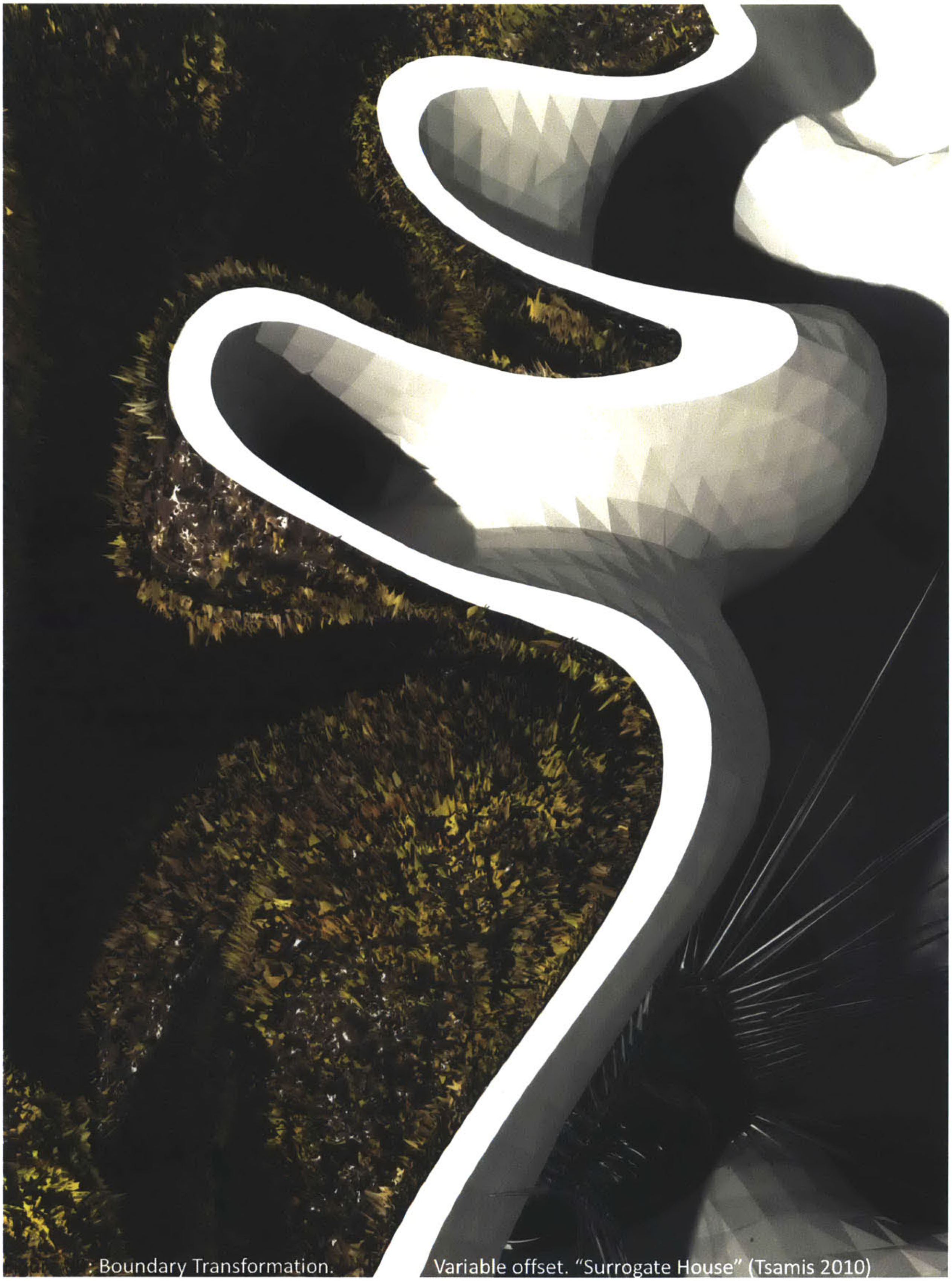
It is important to clarify the concept of **Diffusion Rate**: In any given property distribution we have seen how Property A, B and C can have concentrations CN that can continuously vary in space between 0 and 1. We have seen examples where concentration values change rapidly from one voxel to the next (Figure 16) and we have also seen examples in which the concentration values gradually change producing gradients of transition (Figure 21). The Diffusion Rate indicates how "fast" a given concentration changes in space from one voxel to the next. In VSpace, using the method of standard deviation in a voxel neighborhood, a Diffusion Rate analysis tool is implemented that indicates for any given Property Distribution, the rate with which a Concentration value changes from one voxel to the next[146] (Figures 90, 91). In the case of offset boundaries when the Diffusion rate is constant the geometric distance between boundaries is also constant - the two boundaries are geometrically parallel - while when the diffusion rate is not constant the two boundaries are not geometrically parallel[147].

---

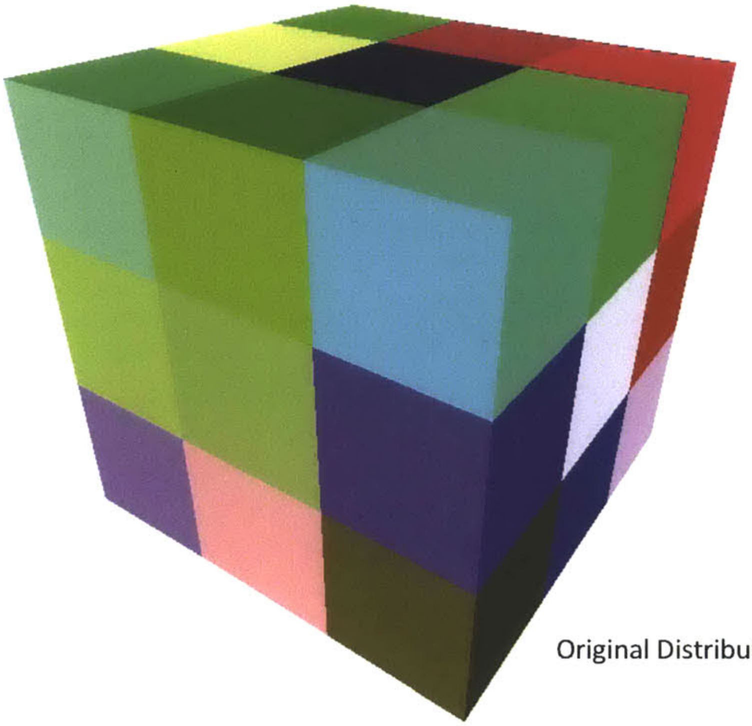
[146] This tool can be thought of as the equivalent to a Curvature analysis tool for NURBS surfaces in B-Rep software.

[147] Think here the variable offset tools that exist in advanced parametric modeling environments such as Rhinoceros's Grasshopper and Bentley's Generative Components.

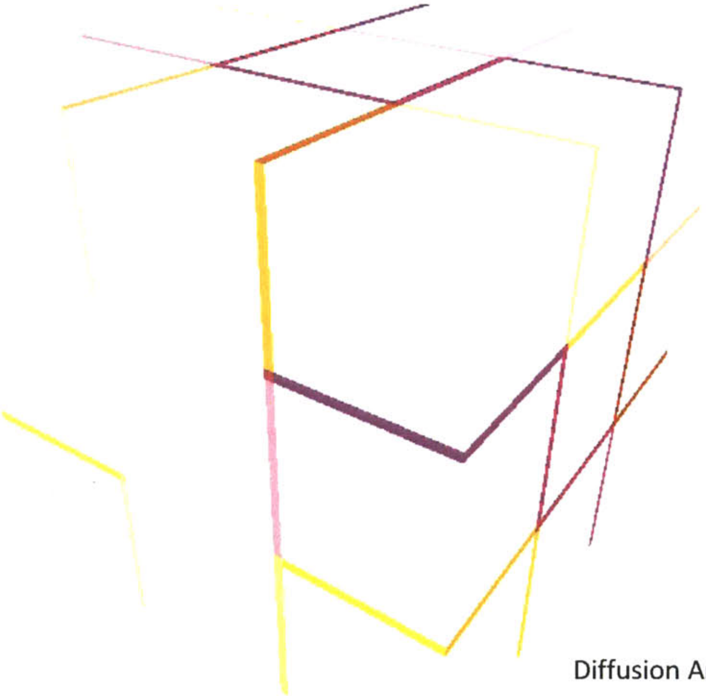
Figure 88: Boundary Transformation. Multiple Offsets . Vspace 3D.



: Boundary Transformation. Variable offset. "Surrogate House" (Tsamis 2010)

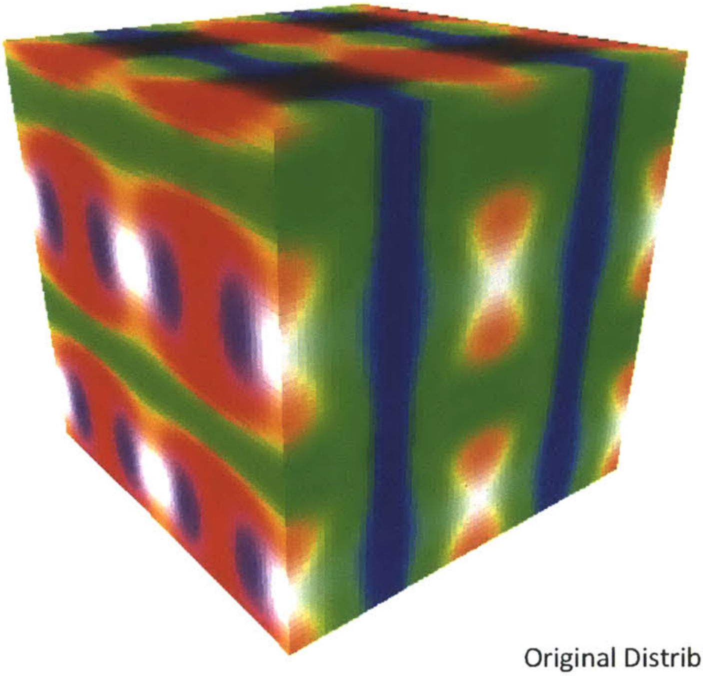


Original Distribution

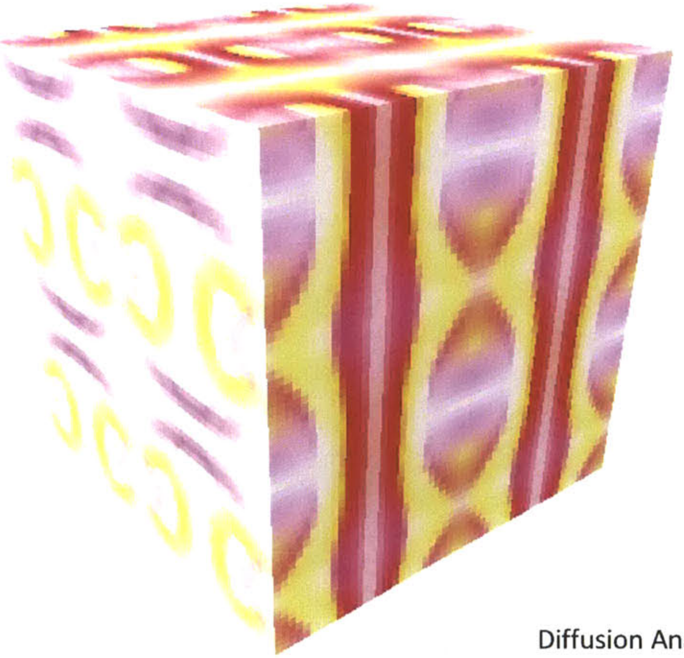


Diffusion Analysis

Figure 90: Diffusion Analysis. High Rate Diffusion Vspace 3D. (screen capture)



Original Distribution



Diffusion Analysis

Figure 91: Diffusion Analysis. Low Rate Diffusion Vspace 3D. (screen capture)

Transformation – Boundary Booleans.

In B-rep software, Boolean operations can occur between two or more boundary objects. Following the Venn Diagrams (Figure 92), for Boundary shapes that define regions A and B, we can have Boolean Difference (A minus B), Boolean Union (A or B) and Boolean Intersection (A and B). As the Venn diagrams suggest, for Boolean operations to work in B-Rep all boundaries have to be closed. In other words, there needs to be a definition of inside and an outside.

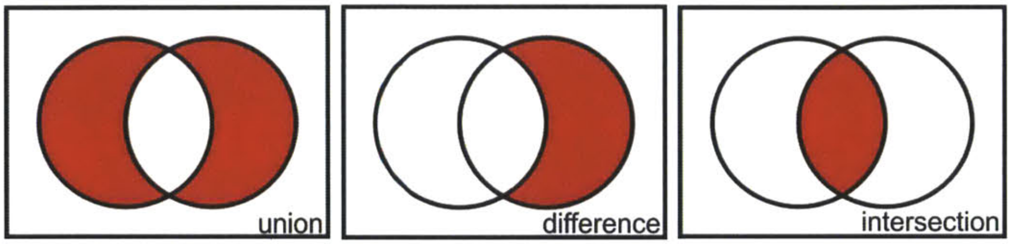


Figure 92 : Venn Diagrams. Union, Difference, Intersection.

In VSpace there are two distinct methods for Boolean operations to take place. For both methods Boolean operations can work for closed as well as for open boundaries.

Boolean Boundary Trim

In this first case boundaries can be trimmed at Voxels of intersection with other Boundaries. Furthermore a convention is established. For any given Boundary MC@CN = v any Concentration CN > v is considered "inside" the boundary while any Concentration CN < v is considered "outside". For two boundaries MC@CNa=0.46 and MC@CNb=0.11 (Figure 93) we have:

1. Transformation - Trim Difference. (Figure 94) The new boundary is composed of Boundary MC@CNa = 0.46 which is drawn only when the containing Voxels also have CNb > 0.11 And MC@CNb = 0.11 which is drawn only when the containing Voxels also have CNa < 0.46

2. Transformation – Trim Union. (Figure 95) The new boundary is composed of Boundary MC@CNa = 0.46 which is drawn only when the containing Voxels also have CNb > 0.11 And MC@CNb = 0.11 which is drawn only when the containing Voxels also have CNa > 0.46

3. Transformation - Trim Intersection. (Figure 96)The new boundary is composed of Boundary MC@CNa = 0.46 which is drawn only when the containing Voxels also have CNb < 0.11 And MC@CNb = 0.11 which is drawn only when the containing Voxels also have CNa < 0.46

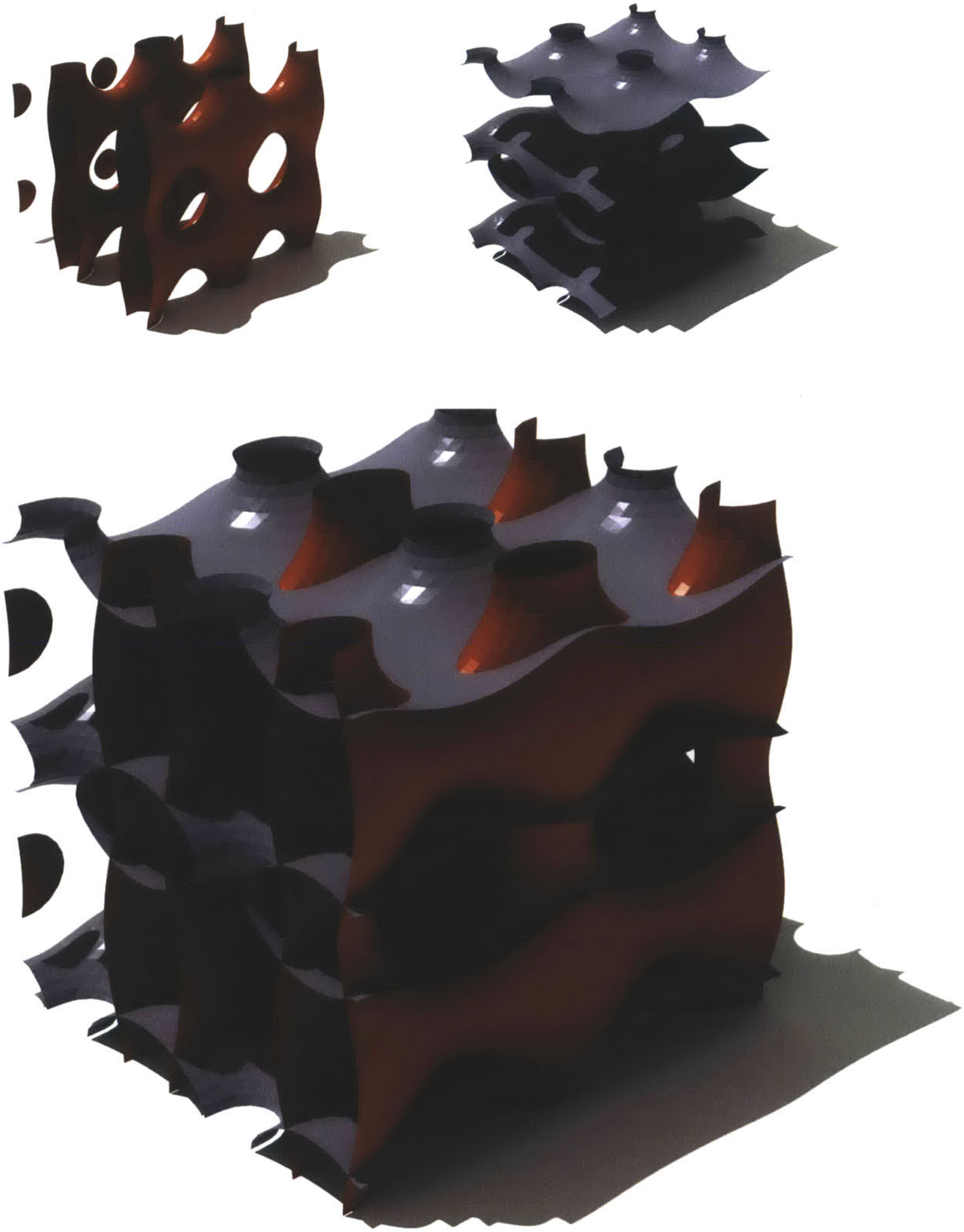
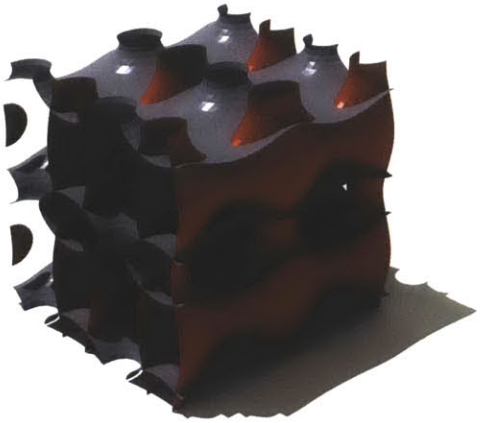


Figure 93: Boundaries MC@CNa=0.83 and MC@CNc=0.64



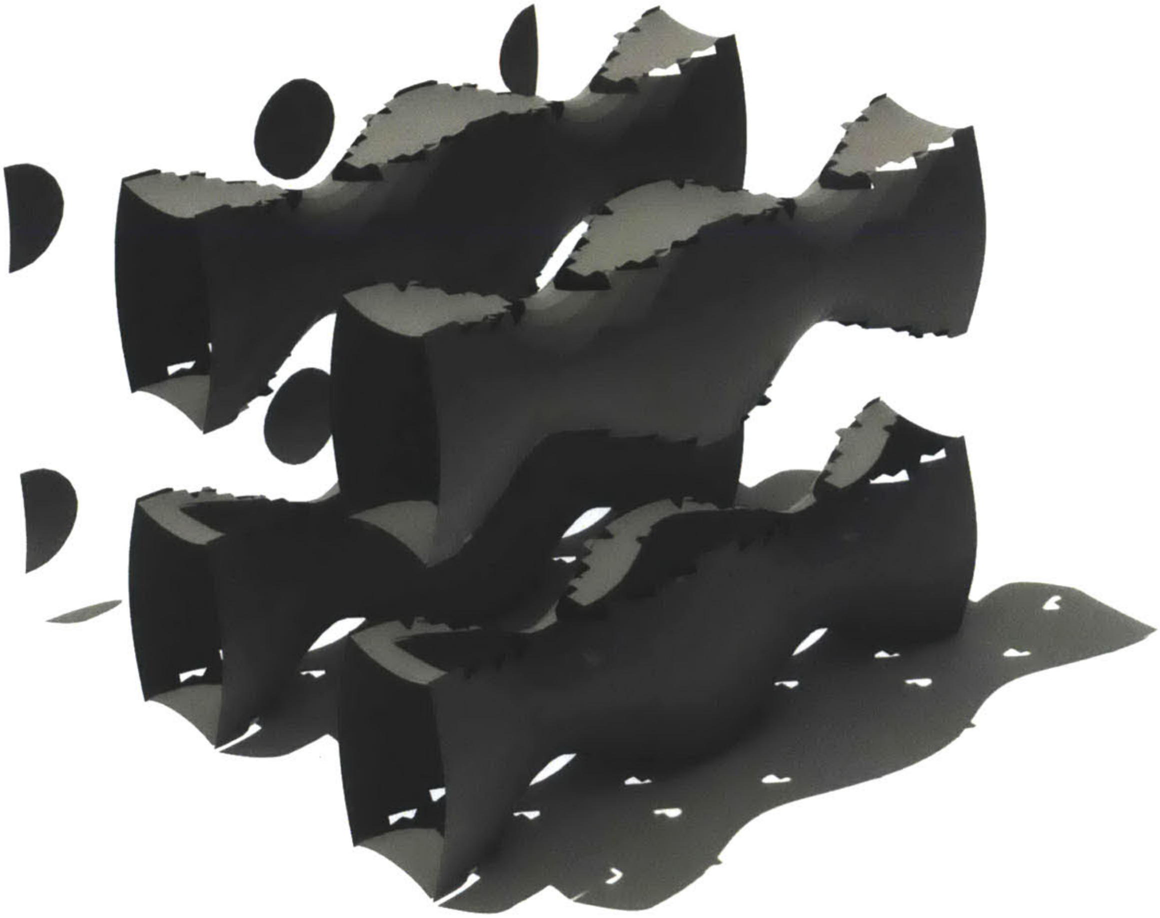


Figure 94: Boundaries MC@CNa=0.83 and MC@CNc=0.64. Trim Difference. (Bug in code at intersection ;)

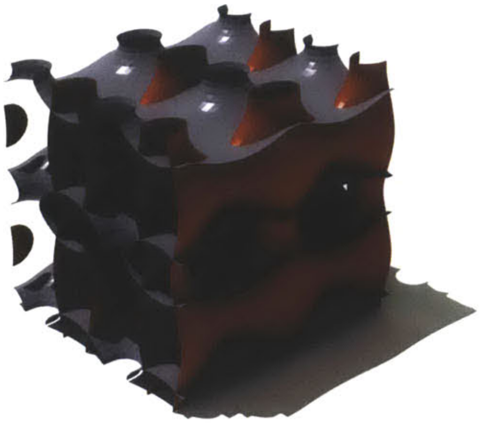


Figure 95: Boundaries MC@CNa=0.83 and MC@CNc=0.64. Trim Union. (Bug in code at intersection ;)

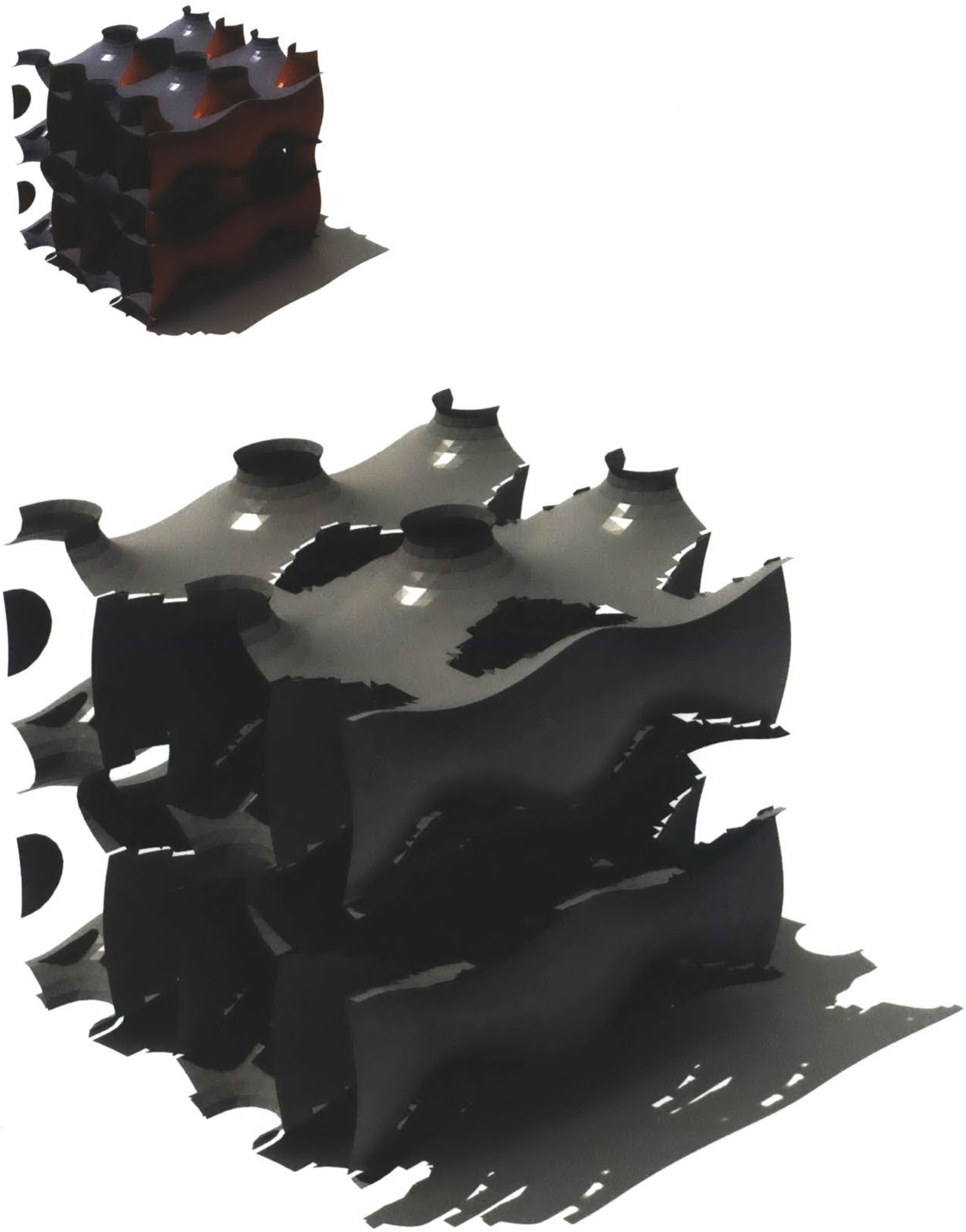


Figure 96: Boundaries MC@CNa=0.83 and MC@CNc=0.64 Trim Intersection. (Bug in code at intersection ;)

Boolean Boundary

In this case Boolean operations first happen at the property level (as seen in the Binary Property Transformations) and then the marching cube is applied at the resultant calculations. For the same two boundaries MC@CNa=0.46 and MC@CNb=0.11 we have:

1. **Transformation – Boolean Difference.** (Figure 97) The new Boolean Boundary is calculated by applying the Marching Cube for Concentration CN = CNa - CNb, in this case MC@CNa-b = 0.35.
2. **Transformation – Boolean Union.** (Figure 98) The new Boolean Boundary is calculated by applying the Marching Cube for Concentration CN = CNa + CNb – CNa*CNb, in this case MC@CNa+b = 0.5194
3. **Transformation – Boolean Intersection.** (Figure 99) The new Boolean Boundary is calculated by applying the Marching Cube for Concentration CN = CNa*CNb, in this case MC@CNa+b = 0.0506.

1.5.10 VSpace - Boundaries + Properties

So far in VSpace we have seen how properties work, how they can be instantiated and also transformed to new properties. In the case of three properties A, B and C, any given voxel can contain all three properties with values that range from 0 to 1. We have also defined a **Property Shape (PS)** as a subset of a given Property Distribution **bound** by an upper and a lower limit. PS (A, upper limit, lower limit).

On the other hand, we have seen how boundaries can be instantiated and transformed relative to properties. At any given moment during the design process, those two modes of representation - (property mode and boundary mode) - exist in parallel. Although all design operations (computations) in VSpace happen at the level of Property, one can choose to work with one mode or the other or both together. In other words, design reasoning can happen within one or the other mode independently.

Since boundaries and properties co-exist, it is easy to imagine that boundaries can inherit properties from the voxels that define it. A **Boundary Shape (BS)!** is a boundary in VSpace with properties associated with it. If a SHAPE in shape grammarian terms can have boundaries and properties combined (in the unstructured space of pen and paper, without hierarchical order) then in VSpace a **Property Shape and a Boundary Shape are the flip side of the same coin.** They are two digital representations of a DIGITAL SHAPE that can exist in parallel.

For example given a Property Shape PS(A,0.2,0.67) (Figure. 100), a boundary MC@ CNa=0.67 although it has Concentration of property A always constant CNa=0.67 the Concentration of properties B and C that are stored in the voxels that derive boundary MC@CNa=0.67 can have values that range from 0 to 1. (0<CNb<1 and 0<CNc<1). Putting a Property Shape and a Boundary together (Figures 101, 102) we can derive a Boundary Shape BS(A) that inherits the properties of the voxels that define it (Figure 103).

From a technical perspective, it is easy to see how Boundary Shapes can be exploited further in the design process to articulate new Boundary Shapes with different color characteristics. In (Figure 104) the darker the color is of the original Boundary Shape the more Green the area of the new Boundary becomes. In the same case we can even begin to hint on representations of physical material properties. In Figure 105 the last Boundary Shape is further transformed to include transparency as a characteristic. White, green and transparent are three properties that can exist on a single boundary representation. More generally, distinct material properties, color, texture, stiffness, insulation and so on can all find a way to exist together in a single gradient definition.

A specific construction method, like the carbon fiber robotic weaving process that Peter Testa brought to the attention of the discipline[148], can further inform the design process. A Boundary Shape queried for its properties, can be articulated as densities of weaved fiber filaments resulting in a more precise material articulation (Figures 106, 107). But this is not a technical question. It is a design question. One that touches upon the subject of Tectonics.

VSpace is a "software" software. It is CAD saturated with thermodynamics. It allows us to imagine space literally derived through the manipulation of distributed properties; it serves as a mode of work that shifts our attention from objects to the articulation of an environment of 'qualities', from edges to gradients, from boundaries to properties. A re-articulation of the notion of environment as a topology of exchange between properties – a milieu of perpetual transformation – would yield a shift in discourse of the part-to-whole relationship and inevitably offer a novel understanding of tectonics-The "software" kind.

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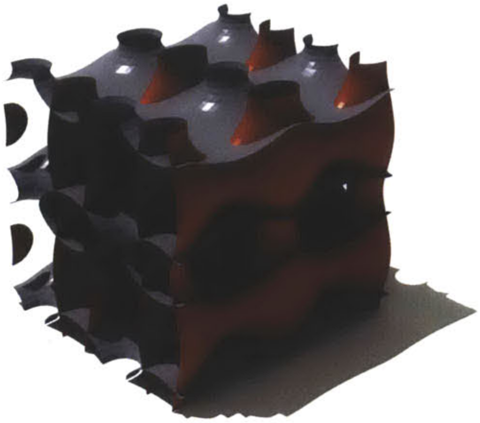
[148] Testa, Peter, *'Carbon Tower'*, in M. McQuaid, *'Extreme Textiles: Designing for High Performance'*, Princeton Architectural Press, (2005).



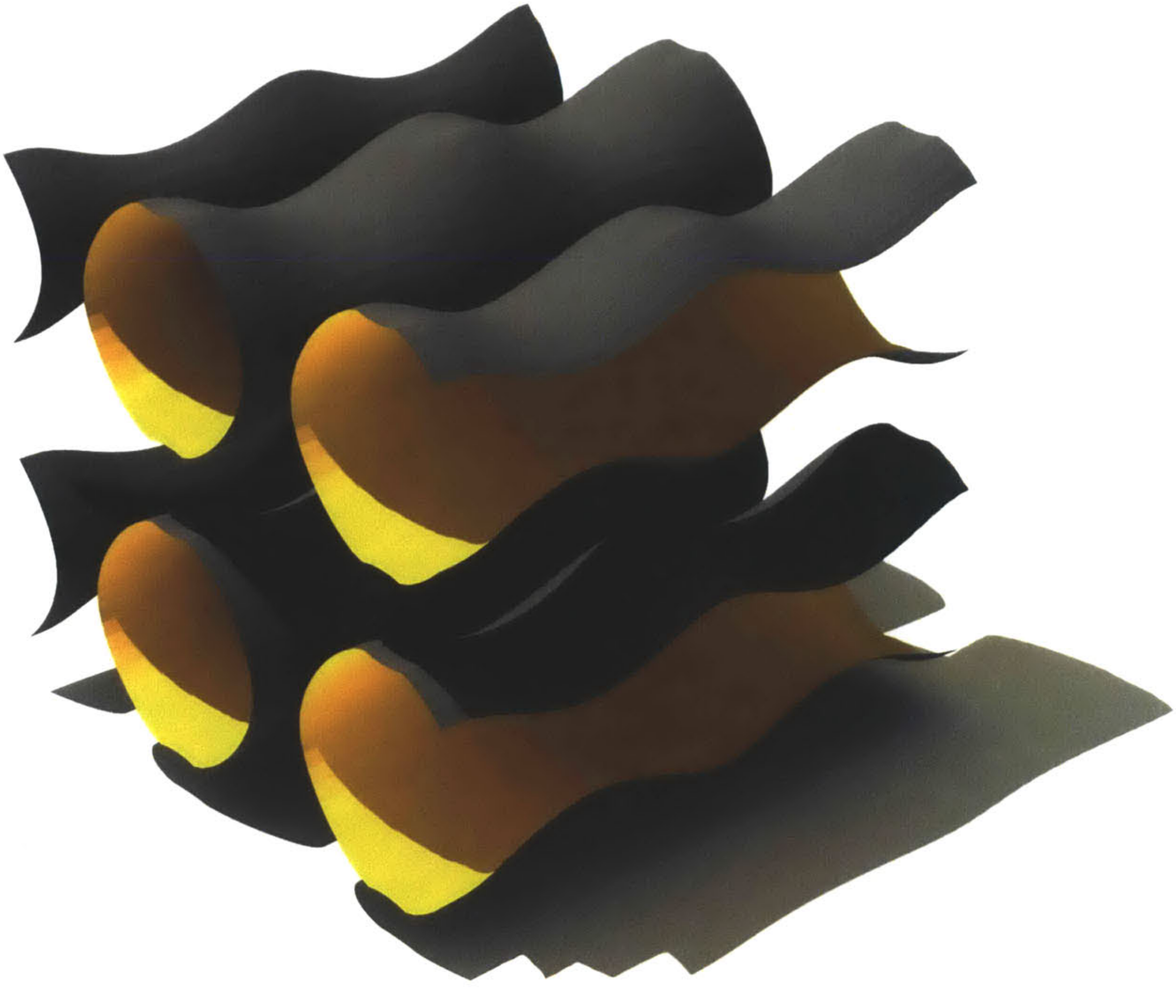


Figure 97: Boundaries MC@CNa=0.83 and MC@CNc=0.64. Boolean Difference.

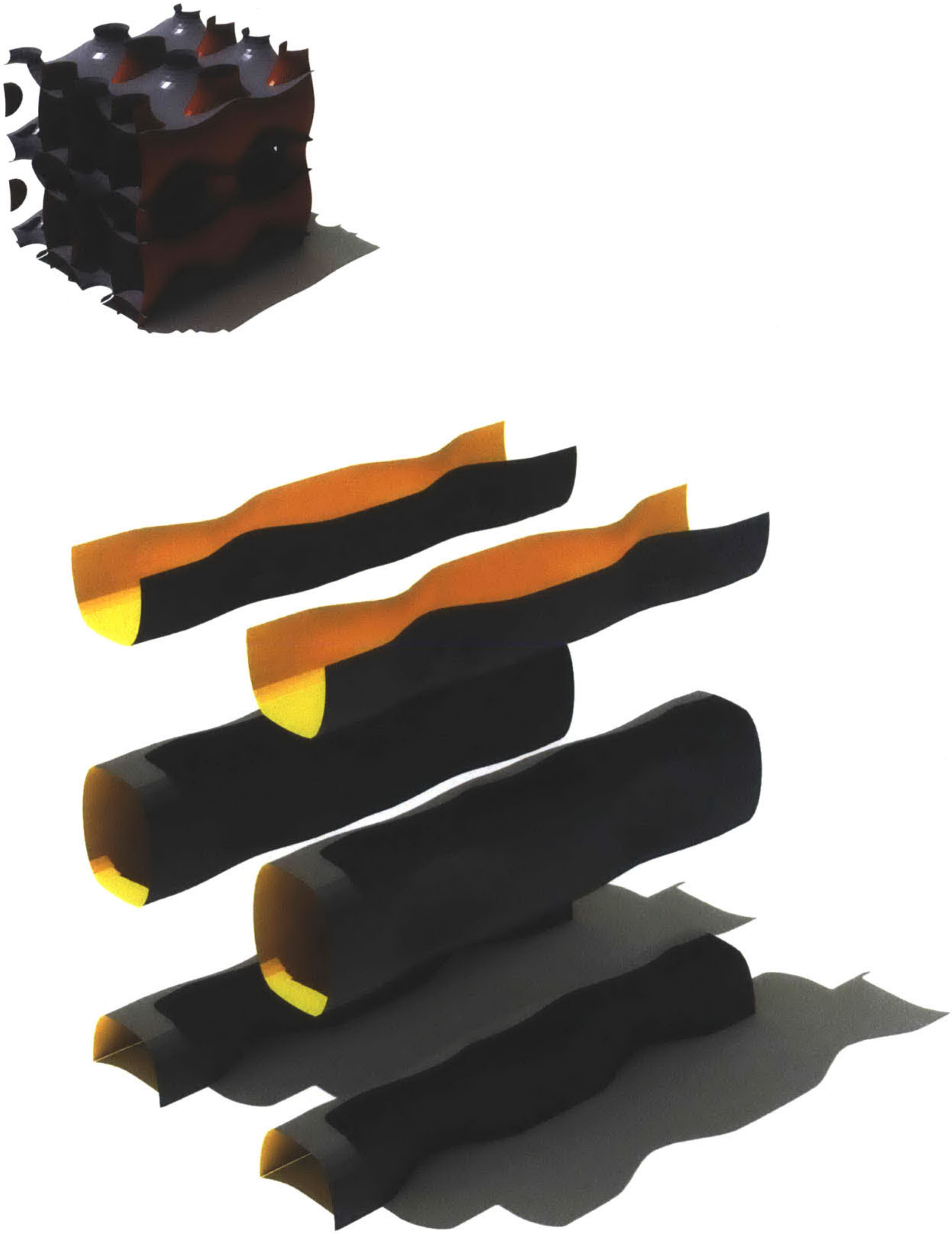


Figure 98: Boundaries MC@CNa=0.83 and MC@CNc=0.64. Boolean Union.

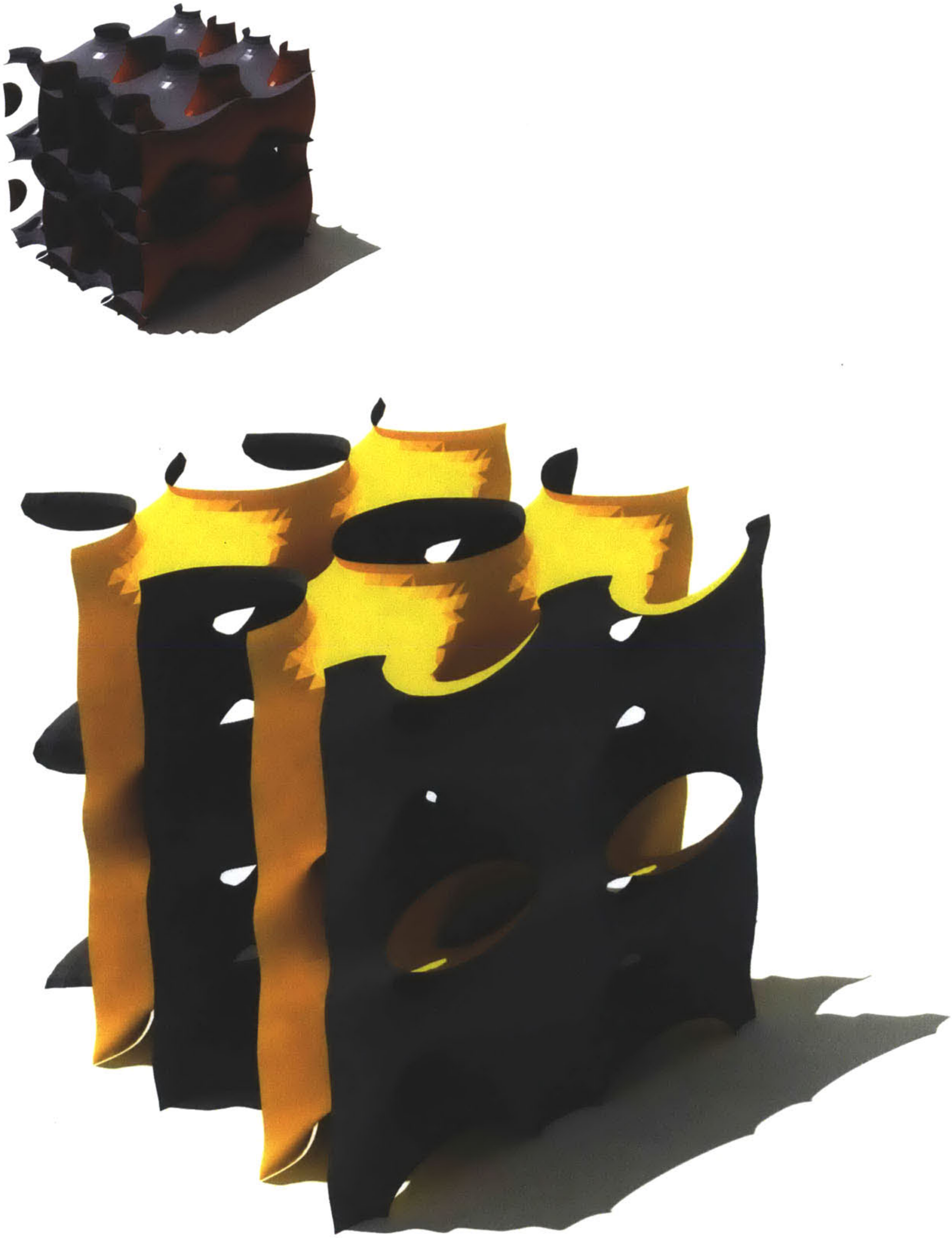


Figure 99: Boundaries MC@CNa=0.83 and MC@CNc=0.64. Boolean Intersection.

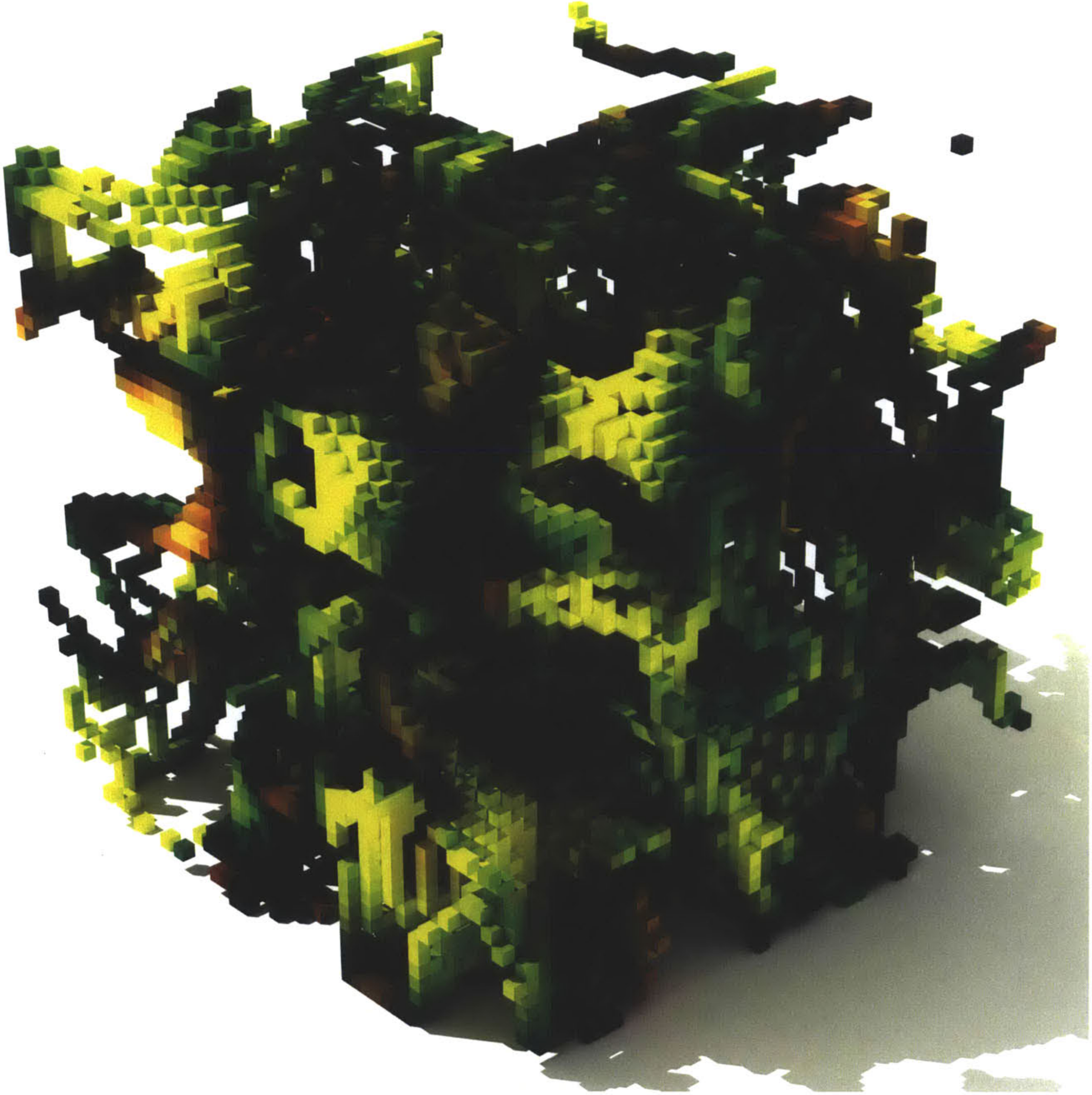


Figure 100: Property Shape PS(A,0.3,0.67)

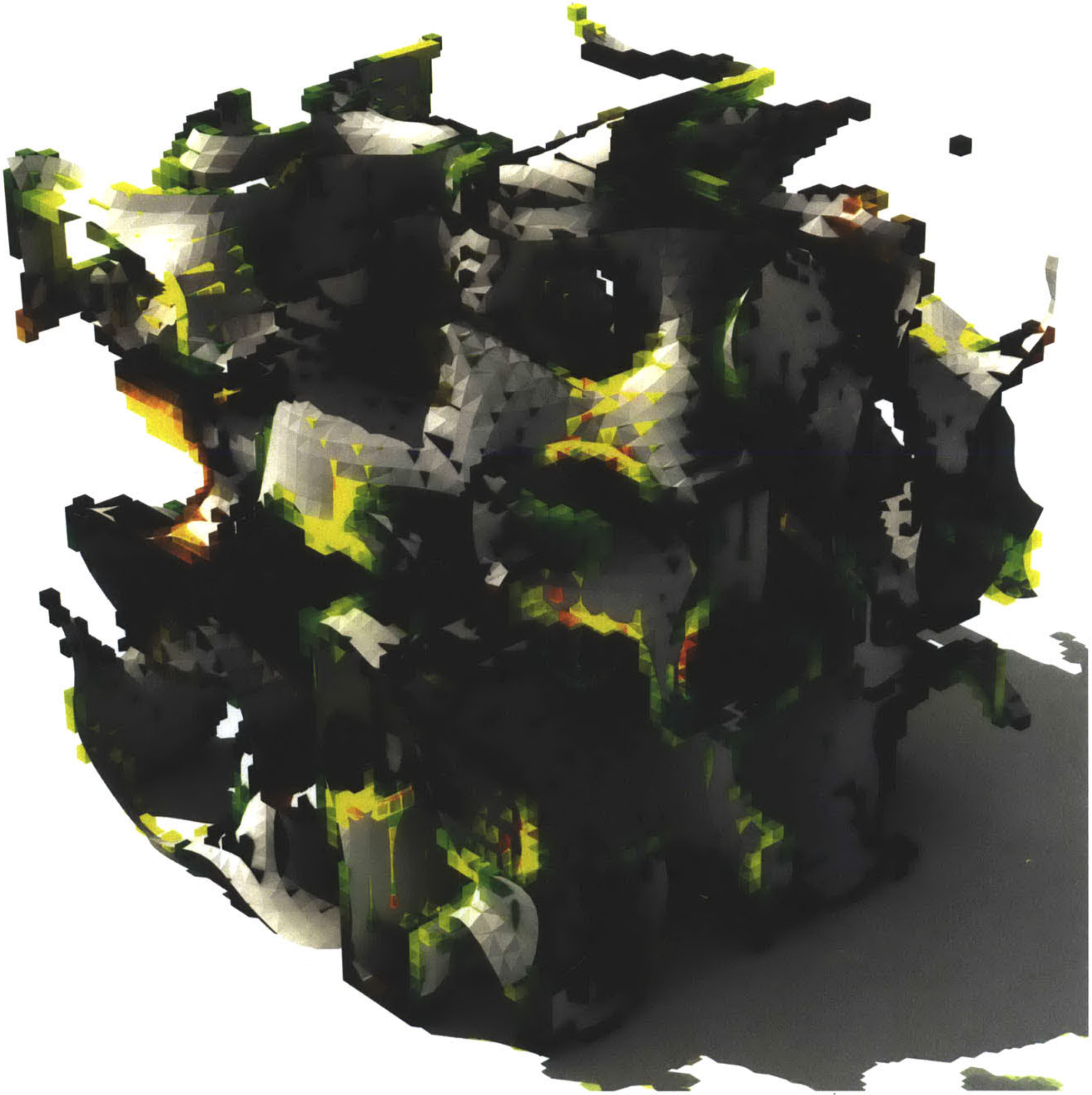


Figure 101: Property Shape PS(A,0.3,0.67) + Boundary MCa@0.67

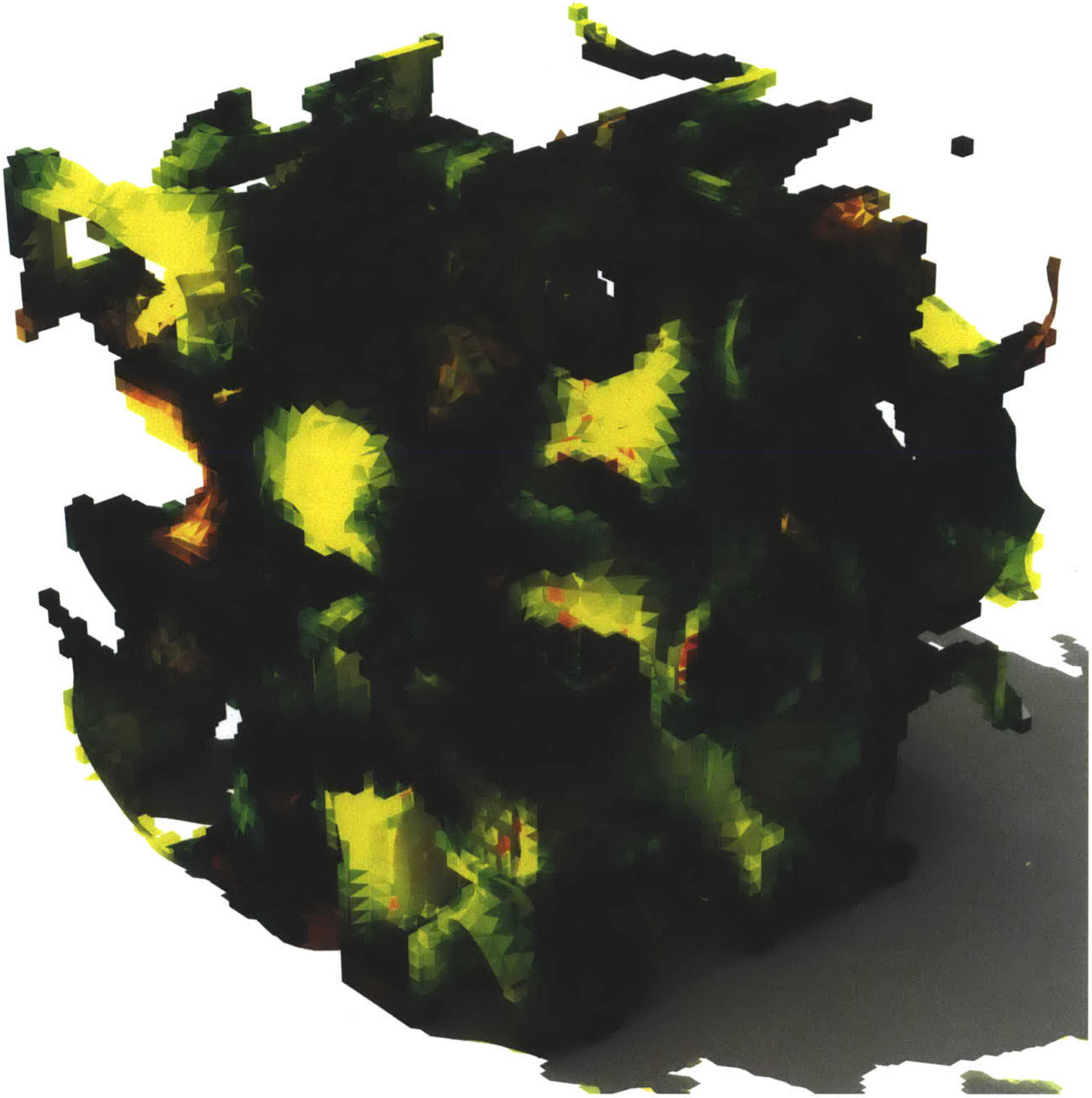


Figure 102: Property Shape PS(A,0.3,0.67) + Boundary Shape BSA

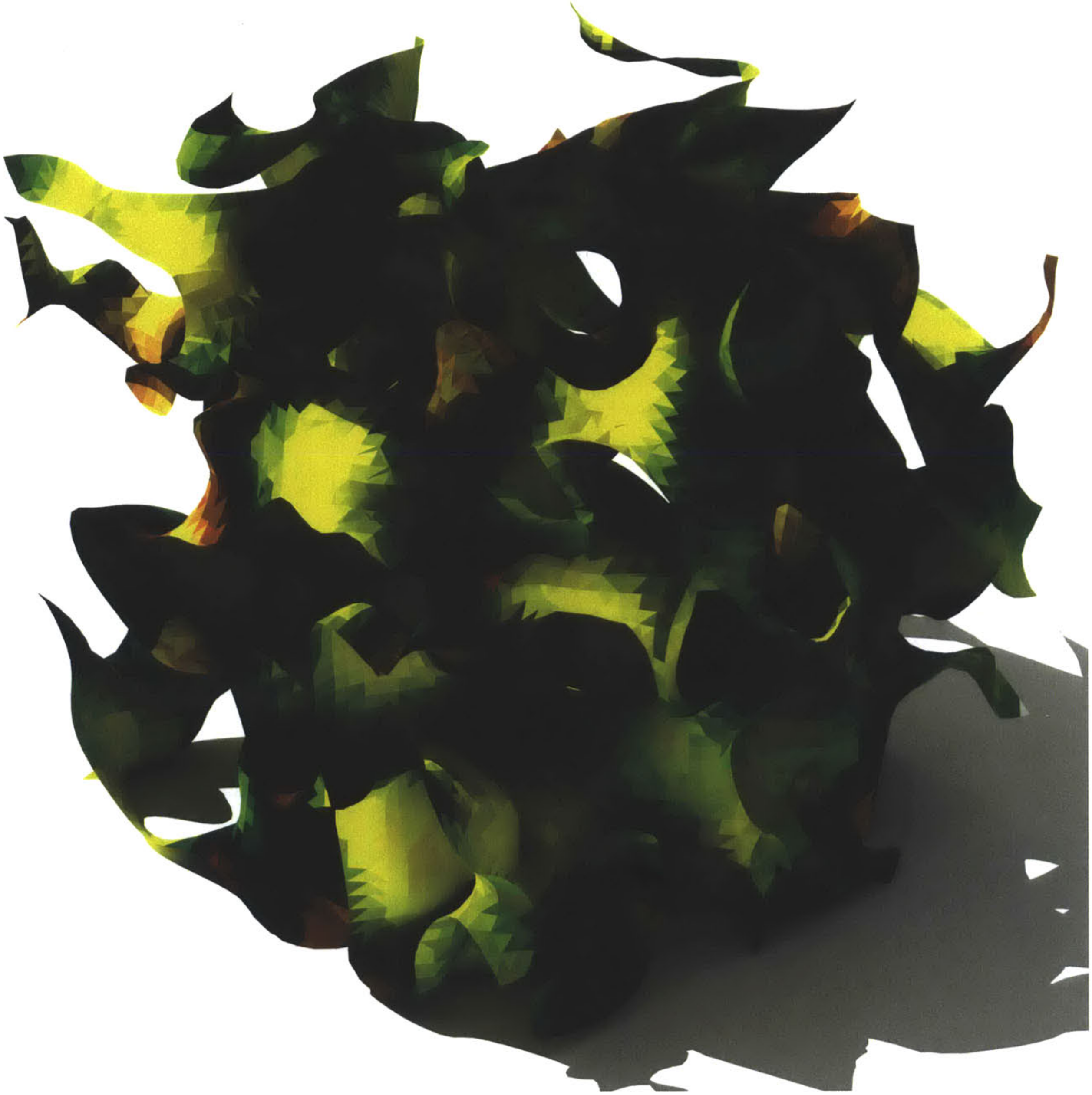


Figure 103: Boundary Shape BSA

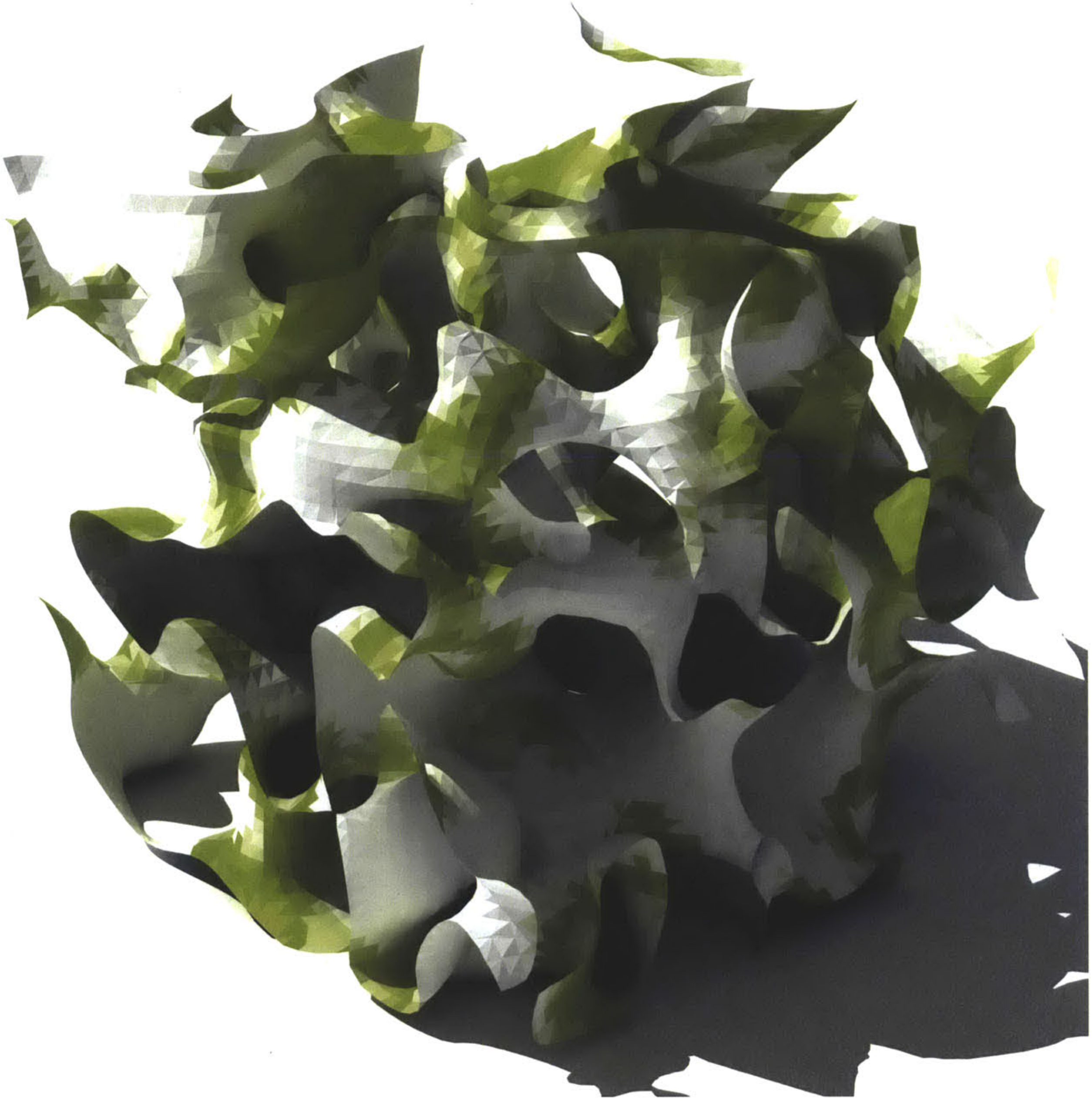


Figure 104: Boundary Shape BSA White-Green

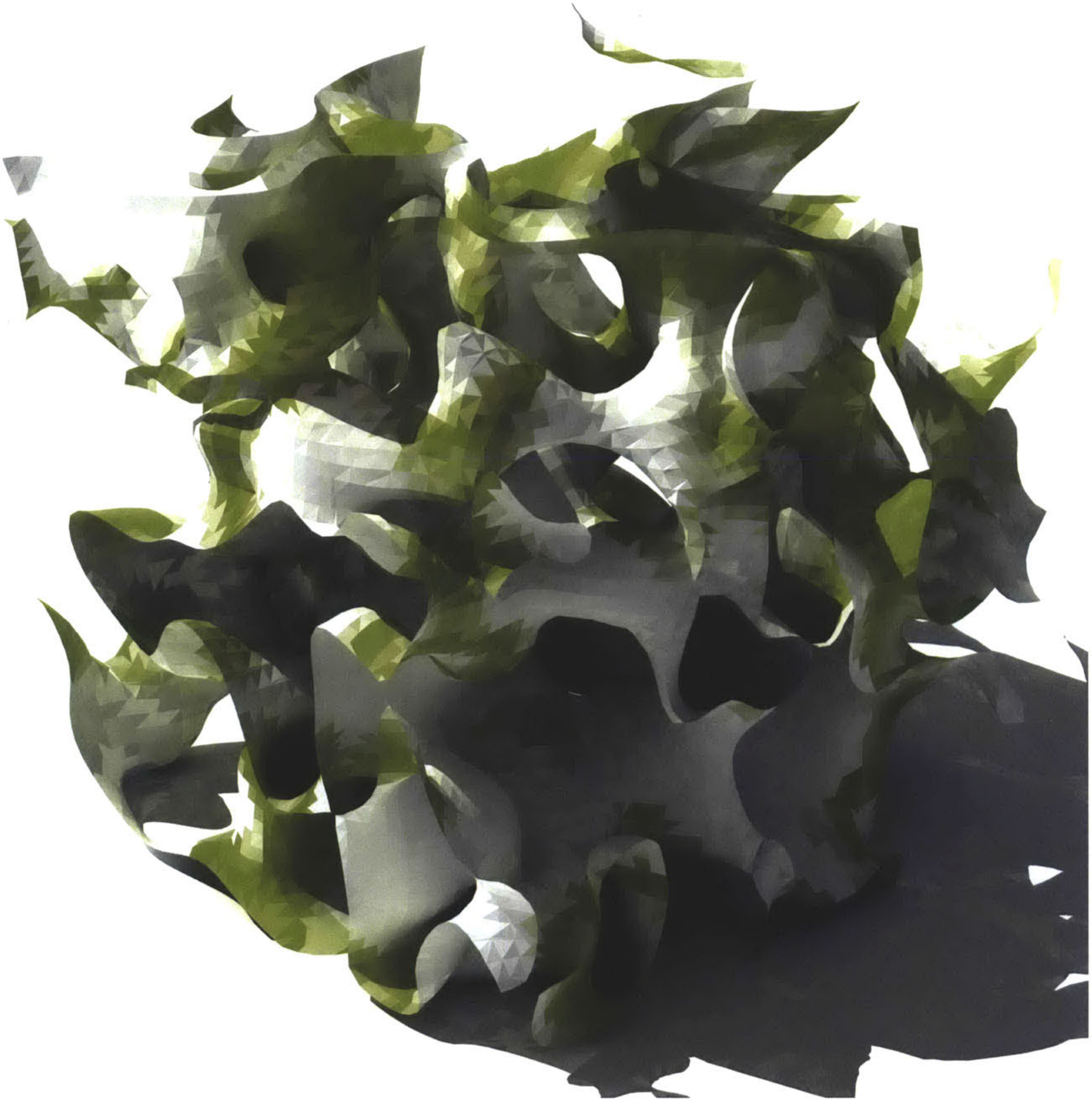
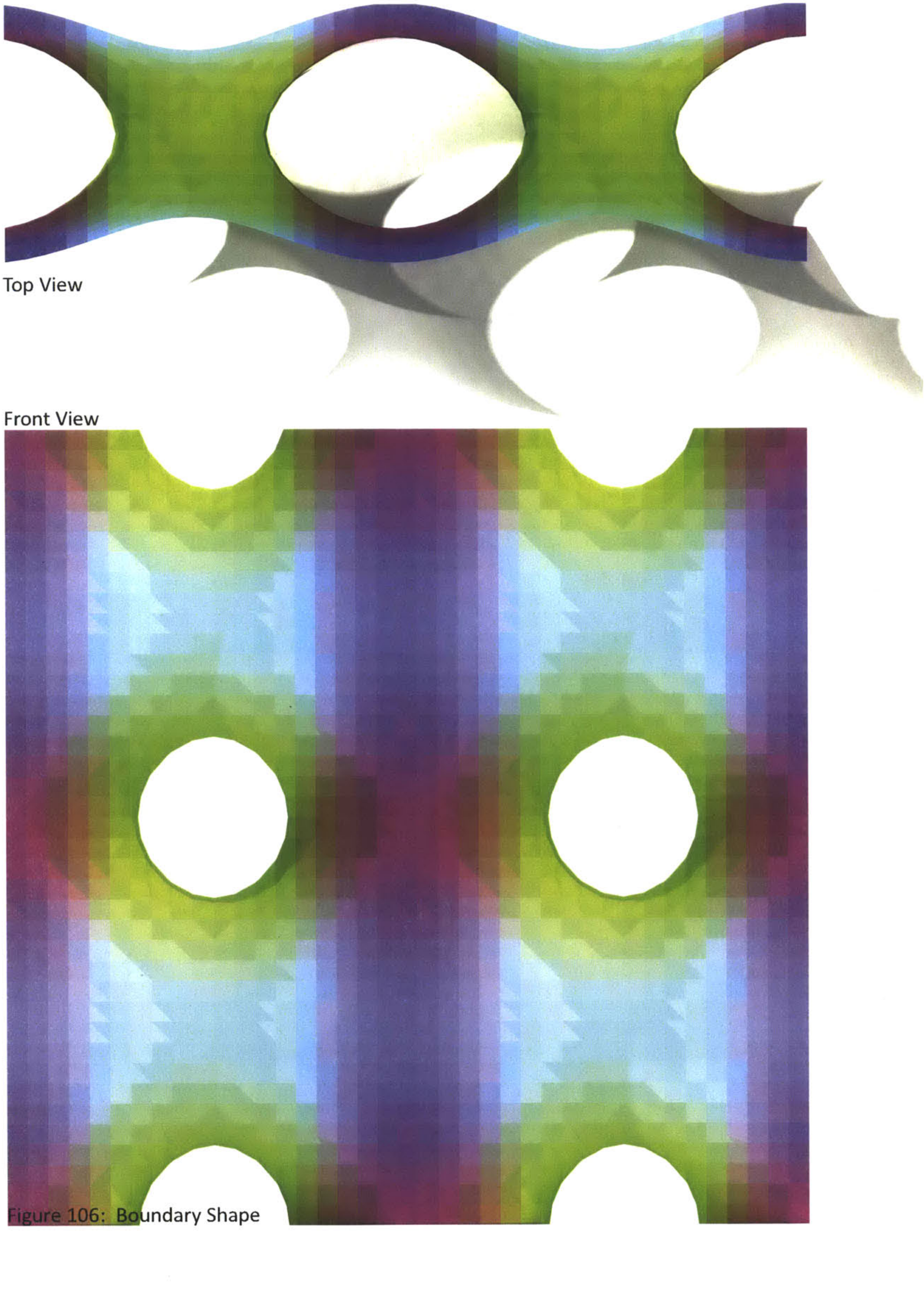


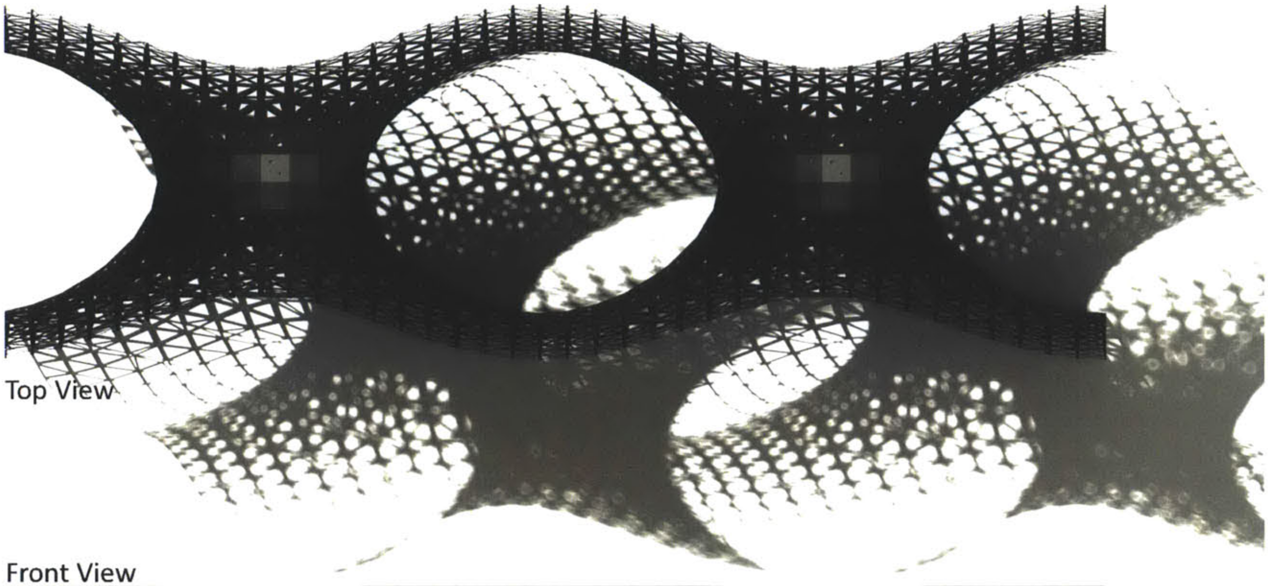
Figure 105: Boundary Shape BSA White-Green-Transparency



Top View

Front View

Figure 106: Boundary Shape



Top View

Front View

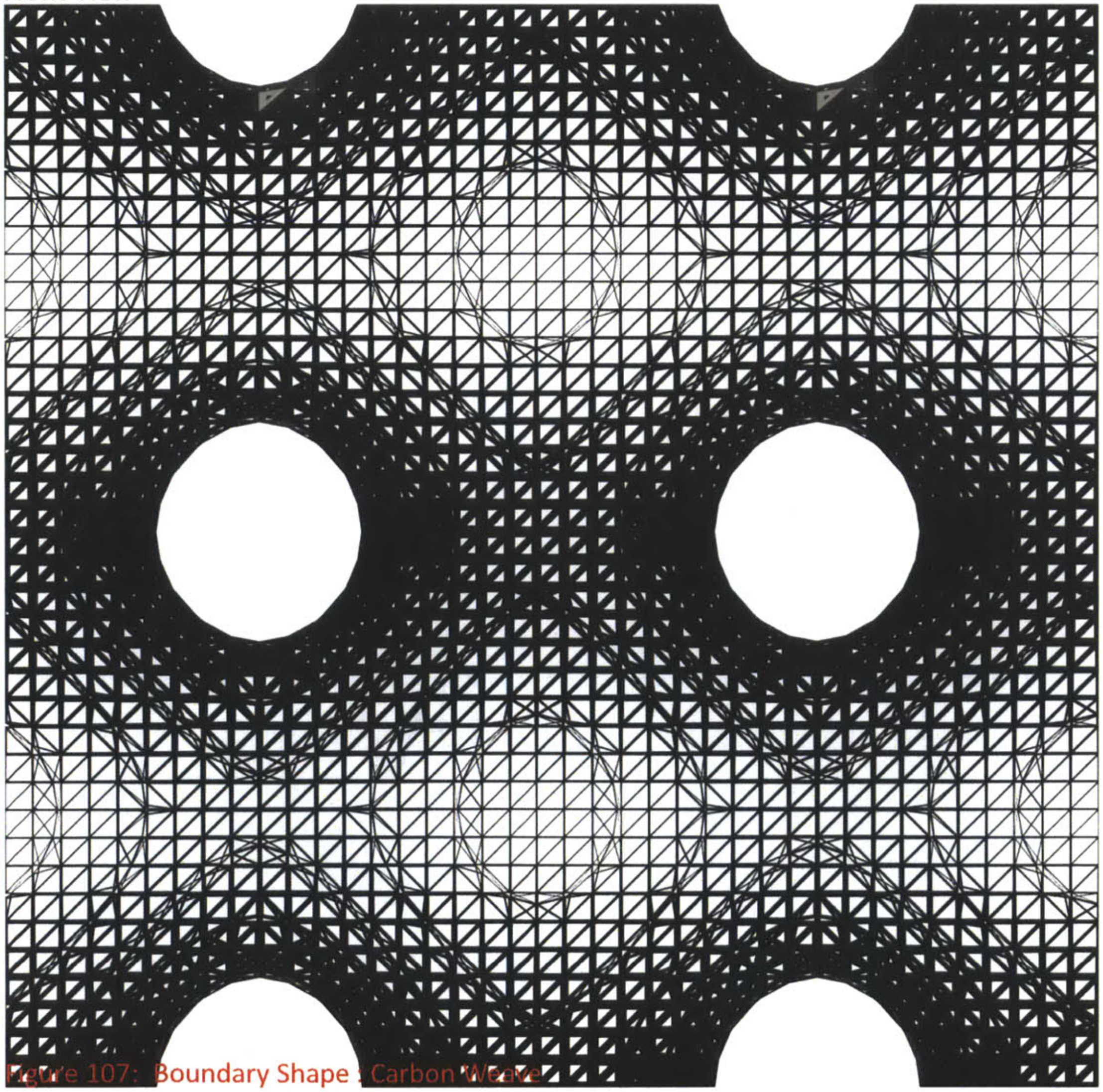


Figure 107: Boundary Shape : Carbon Weave

"Is crystal glass, Grandma?"

"Why, not exactly, yet they have so many qualities in common, that you may almost think of them as one."

"Glass, then, is clear, transparent, bright; what else, Grandma?"

"It is pellucid, that is, not opaque, or dark--it gives admission to the light, and reflects it back again in all its beauty, brilliancy, and purity. I do not wish to see my little boy a green-house, or a glass-house merely, for then he would be brittle, and not strong--easily damaged, if not broken up. But crystals are hard bodies; they resist all injuries, they can bear a beating without breaking; for they are regularly formed, and complete in all their parts. And crystal glass is the firmest and the best, has fewest flaws and imperfections, and can best sustain a storm."

"And so, for all these reasons, they call the great building we are soon to see, a Crystal Palace, I suppose?"[149]

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[149] Sedgwick, Susan, 'The Young Emigrants, Madelaine Tube, the Boy and the Book, and Crystal Palace', Lightning Source Incorporated, Jul 31, 2009

2. TECTONICS

2.1 The Crystal Palace ... a splendid result of advanced civilization

When the Crystal Palace was introduced to the public in 1851, it was received with great enthusiasm. The iron and glass construct caught the public's imagination when its conceptual design was published in the *Illustrated London News* in 1850. England, at the time, was leading the industrial revolution; the Great Exhibition was meant to illustrate its accomplishments to the world - social, industrial, economic, and cultural. The Crystal Palace was seen as a testament to the country's strength and technological progress and its construction was declared a hallmark in foreseeing a new architectural era.[150] Charles Babbage[151], in his book on the Exposition, mentions the influence of the Fine and Industrial Arts upon one another, and the opportunity that the two merge with each other so as to move from singular, unique, handmade productions, to designed objects produced in mass by the machine, and thereby distributed for lower cost and for appreciation by greater numbers of people.[152] He wrote:

---

[150] Giedion, Sigfried, *'Space Time and Architecture: The growth of a new tradition'*, Harvard University Press, Cambridge Mass (1967), p. 249.

[151] Charles Babbage is considered the father of computation long before Alan Turing. A physical device called the "difference machine" allowed one to calculate complex differential equations. Babbage challenged himself with an impossible task : *"Would it be possible at any point in the calculation process to freeze the machine... change the location of numbers at will and continue the calculation without mistake?"* . Those practicing digital computation today know that this is still an impossible task. see Babbage, Charles, *The Exposition of 1851 or Views of the Industry, the Science and the Government of England*, John Murray, Albemarle Street, London (1851).

[152] Babbage, Charles, *The Exposition of 1851 or Views of the Industry, the Science and the Government of England*, John Murray, Albemarle Street, London (1851), p 48.

> The fine arts *idealize nature* by generalizing from its individual objects: the industrial arts realize identity by the unbounded use of the principle of copying.[153]

Babbage was most impressed by the beauty, cost efficiency, and repetitive use of pre-fabricated units in the construction of the "crystal envelope", proof of the creative and productive potential of a marriage of the fine arts with the industrial arts and a building that alone attested to the "...splendid results of advanced civilization".[154]

Sigfried Giedion in the 1960's remarked that the Crystal Palace became a symbol of the, until then, dormant possibilities of modern, industrial civilization- as one of the first buildings of such scale and cultural importance, which realized the potential of prefabricated units in architecture. "It [the Crystal Palace] was essentially a modular building made out of iron, wood and glass built of components meant to be recyclable, since it was understood from the first that it would be removed after the exhibition closed."[155] Giedion made a parallel between the proto-modern Crystal Palace and the landscape paintings of the English Romantic, J.M.W. Turner. The author established a connection between Turner's "Simplon Pass", painted around 1840 and Paxton's Crystal Palace through an *effect*- the effect of blending all materiality into the atmosphere.[156] He believes that Paxton phenomenally dissolves the building into the landscape through the extensive use of glass surfaces.

John Ruskin, the prolific social critic and anti-industrialist, would fail to see that connection. For Ruskin, crystals are of a different nature. He proclaimed the falsity of the nomenclature "crystal" as a description for the oversized greenhouse.[157] As we saw earlier, for Ruskin, Turner is a master of capturing, in his work, nature's constant reconfiguration. While there is arguably a visual effect in his work that can be read as a blending of landscape into atmosphere, the essential aspect of Turner's paintings for Ruskin, was, instead, a registration of ephemeral qualities in nature. Ruskin wrote prodigiously about his distaste for the crystal place, which was for him illustrative of the industrial age's negative influence on artistic production:

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[153] Ibid. 49

[154] Ibid. 68

[155] Hobhouse, Hermione, '*The Crystal Palace and the Great Exhibition: Art Science and the Productive Industry. A History of the Royal Commission for the Exhibition of 1851*', Continuum, New York (2002), p.34.

[156] Giedion, Sigfried, '*Space Time and Architecture: The growth of a new tradition*', Harvard University Press, Cambridge Mass (1967), p.249.

[157] Quoted in Evans, John, *The Lamp of Beauty: Writing on Arts by John Ruskin*, Oxford, (1959), p.285.

> We shall wander through our palaces of crystal, gazing sadly on copies of pictures torn by cannon-shot, and on casts of sculptures dashed to pieces long ago. We shall gradually learn to distinguish originality and sincerity from the decrepitudes of imitation and palsies of repetition. [158]

This antagonism surfaced his particular conception of crystals, and the offense he took at the association between the clean, fragmented and repetitive nature of the glass and iron structure of the Crystal Palace and the impure, unit-less, and aggregate nature he saw in real crystals:

> The smallest atoms, which are visibly and practically put together to make large crystals, may better be described as 'limited in fixed directions' than as 'of fixed forms.' But I can tell you nothing clear about ultimate atoms: you will find the idea of little bricks, or, perhaps, of little spheres, available for all the uses you will have to put it to...the force which crystallizes a mineral appears to be chiefly external, and it does not produce an entirely determined and individual form, limited in size, but only an aggregation, in which some limiting laws must be observed...

Extolling the crystal's virtues through a parable, he continues:

> ISABEL. But you said it was the shape that made things be crystals; therefore, oughtn't their shape to be their first virtue, not their second?
>
> L. Right, you troublesome mousie. But I call their shape only their second virtue, because it depends on time and accident, and things which the crystal cannot help. If it is cooled too quickly, or shaken, it must take what shape it can; but it seems as if, even then, it had in itself the power of rejecting impurity, if it has crystalline life enough...[159]

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[158] Ruskin, John, *'Prosperina, Ariadne Florentina and the Opening of the Crystal Palace'*, Kessinger Publishing, Whitefish (2005), p.421.

[159] Ibid.

Ruskin's crystal is nothing like glass, it is not a perfect arrangement of forms. It does not have uniform properties, nor is its beauty the beauty of purity, consistency, or material homogeneity. Instead crystals are an anisotropic substance formed by varying circumstances involving change, interruption, and difficulty.

> ...most noble stone wants to be symmetrical and perfect, the crystal does not, it has an impurity of will- in the sense the crystal is not trying to be pure. Yet I cannot trace the least difference in purity of substance between the first most noble stone, and this ignoble and dissolute one. The impurity of the last is in its will, or want of will...[160]

Ruskin identifies purity in the act of formation and not in the formal outcome of crystals. For Ruskin, the varying material properties of crystals are more important than their form. This stance set him apart from Viollet-le-Duc who isolated and admired the geometric qualities of the crystal formations and attempted to articulate an absolute, overarching formal order for the triangle's underlying perfection. For Viollet-le-Duc, "The prismatic geometry visible in geological formations helps us understand the transformation of matter. The theory of crystals shows the triangle (trinity) to be generic to natural creative forces. "[161] Viollet-le-Duc's crystal building block is the perfect triangle, while Ruskin's crystal is an impure substance trapped in a process of formation.

There are two points I would like to highlight: The first one is a point-on-the-side and targets the reader who is expecting to see a relationship between this body of work and "nature". There is one. For John Ruskin, crystals are one thing. For Viollet-le-Duc they are another. Their views are primarily influenced by their over-arching ideologies. As a positivist, Viollet-le-Duc, promotes the mores of industrial production's novel technologies to the level of social organization. His views on crystals reflect his views on societal organization. A hierarchical, clear, highly coordinated system of parts, speak primarily of a society as a whole. He also comes from the world of Newtonian physics. On the other hand, Ruskin comes from the world of thermodynamics. His view of the heterogeneous, non-hierarchical, excessive nature of crystals speak of a society; not crystals. He spent the second part of his life aggressively critiquing industrial capitalism and the utilitarian theories that underpin it. Had Ruskin been able to have a favorite movie, it would have been Charlie Chaplin's brilliant satirical film, "Modern Times" from 1936. He would have been sympathetic

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[160] Ibid.

[161] Bressani, Martin, *'Notes on Violet-Le-Duc's Philosophy of History: Dialectics and Technology',* The Journal of the Society of Architectural Historians, vol. 48, no.4. Chicago (December 1989), p.333.

with the little Tramp's quandary, who while working in the assembly line of a factory - tightening bolts on machines- is ultimately driven mad by the repetitious performance of his singular task and at his wits end is chasing a woman to tighten the buttons on the front of her dress. For Le-Duc "nature" is one thing and for Ruskin another. Along the lines of Charles Babbage's remark at the time of the exhibition opening, both Le-Duc and Ruskin endorse an idealized version of nature. One sees triangles , the other particles. Referring precisely to this issue, the French philosopher François Dagognet considers nature a *"blind bricoleur"*[162] arguing that the idea that "nature" is untouched by human hands has not been true for millennia. More provocatively, he asserts that nature's malleability demonstrates an invitation to the "artificial". For Dagognet, "if the word "nature" is to retain a meaning, it must mean an uninhibited polyphenomenality of display."[163]

Effectively, both Le-Duc and Ruskin are applying a model of thought on the object of their inquiry. And the point here is simple. Since those models are ultimately preconditioned by our ideologies, why do we need "nature" to give validity to our design decisions? Since models are there already, either as intuitions or "proven facts", we, as architects, can directly form propositions by critiquing or adopting concepts and concerns from within our own disciplines. The reasons for doing so are not in "nature"; they lie elsewhere. Crystals are what crystals are. Societies on the other hand are always evolving. And it is the expressive possibilities of architecture in relation to society that is of interest to us[164].

The second point lies at the core of this thesis. In the face-off between Le-Duc and Ruskin, obviously Le-Duc won[165]. Factories increased emphasis on standardization. Efficiency and productivity radically affected the way architect's thought about construction and technology in relation to architecture. This shift saw a breakdown of classical Vitruvian conceptions of order and proportion, an intense admiration for engineering practice and its products, as well as attempts to integrate architecture into the industrial model of production. Viollet-Le-Duc, acted at the crux of the transforming nature of "craft" in architecture during the Industrial Revolution and the emergence of a particular discourse regarding architectural tectonics-both concepts that were extremely influential in the formation of avant-garde modernist rhetoric.

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[162] Quoted in Rabinow, Paul *'Artificiality and Enlightenment: From Sociobiology to Bio-Sociality'* in Incorporations (ed.) Jonathan Crary & Sanford Kwinter, *(Chapter 6),* Zone Books, New York, MIT Press, 1992), p. 249.

[163] Ibid.

[164] Think of the human body too; think of the Vitruvian man, the anatomic skinless body, the *Modulor*, the body in a space-suit, Stelarc's man-spider body. The body did not change that much as a physical organic entity in the past 600 years. The body's role in society though, drastically changed.

[165] this of course is not meant to be taken literally...

Viollet-le-Duc embraced the application of new technology in architecture. He considered the Beaux Arts an obsolete institution engaging in stylistic mimicry and a particularly distasteful practice of divorcing architectural form from any articulation of its underlying structure. In contrast, he argued that "style" had quit the arts and "taken refuge amid the industries."[166]

> The improvements in machinery, and in the rapidity of execution, should also have modified the system of construction, and have lessened instead of increased the expense of building; yet never comparatively has building been so expensive as it is now.[167]

While the Beaux Arts relied upon a systemized categorization of forms and their application to architecture, Viollet-le-Duc believed "architectural forms should emerge from the application of correct principles and not from the manipulation of a repertoire of forms."[168] He advocated that architects abandon dressing buildings in the garb of old styles and instead work towards a kind of structural transparency and hence formal integrity, that adopts new industrial technologies and materials. Architectural form should emerge from legitimate processes that result in a distinct style appropriate to a particular object, unlike the Beaux Arts methodology where architecture exhibits "total surrender to the forces of tradition. It is inorganic and dead because it does not spring from a direct confrontation with materials and natural laws."[169] In contrast to the lifeless productions of the Beaux Arts, Viollet-le-Duc advocated a method in which material and structure become considered objects, one wrought through the other's transformative logic into *form*.

Viollet-le-Duc deeply embraced the emerging technologies of his day for their strength and the clarity of their formal execution. He considered the locomotive as "almost a living being, and its external form the simple expression of its strength."[170] In his writings, Le-Duc hoped that architecture could channel this industrial prowess and exhibition of industrial will. For him, iron - a material then produced in great abundance but that was only used by engineers in the construction of bridges - awaited its appropriate architectural application. Viollet-le-Duc was aware that "structure" was a result of contemporary social realities as well as the influence of the

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166 Viollet Le-Duc, Eugène-Emmanuel, *Lectures on Architecture, tr. by B. Bucknall, (1881),* p.175-183.

167 Ibid p. 52.

168 Colquhoun, Alan, *Essays in Architectural Criticism*, MIT Press, Cambridge Mass (1985), p. 161.

169 Bressani, Martin, *'Notes on Violet-Le-Duc's Philosophy of History: Dialectics and Technology'*, The Journal of the Society of Architectural Historians, vol. 48, no.4. Chicago (December 1989), p. 340.

170 Ibid.

technological culture of his era. He hoped to integrate modern materials as well as progressive construction techniques in order to express the ethos of the industrial era. The point to be made here is that a tectonic expression of structure, as an ideological expression of industrial society, became consistently synonymous with the industrial logic of a hierarchical - clear - assembly of parts. Had Ruskin's views of the crystal's nature prevailed, I am fairly certain that a tectonic expression of structure in relation to other characteristics of the designed object, would acquire a different form.

Forward in time

Recently, echoing Ruskin's views, Sanford Kwinter points towards the forces behind the materialization of the impure crystal. His model of thought becomes indicative of a reversal of the mechanics of the form - material relationship. A model that speaks of a dynamic relationship between material properties, geometric configuration and environment. Kwinter describes:

> Its genesis is dynamic and can be seen situated initially at the convergence of three distinct fluxes: mica and mineral particles; a moisture saturated field; and a thermal flow of heat exchange. One does not know in advance when or where such a crystal will begin to nucleate or form, but one knows it will emerge –apparently spontaneously - from a flux of convergence of flows, not in a prepared form or state.[171]

Kwinter's fascination with the snow crystal derives from the complexity of its formation. What he finds compelling is that despite its partially predetermined, regular crystalloid form -or it's "will" according to Ruskin - no two specific crystals are ever identical. As he suggests, "each is different because it *maintains its sensitivity* both to time and to its complex milieu. Its morphogenetic principle is active and always incomplete (i.e., evolving)"[172]. In this sense, our general understanding of a crystal as a rigid tetrahedral lattice of hydrogen and oxygen, which determines the even formation of hexagonal plates, cannot encompass the entire spectrum of

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[171] Kwinter, Sanford, *Architectures of Time: Toward a Theory of the Event in Modernist Culture'*, MIT Press, Cambridge Mass (2002), p. 26.

[172] Ibid. 28

its fundamental[173] nature.[174] It seems to me that kwinter, through this example, is asking us to see the crystal's material manifestation as an expression of a non-hierarchical environment in constant flux. The crystal's local adaptation to mica and mineral particles exceeds its conception as a convolute geometric configuration. The crystal becomes a body consisting of variable material properties, due to its non-rational, non-determined mode of formation- a production without a plan. From the perspective of this thesis, what matters in our discipline is how such models of thought (the ones that inform the way we see crystals) could affect the way we think of the material manifestation of buildings. In this case, how a shift from the design of an object to the design of an environment can find its expressive potential into a physical construct.

2. 2 Tectonic debates in the contemporary architectural discourse

In 2011, I witnessed an interesting debate at Columbia University's plastics conference[175] *(Permanent Change: Plastics in Architecture and Engineering)*. In his keynote lecture entitled: *"Goodbye Tectonics, Hello Composites"*, Greg Lynn elaborated on issues of design and construction[176]. Lynn explained that we can witness in his work as it evolved from the 90's a gradual shift from the "tectonic" paradigm to the "composite" paradigm. This shift meant a transition from a "surface on a frame to a surface in a bag". He argued that tectonics answer questions about "the way we put things together" and also that "tectonics try to resolve two materials coming together". He argued that the tectonic paradigm refers to the arrangement of components, the hierarchy of systems in an assembly as well as the discrete layering of parts. He also briefly commented on the recent tendency in parametric design towards "digital tectonics". He explained how 99% of students in architecture schools today, when dealing with parametric design, are exclusively dealing with the translation of variable geometry into construction components. **In contrast**, the

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[173] I will still maintain that it doesn't matter if we know what they really are. I think we had this discussion with Sanford once in class at MIT. He told me that it is not about realities. It is about leaps of faith!

[174] Kwinter, Sanford, *Architectures of Time: Toward a Theory of the Event in Modernist Culture'*, MIT Press, Cambridge Mass (2002), p. 27.

[175] Permanent Change: Plastics in Architecture And Engineering. The fourth Conference on Architecture Engineering and Materials, March 30 - April 1,2011, Wood Auditorium, Avery Hall, GSAPP.

[176] The lecture can be accessed on youtube.com at http://www.youtube.com/watch?v=C12UHwONh2M

composite paradigm, he suggested, is the fusion of materials in a matrix, the layering of materials without distinction and the substitution of fibers over members. He demonstrated through his work how he uses "surfaces to do the job of one or more components". He gave the example of a piece of furniture he designed in which parts are not assembled but instead are *articulated*. Lynn, instead of attaching a handle in a mechanical way as a separate piece, chooses to use surface deformation to transform - in a geometrically continuous way - a cabinet lid to a handle and back to a cabinet lid.

Toward the end of the three day conference in a roundtable discussion, directly addressing the issues raised by Lynn, Steven Holl said: "What is wrong with parts? I like parts". For him, beyond construction, parts were a measure of thought. They produced a unit of measurement that allowed the expression of part to whole relationships in space. Furthermore, parts accommodated for the need in construction to change material, an essential characteristic that Lynn's composite paradigm was unable to address.

What is of interest to me in this point, in the debate between Gregg Lynn and Steven Holl, is that although they are coming from different points of view (they would probably pick different sides in the original crystal debate), they are both interested in expressing the part's relationship to the whole. The specific role of the part in relation to the whole for both Lynn and Holl is different, but this is a separate story that we will touch upon later. In construction, Lynn is expressing a part through the composite (continuous surface transformation) paradigm while Steven Holl is doing so through the traditional, tectonic one. One, through the expression of part as a local instance of whole, while the other, as a distinct part of an assembled whole. Catherine Ingraham, who effectively elaborated on the recent shift in architectural discourse from a mechanical to a biological paradigm, offers insight on the topic. She argues:

> "...one aspect of architecture requires an intense concentration on the assembly of parts, their transportability, composition, adhesion to each other, manners of assembly, it is always profoundly indebted to a material and until recently a mineral history. Even more exotic synthetic materials-the new building materials we are interested in today, such as polymers, DuPont's bulletproof Kevlar, aerospace metal composites.... continue the argument that architecture, in order to make a conceptual whole, must master the material part, even if that part is now, itself almost alive."[177]

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[177] Ingraham, Catherine, *'Architecture, Animal, Human: The Asymmetrical Condition'*, Routledge, New York (2006), pp 42–43.

Primarily, there are two issues that this thesis is attempting to address: What happens to the part to whole relationship when we are dealing with the expression of an environment? How does the shift from the design of objects to the design of environments inform the transition from design to construction? The privileging of properties over boundaries in design, would require an altogether different strategy.

Antoine Picon clearly argues that "Sustainability is indeed relatively indifferent to the soundness of load-bearing trajectories and the translation of structural choices into legible tectonic. It involves factors like ecological footprint or dynamic energetic behavior that obey another type of logic, a logic that involves the entire environment instead of remaining within the limits of the built object[178] like traditional structural requirements."[179]

In my view, as we will examine in depth in the sections that follow, current investigations in construction - even the speculation ones - revolve either around assemblies of non-standard, single-purpose parts (digital tectonic) or around the continuous deployment of undifferentiated - plastic in most cases - materials (composite strategy). The first, while it accommodates for the need in construction of variability in material properties, as a tectonic strategy lurks back to the ethos of mechanical production of the industrial age. The second approach, although it acknowledges the need for an expression of continuity, is geared towards the production of monolithic objects whose parts are expressed solely through the manipulation of the object's geometry. In construction, whenever a continuous surface cannot accommodate the functional need for a distinct material, a joint is inevitable. The first comes as an expression of Banahm's "hardware" while the second, as Sylvia Lavin pointed out becomes an expression of "soft hardware".

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[178] again another argument, this time by Antoine Picon that indicates a clear shift from the design of objects to the design of environments.

[179] Picon, Antoine *'Digital Culture in Architecture. An Introduction for the Design Professions'*, Birkhauser, Basel (2010), pp. 131-132.

Software Tectonics perceived as a "critical tweak" of Gregg Lynn's Composite paradigm introduces a strategy that stands between the two. This is neither an "average" type of argument nor a "both-and" type of argument. Instead it realigns the notion of tectonics with current speculations in ecological design and recasts it as an expression of a designed environment. While it is not concerned with singular, top-down hierarchies, it seeks to accommodate for the expressive and performative requirements of material change.

Software Tectonics interrogates the strategies of design and fabrication within the digital and shifts the attention from parts to properties. Here parts still exist as functions and more importantly as intellections but not necessarily as distinct objects. It introduces the notion of a single-variable purpose "chunk" that varies locally in its material composition.

Software Tectonics shifts the attention from edges to gradients. Structure, color, infill, transparency, insulation, ornament, pollution, energy exchange and so on would be expressed continuously (not assembled) within a chunk's non-homogeneous material composition.

2.3 Idiosyncratic Tectonics

In the same year that the Great Exhibition was hosted at the Crystal Palace, Gottfried Semper published his book, *The Four Elements of Architecture*. Semper had visited the Crystal Palace that year and his book includes a drawing of a Caribbean Hut from the exhibition. Semper's contribution to the discourse regarding the primitive hut, can be appreciated as a critique on a previous interpretation by Laugier. The latter built upon the Vitruvian paradigm, and visualized the primitive hut for the first time in the cover of his book *Essays on Architecture*. For Laugier, the primitive hut was neo-classical, it consisted of columns, beams and a pediment roof, which therefore formed the fundamental principles of architecture and embodied true architectural form.[180] For him, the Greek Doric Temple was the closest approximation of this true, built form.

> With the help of all the geometric figures; from the circle to the most elongated ellipse, from the triangle to the ultimate polygon.[181]

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[180] Quoted in Broadbent, Geoffrey, *'Emerging Concepts in Urban Space Design'*, VanNostrand Reinhold, London (1990), p.88.

[181] Ibid. 88

The Greeks interpreted, through their use of descriptive geometry, the form of the primitive hut (found in nature) to the structure of the Greek temple. Structure, for Laugier, becomes *perceived form.*[182] In Semper's *Four Elements of Architecture*, he challenges Laugier's neo-classical description of the primitive hut, thereby developing a system of classification that supplants the Vitruvian *utilitas*, *fermitas*, and *venustas*. He bases his classifications instead on four elements: hearth (ceramic), roof (frame or tectonics), enclosure (textile), and mound (stereotomy).[183] Regarding tectonics/stereotomic distinctions and Semper, Frampton writes:

> Semper went on to classify the process of building and, by extension, craft production, into two basic procedures; into the tectonics of the frame, in which light-weight, linear components are assembled so as to embody a spatial matrix and the stereotomics of the earthwork, formed out of the repetitious stacking of heavy-weight units.... This distinction between light and heavy reflects a general differentiation in terms of material production, in which the architectonic attributes of one mode are expressed in another for the sake of retaining traditional symbolic value, as in the case of the Greek temple, where stone is cut and laid in such a way as to reinterpret the form of the archetypal timber frame."[184]

Semper's categorization departs from Vitruvius' in a radical way, as Semper elevates the status of the technical arts in contributing to the origins of architecture. What Semper is describing as the fundamental building blocks of what he later deems architectural tectonics are processes: weaving, masonry, carpentry, etc. Therefore, he describes processes of transforming material into form, an observation that distinguishes him from Laugier's formal interpretation of the primitive hut and its ultimate translation into Greek architecture. Semper's four architectural elements-hearth, frame, textile, and stereotomy, essentially shift the focus of architectural discourse of his time from form to techniques of material manipulation. A direct link was hence forged between architectural tectonics and industrial and technical processes, a thread that associated Semper to later handicraft movements in architecture,[185] or even more recently influenced contemporary

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[182] See Laugier, Marc-Antoine, *'Essays on Architecture'*, Hennessey & Ingalls, Los Angeles 1977.

[183] Semper, Gottfried *'The Four Elements of Architecture and Other Writings*, Cambridge University Press (1989), p. 103.

[184] Frampton, Kenneth, *'Botticher, Semper, and the Tectonic: Core Form and Art Form'*, in What is Architecture, (ed.) Andrew Ballantyne, Routledge, London (2002), p. 142.

[185] Banham, Reynar *'Theory and Design in the First Machine Age'*, MIT Press, Cambridge Mass (1980), p. 12.

digital theorists.[186]

Today, Antoine Picon rightfully so, characterizes Semper's tectonic definition as "somewhat idiosyncratic"[187]. It is true that Semper is not interested in understanding structure as an ordering principle of space. He does not look at space from the outside. What becomes important for this thesis is that Semper's approach removed tectonics from the eye of the historian and placed it in the hands of the practicing architect. For Semper tectonics transformed from an analytical tool to an operational strategy of material transformation. This is how tectonics is understood here. Software Tectonics is a kind of "new poetics",[188] a kind of expression that negotiates technological advancements in design and construction with the ever increasing need for the discourse to tackle broader issues of ecology.

Tectonics is used here as a theoretical frame to negotiate architecture's significance as an artistic/cultural expression with the pragmatic requirements of function, material performance and environment. The framework of tectonics allows the architect to actively consider technologies of design and production and the relationship the two form. This thesis acknowledges our discipline as autonomous, having evolved into developing its own language and its own concerns. It attempts to align it with the pragmatics of ecological design as it shifts from the design of objects to the design of an environment of perpetual transformation.

Even the realm of the symbolic, where traditional tectonics have played a role in revealing the relationship between architecture and time, through the process of ruination[189], becomes today pressingly important. As I have mentioned elsewhere[190],the latest aesthetic fascination with "greenery", denies the necessary symbiosis of societies with their waste. Hidden under the "Green umbrella" and the sustainability discourse, byproduct has not yet found its rightful place within architectural objects. Social sustainable sensitivities, which gravitate towards questioning the strict hierarchy of social classes[191], would necessarily have to acknowledge a global reshuffling of waste. Excrement cannot just disappear. If we remove it from here it will resurface there. Beyond the technical pragmatics of clean, renewable, passive energy and so on and so forth,

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[186] See Bernard Cache, *Digital Semper.*

[187] Picon, Antoine '*Digital Culture in Architecture. An Introduction for the Design Professions*', Birkhauser, Basel (2010), p. 126.

[188] ibid p. 130

[189] ibid p. 134

[190] Tsamis, Alexandros, '*Go Brown. Inner-disciplinary Conjectures*' in Architectural Design (AD) : Ecoredux. Design Remedies for an Ailing Planet, (Ed) Kallipoliti Lydia, John Wiley and Sons, London (June 2010).

[191] Davidson, Mark (2009) 'Social sustainability: a potential for politics?', in Local Environment, 14: 7,p.610.

an aesthetic for ecological design would entail the reconsideration of waste and the chemical decomposition it induces as part of the architectural object.

Today's process of ruination can reveal a building's **chemical** dimension. A dimension which in my opinion includes the structural one. The chemical dimension although it has been acknowledged in the discipline for some time now it has only recently been introduced as an "active ingredient" in design practice. Francois Roche's project "things that necrose" is an active ruin. Rosche's dust collecting façade which transforms the surface into an environment of pollution, is a constant reminder of times irreversible impact on buildings. Here, for Rosche, a ruin is not playing the role of sustaining a memory of the past, instead it capitalizes on the inevitable catastrophes of a building's natural history.

2.4 The origins of the "Digital Tectonic"

In Chapter XIII, the Construction of Buildings, while advocating the architect's need to be in greater control of the cost of materials, their judicious use, and the means of execution, Viollet-le-Duc proposes that the parts be made in advance. It is here that we see his support for pre-fabrication in building construction, which later permeates modernist discourse[192]:

> It is evident that in construction of this kind [iron and masonry] everything should be prepared in advance. The various parts of the work can be executed in manufactories or special workshops, and can be brought to the building ready-fitted, so that they can be raised into place without further trouble.[193]

The nascence of the avant-garde modernist movement can be traced back to Viollet-le-Duc's attempts to integrate new technologies in architecture, his argument for material and structural integrity in the expression of architectural form, the coalescence of the fields of engineering and architecture, and most importantly, an integration of the industrial model of assembly into building practice through pre-fabrication.

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[192] Viollet Le-Duc, Eugène-Emmanuel, *Lectures on Architecture, Volume I*, Dover Publications, New York (1987), p. 81.

[193] Ibid

Le Corbusier embraced the reigning technologies of the day also, and incorporated them into an architectural manifesto. A cursory glance at the table of contents in *Towards a New Architecture* reveals his admiration of specific machines and also of the process and necessity of architectural standardization. His first chapter, "The Engineer's aesthetic and architecture," [194] shows the engineer is inspired by "economy" and "mathematical calculation", through which he achieves "harmony" unlike the architect.[195] The architect creates formal relationships, which move our hearts, and yet fail, at his current time, to create satisfying geometries because they do not work by calculation. LeCorbusier is not unusual in applauding the technological innovations of the day; like Viollet-Le-Duc, he marvels at modern technologies such as the airplane, automobiles and steamships. He also supports the novelty of engineering forms, and advocates original style, much like Viollet-le-Duc did before him.

A departure in Corbusier's analytic framework from Viollet-le-Duc is his collapse of architectural ideology with the mores of industrial production. Efficiency becomes an ethos, stemming from the economies of mass production, evolving into a model for the basis of modern man's lifestyle and built environment. The house thereby becomes a machine for living and furthermore demands to be incorporated into the process of mass production, unencumbered by the "styles". [196] He writes:

> Industry, overwhelming us like a flood which rolls on towards its destined ends, has furnished us with new tools adapted to this new epoch, animated by the new spirit....Economic law inevitably governs our acts and our thoughts... Mass-production is based on analysis and experiment... We must create the mass-production spirit.[197]

Mass production was the major industrial innovation of the time and Le Corbusier radicalized its integration into architecture by pushing it to its limits and incorporated it into a "new" architecture. He writes:

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[194] LeCorbusier, *Towards a New Architecture*, Dover Publications, New York (1986), Table of Contents.

[195] Ibid. 7

[196] Ibid. 13

[197] Ibid. 12

> The prime consequences of the industrial evolution in "building"...[are] the replacing of natural materials by artificial ones, of heterogeneous and doubtful materials by homogeneous and artificial ones (tried and proved in the laboratory) and by products of fixed composition. [198]

His five points towards a new architecture includes a list of new architectural elements, some of which are direct products of mass production, such as the horizontal band window. Le Corbusier, at least in theory, establishes a direct relationship between architecture and industry that involves the architect integrating industrial products into architectural design (from industry to architecture).[199] Seigfried Gideon analyzed the assembly line, seen, mistakenly, even today, to be the major innovation that occurred in Ford's motor plants. Instead, Ford's major innovation was in the production of standardized parts using *precision single-purpose machinery*.[200] This is what radically reduced manufacturing costs of the Model T car.

In the preface to *Mass Customization*, Stan Davis writes:

> Pre-industrial technologies....premised on small volume with high unit costs. Industrial technologies...were premised on the opposite approach: high volumes and low unit costs. Businesses had to wait for today's technologies to merge the two into mass customization, the production and distribution of *customized* goods and services on a *mass* basis.[201]

The mass production of the late 19th and early 20th centuries, where machines produced regular, standardized parts, has segued into an era in which manufacturing is being tailored to individual needs. Mass customization has reversed the relationship between industry and architecture; the architect has made a significant step forward into commanding the industry in the manufacturing of parts, thereby promising more control over the relationship between structure and construction. But, has mass customization really divorced itself from mass production?

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[198] Ibid. 232

[199] Of course, the relationship between architecture and industry, could be considered indirectly reciprocal although the architect does not directly shape industrial products during mass production.

[200] Licht, Walter, *'The Rational Factory: Architecture, Technology, and Work in America's Age of Mass Production'*, in Journal of Social History, September 1999.

[201] Pine, Joseph B. II, *‚Mass Customization: The New Frontier in Business Competition'*, Harvard Business School Press, (1999).

Today's CAD/CAM technologies stress mass customization as an optimal design feature, akin to architecture's conceptualization of its practice in relation to technologies of mass production in the 20th century. Nevertheless, for the most part, mass customization is a means to an end, divorced from any engagement with tectonic discourse. Current uses of CAD/CAM technology continue to produce single-purpose parts, which are then assembled in an attempt to translate the digital realm to the physical.

Marshall McLuhan, in his seminal text *Understanding Media*, argues that when they are first introduced, new media contain the traces of the medium they are meant to supplant. In his "Reversal of the Overheated Medium" he states:

> "One of the most common causes of breaks in any system is the cross-fertilization with another system, such as happened to print with the steam press, or with radio and movies (that yielded talkies). Today with microfilm and micro-cards, not to mention electric memories, the printed word assumes again much of the handicraft character of a manuscript. But printing from movable type was, itself, the major break boundary in the history of phonetic literacy, just as the phonetic alphabet had been the break boundary between tribal and individualist man."[202]

If, as McLuhan states, new media carry traces of the old, then what are the traces carried by current CAD/CAM technologies in the move from mass production to mass customization?

The contemporary use of a broad range of software and algorithmic or parametric processes, combined with numerically controlled fabrication techniques in architectural production, has greatly saturated the avant-garde field. The architecture of Frank Gehry serves as a case in point. Gehry's projects, enabled by the use of advanced computer software, rely upon the transformation of crumpled paper models into titanium-clad buildings. The fabrication technologies behind Gehry's architecture, premised upon processes of mass customization, surface and structure into optimized assemblies. These are then fabricated as unique pieces by numerically controlled machines. The innovation lies in the fact that the formal complexity of the design demands unique, "non-standard" pieces for assembly.

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[202] McLuhan, Marshall, *Understanding Media: The Extensions of Man'*, Routledge (2006), p. 39.

In its most noble form Gehry's approach could speak of a total suppression of the part to the coherence of the whole, an extension of the modernist discourse as Catherine Ingraham suggests. It could also be, as Jesse Reiser[203] critiques, a mere optimization towards form. Lastly, it could be just an expression of "look what I can do".

In all of those cases, the question remains: How "non-standard" is this procedure really? The *single-purpose machine* of the Fordist model revolutionized construction through the production of *single-purpose parts*. Today's avant-garde construction discourse (digital tectonics) still revolves around the production of the very same, single-purpose parts in an attempt to translate the digital realm to the physical. The machines may be more sophisticated and the forms more complex, but the function of the construction part remains singular, as before, a relic of industrial technology and its ethos of mass production. Structure for structure, skin for skin, infill for infill- the fundamental notion of a building as systems- skin, structure, cladding, insulation, etc, all persist. Jesse Rieser offers insight on the role of tectonic part in architecture. He suggests:

> The most pregnant tectonics may be found in the intermediate state between two forms of optimization. For example, on one extreme we might encounter a classical modernist infill structure, where there is a clear articulation structure-infill/structure-ornament. Here structure, guided by standardization and efficiency, delimits and constrains what is in between. At the other extreme, this dialectic is materially and semantically synthesized. Over optimized technology is solving the problem by erasing it, advances the early modernist ambition to become "almost nothing". In becoming too smooth, in reducing difference to total homogeneity, the model actually looses qualities.[204]

Within the realm of assembly, Reiser seems to suggest also a strategy between the two. In contrast to the Venturian "both-and" argument, Reiser's projects postulate an "and and and" argument which as he says is "neither pure classical models, nor pure structural honesty nor pure compositional formalism"[205] . In his projects, "systems become other system"[206], the same element repeated and varied can be a structural column here, a member of a space frame there

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[203] Reiser, Jesse and Umemoto, Nanako, *'Atlas of Novel Tectonics'*, Princeton Architectural Press, New York (2006), p. 96

[204] Ibid.

[205] Ibid. p.27

[206] Ibid. p.156

an ornamental shading device even further. In short, for Reiser, "each element has no intrinsic and stable meaning outside of its contextual relationships"[207]

Along the same lines, but looking from the material scientist point of view, Ann Dyson in her article "Recombinant Assemblies," challenges us to reject linear models of production and assumptions, situating this within an implicit critique of the reticence with which we accept the use of current CAD/CAM processes:

> Free-form manufacturing (such as 3-D templating) has allowed us to build complex 3-D prototypes from the ground up, one layer at a time. But one of the keys to bio-performance is the micro-compositing of more than one material. Two or more must be employed as natural systems blur boundaries at multiple scales within composite structures to facilitate symbiotic performance behavior....[208]

Dyson's plea is to reject the production methodologies that were exemplified by modernism's emphasis on mass production.[209] Although still in the realm of assembly - the micro-compositing of parts would require an even more massive production of micro-components and therefore would imply a massive micro-assembly, Anna Dyson's comment points towards a new role of the material production's expressive capacities.

My bias is altogether different. Extending Reiser's logic and applying it to contemporary modes of production of non-assembly, contemporary CAD/CAM machines are not single-purpose machines. Instead, they are single, variable-purpose machines that could be used to produce variable-purpose *chunks*. I am advocating for the **fabrication of non-assembly**, where parts, are limited by size and not by function.

2.5 TURKISH BOWS .... and other uncivilized matters

One of the first composite bows, dating back almost 5,000 years, is of Turkish origin. The efficiency of a bow in general was judged based on the breadth of the trajectory of its arrow. In typical wood constructions, an arrow shot from a larger bow generally traveled further, yet the bow became heavier and more cumbersome. This particular bow arose to compensate for this

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[207] **Ibid p.40**

[208] Dyson, Ann, 'Recombinant Assemblies', in Architectural Design (AD), Vol. 72. No 5, John Wiley & Sons Limited, London (2002), p.62

[209] Ibid. p.62

increased size and weight. The craftsman had to deal with an explicit technical problem - he had to extend the arrow's trajectory to make the weapon efficient, and reduce the bow's size and weight so that it could be easily used by horsemen. The composite bow:

> ...consisted of a slender strip of wood – or a laminate of more than one - to which were glued on the outer side (belly) lengths of elastic animal tendons and on the inner side (back) strips of compressible animal horn, usually that of the bison. The glues, compounded of boiled-down cattle tendons and skin mixed with smaller amounts reduced from the bones and skin of fish, might take more than a year to dry and had to be applied under precisely controlled conditions of temperature and humidity.[210]

The bow's sections display an intriguing configuration along its length. A close study reveals that the unusual configuration is the result of layering mass and matter, rather than the manipulation of shape (Figure 108). The final product is the result of mixing and blending of dissimilar materials chosen for their respective tensile and compressive properties - the craftsmen varied the thickness and location of material, in order to locally control the elasticity of the bow. The central part, or core, became stiffer, making the limbs more flexible, rendering the bow's trajectory equal to that of a much larger wooden bow. The craftsman's focus during production is on material property rather than shape. The Turkish bow was not designed in the Vitruvian sense of the word, it was "approximated."

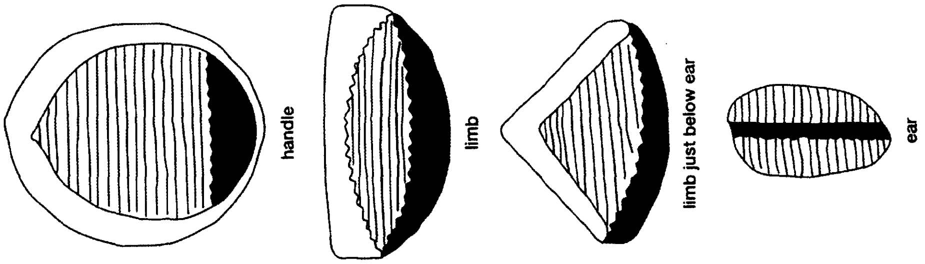

Figure 108: turkish bow sections. In Adriaan Beukers & Ed van Hinte, *Lightness*.

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[210] Beukers, Adriaan & Hinte, Ed Van, *'Light-ness'*, 010 publishers, Rotterdam, (2005), p. 86.

I cannot help but draw a relationship between the modes of operation in pre-geometric societies, which Derrida classifies as perceptive instead of eidetic,[211] and their extensive use of composite materials. The following diagram (Figure 109) maps the evolution of materials in time, illustrating the fact that composites were widely utilized from around 10,000 BC to 500 AC.

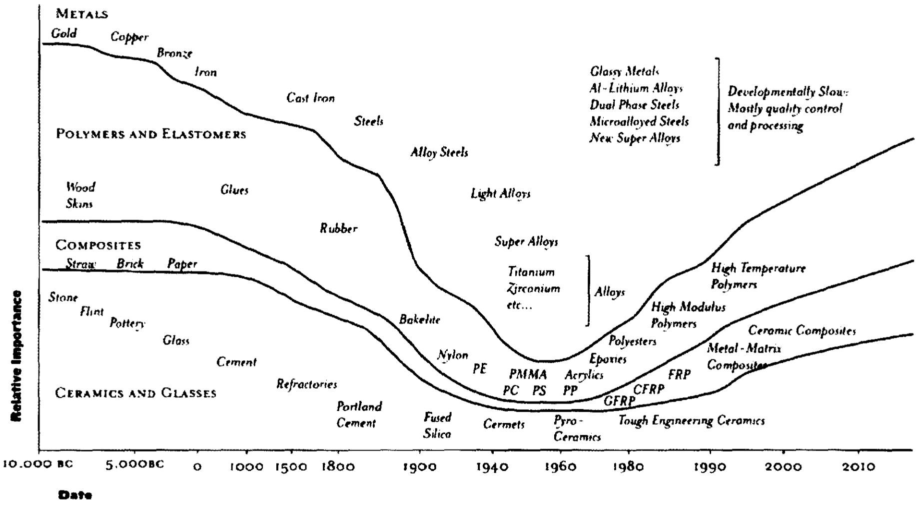

Figure 109: Composites Chart. In Adriaan Beukers & Ed van Hinte, *Lightness*.

In fact, composite materials are of prehistoric origin,[212] and were extensively used by nomadic populations in shelters, transportation vehicles and weaponry, which consisted of mixtures of straw, mud, wood, and other local materials. The black hut, constructed out of fabric and hair from goats, sheep, and camels, is an example of composite materials deployed in nomadic habitats.[213]

The Turkish bow's materiality derives out of the craftsman's ability to locally control the thickness of material along its body. Instead of accepting a singular application or determining one function for one material, varying materials are mixed, which, in combination achieve a gradient level of flexibility. The Turkish bow is a composite artifact with varying material properties.

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[211] Derrida, Jacques, '*The Problem of Genesis in Husserl's Philosophy*', University of Chicago Press, Chicago (2003).

[212] I assume here that prehistoric society is also pre-geometric.

[213] Beukers, Adriaan & Hinte, Ed Van, '*Lightweight Structures*', Architectural Design (AD), Vol.72 No.1, John Wiley & Sons Limited, London (2002), p. 102.

One can argue that 5,000 years ago, the craftsman's intuitive action was to transfer traits from the surrounding environment into his artificial constructs. Jacques Derrida, while trying to trace the origins of geometry, makes a distinction between a "morphological ideality" and an "exact ideality."[214] While the former is coupled with the idea of "roundness"- a morphological approximation- the latter is associated with that of the "circle"- an exact geometric specification. Derrida explains that early societies must have been operating within the realm of morphological ideality that stems directly from *perception* and not from thought. He believes that material qualities such as color, weight and hardness must have been related to these pre-geometrical, spatiotemporal shapes (morphological ideality) by a supplementary eidetic determination.[215] He asks to beware of scientific naiveté, which causes the "anexactitude" of the object to be considered as a "defect", as an "inexactitude"[216]. For those concerned with issues of design and computation, in my view, the closest, mathematically precise description of the anexact can be found in shape grammar's SHAPE. But even beyond theoretical computation or software already both Both Husserl and Bachelard have pointed out the significance that geometry[217] has played in shaping the perception of "sensible" things. In Bachelard's "The Phenomenology of Roundness" he writes: "the difficulty that had to be overcome in writing this chapter was to avoid all geometrical evidence". [218] Additionally, Husserl in his book *Crisis* writes:

> Out of the praxis of perfecting, of freely pressing toward the horizons of *conceivable (erdenklicher)* perfecting again and again *(Immer-wieder), limit shapes* emerge toward which the particular series of perfecting tend, as toward invariant and never attainable poles. If we were interested in these ideal shapes and are consistently engaged in determining them and in constructing new ones out of those already determined, we are "geometers"... in place of real praxis ...we now have an *ideal praxis* of pure thinking which remains exclusively within the *realm of pure limit shapes.*

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[214] Quoted in Husserl, Edmund, '*Origin of Geometry: an Introduction*', University of Nebraska Press, (1989), p.134.

[215] Quoted in Husserl, Edmund, '*Origin of Geometry: an Introduction*', University of Nebraska Press, (1989), p. 122. This is one of the four axioms that Derrida uses as a precondition to the advent of geometry.

[216] In my opinion, the 90's pliancy discourse, probably based on the insufficiency of CAD software to make property a manipulable entity, failed to acknowledge the non geometric characteristics of the "anexact" as part of its definition.

[217] Husserl makes a distinction between different kinds of geometry. I am referring the kind that has been commonly used by architects and engineers to represent their designs, the descriptive one. see Husserl, Edmund, '*Origin of Geometry: an Introduction*', University of Nebraska Press, (1989), p. 134

[218] Bachelard, Gaston, '*The Poetics of Space*', Beacon Press, New York (1964).

2.6 The origins of the composite paradigm

In the 1960s, under the umbrella of cheap energy, a renewed significance for the use of composite materials arose. After World War II, US manufacturers began producing fiberglass and polyester resin composites. The automotive industry first introduced composites into vehicle bodies in the early 1950's. Because of the highly desirable lightweight, corrosion resisting and high strength characteristics of the composites, research emphasis went into improving the materials' science and manufacturing process.[219]

Composite materials have resurfaced recently in architectural propositions, but not without a significant change in their consistency- they are now homogeneous. In practice, a contemporary composite material consists in most cases of a combination of two principal elements: *reinforcement* and *matrix.* The Reinforcement provides high strength and stiffness, and plays the principal role of load carrying. The matrix provides a surrounding medium for the reinforcement, distributes the load carrying forces evenly, and protects the reinforcement from environmental damage, such as elevated temperature and humidity.

The "Raybould House" project (1997) by Sulan Kolatan and Bill McDonald is an early example of a project, which, through composite materials, attempts to define a method of construction that directly links digital continuities with a material expression. The house is articulated as continuous surface, which blends the building with the landscape, and simultaneously organizes the interior space. The envelope becomes a mediator for diverse conditions, transforming from exterior envelope all the way to furniture. The same surface becomes a wall, a ceiling, a bathtub and a staircase. This design intention defied most deeply embedded postulations of construction and necessitated new fabrication and construction techniques to be set into practice. The plans involved the fabrication of templates cut in plywood at 1:1 scale with a CNC machine, which were then erected on site (Figure 110). Once assembled, they would form a skeleton for the overall building envelope. Spray-on foam would be applied to the rib frame matrix. An aluminized polyurethane skin would be applied to the exterior, while the interior shell would be finished in a smooth, cement-like acrylic mix.

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[219] Benjamin Tang, *"Fiber Reinforced Polymer Composites. Applications in the United States,"* in www.fhwa.dot.gov/bridge/frp/frp197.htm.

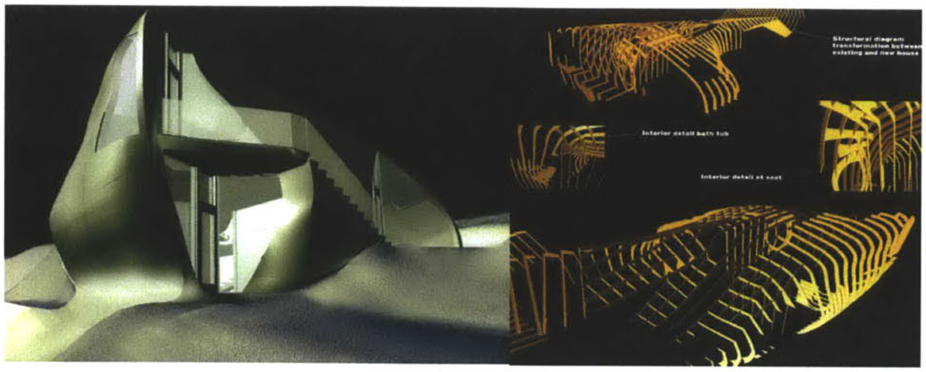

Figure 110: Sulan Kolatan and Bill McDonald "Raybould House".

The question that the 'Raybould House' poses is - What does it mean to conceive of a composite *super-surface* that incorporates within its unified body the properties of a wall, a window, a ceiling and a bathtub?

Today, Gregg Lynn, pushes this logic to a more consistent material expression by marking the shift from surface-on-a-frame to surface-in-a-bag. Especially in his smaller scale propositions, he eliminates the need of a frame or a skeleton constructed as a separate element. Nevertheless still, the composite expression is homogeneous and whenever a functional requirement necessitates a change of material, a cut is imposed and a separate assembly process is required (Figure 111).

Figure 111: Gregg Lynn "Bloom house"

2.7 Towards a Software Tectonic. The origin of Chunks

Ironically, both Viollet-le-Duc and his archrival Ruskin admired Gothic architecture, albeit for distinct reasons. Viollet-le-Duc, as discussed above, isolates material and structure as determining elements of form and so finds their utmost expression in Gothic Architecture. He writes:

> Gothic construction is not as antique construction of one piece, absolute in its means; it is flexible, free, and searching like the modern spirit. Its principles allow the use of all natural and industrial materials following their own properties; no difficulty is beyond its means, it is ingenious: that word says it all.[220]

Furthermore, he measured material expression in a building in regards to its structural fidelity; structural expression lay within the "judicious employment of material."[221] Greek and Roman architecture in comparison to Gothic architecture form a case in point. The Greeks are associated with frames, with relative light construction, and modular systems of proportion, the Romans with weight and mass and hence inertia. He describes the historic change from stone to timber construction with two-fold significance, materially, but also from a singular to a composite attitude towards construction, where multiple materials are used in the assembly of such architecture. Because he believes that structural expression should embody conditions of the era in an appropriate form, he valued Gothic architecture's structurally "composite" nature, which manipulated the Greek frame structure combining it with the Roman vault, which resulted in a unique, unprecedented form. [222]

> When the Romans sought for or were otherwise able to discover the principle of the molded vault- the hive structure- they certainly started from a simple principle; but what combinations did they not obtain by working out this primitive conception? When the French architects of the twelfth century added to this principle of the concrete vault that of elasticity and equilibrium, what did they not

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[220] Viollet Le-Duc, Eugène-Emmanuel, *Dictionnaire, IV* in *'Lectures on Architecture',* (tr) by B. Bucknall, (1881), *p*.58.

[221] Viollet Le-Duc, Eugène-Emmanuel, Lectures XI in *'Lectures on Architecture',* (tr) by B. Bucknall, (1881).

[222] Viollet Le-Duc, Eugène-Emmanuel, Lectures I in *'Lectures on Architecture',* (tr) by B. Bucknall, (1881), p.454

> accomplish? Did they not in less than a century reach the extreme limits imposed by the conditions of matter?[223]

A more fundamental reason for Viollet-le-Duc's admiration of Gothic architecture is more philosophical- his belief that unity in architecture was derived from the part to whole relationship. This is consistent with his admiration of the industrial logic of an assembly of parts. "No one will ever assert that unity is the work of chance. *Unity is the combined product of parts*."[224]

This last point brings us to the theoretical tensions between Viollet-le-Duc and his architectural ethos with that of John Ruskin. In the *Stones of Venice*, Ruskin tells us that the characteristic elements of Gothic architecture, placed in order of importance are:

1. Savageness
2. **Changefulness**
3. Naturalism
4. Grotesqueness
5. Rigidity
6. Redundancy

I am most interested in Ruskin's second characteristic, changefulness, which goes to the heart of his critique of industrial production. For Ruskin, changefulness, as it refers to the builder and not the building becomes *"the love of change"*[225]. He believes that the builder should be freed from repetitive tasks and celebrates the idea of a builder being able to change his mind during the construction process. Ruskin points out that the forms of medieval masons were 'capable of perpetual novelty'[226]- , something industrial processes were not designed to deliver.

> Wherever the workman is utterly enslaved, the parts of the building must of course be absolutely like each other; for the perfection of his execution can only be reached by exercising him in doing one thing, and giving him nothing else to do. The degree in which the workman is degraded may be thus known at a glance,

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[223] Ibid pp. 455-6.

[224] Viollet Le-Duc, Eugène-Emmanuel, '*Lectures on Architecture*', (tr) by B. Bucknall, (1881) p. 33. Italics added.

[225] Ruskin, John, '*The Stones of Venice: Characteristics of Gothic Architecture*', volume II, Chapter VI, Smith, Elder and Co., London (1853) p.154.

[226] Ibid. p.175

> by observing whether the several parts of the building are similar or not; and if, as in Greek work, all the capitals are alike, and all the moldings unvaried, if so the degradation is complete; if, as in Egyptian or Ninevite work, though the manner of executing certain figures is always the same, the order of design is perpetually varied, the degradation is less total; if, as in Gothic work, there is perpetual change both in design and execution, the workman must have been altogether set free.[227]

For Ruskin, unlike Viollet-le-Duc, the most admirable quality of Gothic architecture was not a unity which resulted from the coherence of its parts, but instead its integral wholeness- one piece absolute in its means.[228] He admires its ability to morph from its application in a turret and expand to its application in a spire: it is altogether malleable and lends itself to a transformation of its principles and forms with great plasticity and without any loss to its unity across architectural scales.

> And it is one of the chief virtues of the Gothic builders, that they never suffered ideas of outside symmetries and consistencies to interfere with the real use and value of what they did. If they wanted a window, they opened one; a room, they added one; a buttress, they built one; utterly regardless of any established conventionalities of external appearance, knowing (as indeed it always happened) that such daring interruptions of the formal plan would rather give additional interest to its symmetry than injure it. So that, in the best times of Gothic, a useless window would rather have been opened in an unexpected place for the sake of the surprise, than a useful one forbidden for the sake of symmetry...[229]

Ruskin, unlike Viollet-le-Duc, found Greek architectural principles of modularity, ratio, and measure reprehensible, because he believed this was all it contained. Gothic architecture followed the principles of variation, instead of repetition. The Greeks employed modularity in their repetition of parts to create a whole. The removal of one stone from Greek architecture would compromise its aesthetic; the removal of one stone from Gothic architecture would compromise its integrity. There is no hierarchy in Gothic architecture; instead, there is a novel "disposition of the masses."[230]

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[227] Ibid. p.172

[228] See Ruskin, John *'The Stones of Venice'*, Smith, Elder and Co., London (1853).

[229] Ibid. p.179

[230] Ibid. p. 63

> The assertion that Greek architecture, as opposed to Gothic architecture, is the 'architecture of proportion' is another of the results of the same broad ignorance... so far as modern Pseudo-Greek work does not depend on its proportions more than Gothic work, it does so, not because it is better proportioned, but because it has nothing but proportion to depend upon.[231]

I would like to draw a distinction between Ruskin's Gothic "chunk" and Viollet-le-Duc's Gothic "part". Viollet-le-Duc's inclination towards industrial production makes him interpret the Gothic as a "composite" structure- the perfect synergy of parts towards the manifestation of a whole. Ruskin, who is against the influence of the industrial revolution in architecture, interprets the Gothic as an accumulation of variable, coherent "chunks". For him a "chunk" simultaneously serves the purposes of structure, surface, and decoration. Furthermore, for Viollet-le-Duc, Gothic construction is an assembly of multiple "parts" each with a singular purpose. For Ruskin, the "chunk" is not assembled, but instead is "sculpted." Ruskin's idea of changefulness in architecture, exemplified by the Gothic, is about a singular material "chunk" that has *multiple* identities. It is only limited by its size, per se, and not by its purpose. A contemporary interpretation of a "chunk" becomes the object of investigation in this thesis. And it is contemporary - *cutting edge* - research in material science and engineering that can give us clues of the expressive and operative possibilities of a "chunk" in architectural practice.

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[231] Ibid.

2.8 Material science, composites with anisotropic properties

In material science and engineering, the re-emergence of composite materials is associated today with highly advanced manufacturing techniques, fabricated precisely to meet predefined conditions. Like the Turkish bow, objects produced by these techniques exhibit variable behaviors but as a result of a "micro-designed" material definition. In the same way that elasticity is controlled, for example, through the mutual direction of fibers, other material properties can be controlled through similar micro-manipulations.[232] Current research on composite materials hints their potential use and applications in architecture. The demand for a surface to serve multiple functions, such as those emerging from Kolatan and MacDonald's design for the Raybould house has already been addressed in the field of material science.

> Making composite structures is more complex than manufacturing most metal structures. To make a composite structure, the composite material, in tape or fabric form, is laid out and put in a mold under heat and pressure. The resin matrix material flows and when the heat is removed, it solidifies. It can be formed into various shapes. In some cases, the fibers are wound tightly to increase strength. One useful feature of composites is that they can be layered, with the fibers in each layer running in a different direction. This allows material engineers to design structures that behave in certain ways. For instance, they can design a structure that will bend in one direction, but not another. [233]

Recent developments in the aviation industry have led to the construction of airplanes manufactured entirely of composite materials. In comparison to pure materials and assemblies, composite materials and assembly present the advantage of yielding a certain kind of performance orchestrated to respond to fluctuating external circumstances- such as the different forces that will be exerted in different parts of the aircraft during flight. Therefore, a major property of a composite material is its ability to be tailored to specific needs.

In the case of the stealth B2 bomber, a primary manufacturing concern is the enhancement of the stealth capability, meaning the aircraft's invisibility to radars, which can be achieved through the reduction of its parts. The wing should be produced mostly as a singular component

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[232] Beukers, Adriaan & Hinte, Ed Van, *'Light-ness',* 010 publishers, Rotterdam, (2005), p.60.

[233] Day, Dwayne A., "Composites and Advanced Materials" in http://www.centennialofflight.gov/essay/Evolution_of_Technology/composites/Tech40.htm

that requires minimal assembly. Given its monolithic fabrication, and in order to control the main body's elasticity and enable it to adapt its shape to flight speed, the fibers in the composite material are layered locally in multiple directions and densities. Consequently, certain areas of the wing are more elastic than others. Its construction technique implies a radical breakthrough; it demonstrates a manner in which non-homogenous material distribution is strategically allied with the performance of the aircraft and even more so, where the performance is calculated in detail through the specifications of local resilience.

> We presently process a variety of materials, cut them up into shapes and then fix them together to create the built environment for our particular needs. The majority of design recourses are directed into trying to solve the technical problems brought about by the bringing together of different building components, whether they be structural, finishes, or service equipment of varying magnitude. However the advancement of material science is revealing a new construction process initiated at an atomic level. Instead of cutting and stitching a patchwork of structural and non-structural elements in the hope that they will work in harmony, the atomic revolution will provide us with the means of creating building enclosures by manipulating the molecular matrix and the atomic ingredients to the required structural and environmental specifications.[234]

From the view of the material scientist, composites point towards a paradigm of non-assembly in which material properties can be locally custom-tailored to functional requirements. Even beyond function, my inquiry probes the absence of such an expression in architectural discourse. The Composite strategy proposed by Gregg Lynn, suppresses the possibility of exposing the locally varying composite nature of elements and instead hides it behind "sharp plastic wraps".

In the spirit of Bauhaus, fashion designer Issey Miyake does not accept fabrication technologies as they exist in his industry. Instead, he "tweaks" them in order to become an integral part of his desired aesthetic. Miyake's clothing line, APOC (a piece of cloth) from 1999, exemplifies production created through the use of a single, variable-purpose machine. In this project, Miyake challenges the most deeply-rooted assumptions in tailoring, which entail weaving a fabric, cutting it into pieces and sewing the pieces together to produce the final garment. He proposes, instead, a *seamless production* in which the clothes are woven directly as one unified entity using a computer controlled machine. The technology involved in this process is unique in

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[234] Battle & McCarthy, *'Multi-Source Synthesis. Atomic Architecture'*, in Architectural Design (AD), Vol.65, No.1/2, (London: Academy Group Ltd, 1995), III.

the design industry as it involves an 'intelligent' weaving machine.

> Computer – controlled levers move the warp threads into the up or down position according to the digitalized pattern instructions, and an automated shuttle pulls the weft thread through a dizzying 200 times a minute... the key to the whole process is the digital Jacquard machine overhead, a loom attachment that automates the weaving patterns.[235]

Through this process, designers can *locally* specify the density and the type of knot in the weave, in order to make, for instance, the cuffs of a shirt less elastic than the neck. In a more general sense, this process enables the designer to manipulate material, embedding into the final object attributes that in any other case would be derived from an assembly of different parts. Although CNC weaving technologies have already found their way into speculative architectural projects, it is another technology that catches my attention.

2.9 3D Printing Technologies

Probing into the fabrication implications for architecture of such propositions, we find new production technologies that have been rapidly developing over the past ten years, namely rapid prototyping and 3D printing machines. Unlike plasma, laser and water jet cutters that are geared towards fabricating components out of sheet material or multi axis CNC milling machines that are designed to remove material from solid blocks, 3D printing machines directly deposit the required material to produce 3dimensional objects. What distinguishes them from other CNC fabrication methods is that they promise to minimize material waste. The volume of material used by 3D printers, in most cases, equals the volume of material embedded in the final product, thus reducing the energy footprint of material production. Essentially, 3d printers realize digital objects (B-Reps) into physical constructs by either extruding or spraying from a print head a molten substance (plastic in most cases) or by hardening a material in powder form (ceramic in most cases) with the use of a binding agent (glue). Although in most cases 3D printers are most commonly used at a smaller scale, on the basis of functional requirements, a few research projects have recently been launched that apply similar technology at the scale of architectural production.

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[235] Scanlon, Jessie 'Seamless' *Wired Magazine: Break the Rules*, (April 2004), p.167

A "Contour-Crafting"[236] robot, receiving instructions from a digital file, is able to print houses, by pouring successive layers of semi-cured concrete, essentially scaling up available technologies. Engineer Behrokh Khoshnevis suggests that he will be able to construct on site, without the aid of human hands a 2,000 square foot house with all utilities for electrical and plumbing in less than 24 hours. This process caught the attention of Francoise Roche who pushed it to its extremes with his "I have heard about"[237] project. Along the same lines and equally rigorous in its execution, Enrico Dini, has launched D-shape[238], a large scale 3D printing machine that uses sand and a binding agent to solidify contours of a CAD file into a solid 3D object made out of a material the resembles stone. The morphologies that Dini exploits for demonstration purposes, take cues from mesh relaxation design technologies that have seen wide spread use in recent speculative projects. Francoise Roche's "hypnosis room" project[239] speculates over the formal consequences of such processes.

Both large scale 3d printing technologies, one using the extrusion solution and the other the powder solution, fabricate large scale objects, without assembly. Furthermore, since assembly is not an issue, technologies like these are able to produce objects of high formal complexity. Beyond the promise of instant material production (one hits the button and the building is there...in front of you), in my view, the proposed technologies do not satisfy the imaginative potential of design propositions. The reason is simple: In both cases, the objects are made of a single material. Any expressive or even in more pragmatic terms functional requirement, that necessitates a material with different properties, would still have to be added later. Francoise Roshe's rendition of the project "I have heard about", although speculative in many ways, serves as a case in point[240]. The green translucent surface of this project, rendered as a separate layer, implies either a second printing process or an assembly (Figure 112).

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[236] Khoshnevis, Behrokh 'Houses of the Future: Construction by Contour Crafting. Building Houses for Everyone', Viterbi School of Engineering, Information Sciences Institute, University of Southern California, 2004.

[237] Exhibited in MAM Musee d'Art Moderne Paris, (2005). I doubt that R&Sie(n) would ever put this project out there in order to discuss the pragmatics of construction. Even though it is here that they speculate on a collaboration with «contour crafting», I examine the imagery based on its expressive potential.

[238] Dini, Enrico 'D-shape' 2007, in www.d-shape.com

[239] exhibited in MAM Musee d'Art Moderne Paris, (2005)

[240] ibid

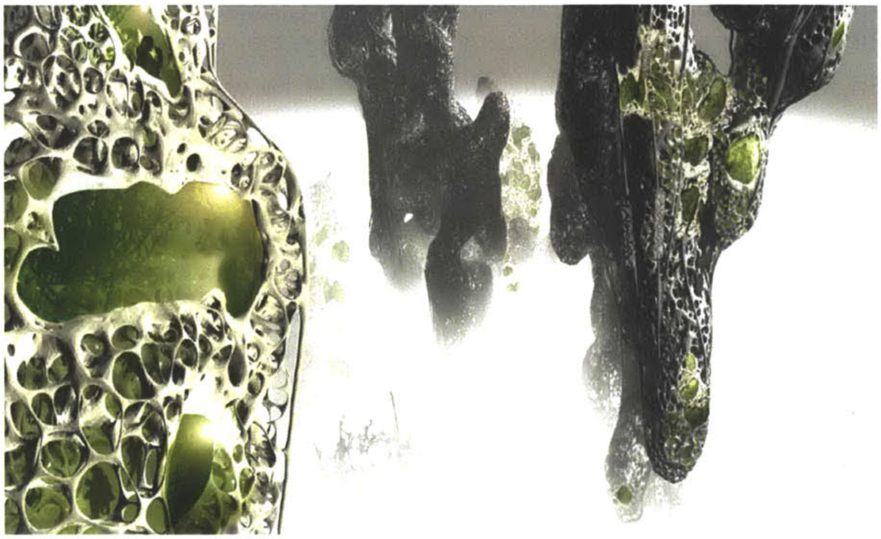

Figure 112: R&Sie(n), François Roche - Stéphanie Lavaux, *I have heard about*. (2005)

At the same time that research in 3D printing is being developed at the scale of architectural production, at a smaller scale, 3D printers that can print two or more distinct materials have already become available for designers. In this smaller scale, a single object can be printed out of multiple materials. Here, materials are extruded separately out of multiple print heads. The two distinct technologies that should be mentioned here are namely *Stratasys*[241], that invented and patented the *Fused Deposition Modeling (FDM)* and *Objet*[242], that uses the *PolyjetMatrix*™ technology to literally spray multiple materials[243].

In the case of *Stratasys*, their *Dimension* series is capable of using two different materials in the same model. One distinct region can be specified for each material. In practice, in order for two materials to be printed in the same model, one has to define the distinct boundary objects even if they share some faces. The material used is usually ABS plastic comes in solid form and in many different colors. Objects are built on a flat surface that is able to move in X and Y directions, while a nozzle which can move in the Z direction deposits molten material layer by layer, with sub millimeter precision, until the whole object is completed. ABS plastic comes in the form of a round filament that gets pushed through a heated nozzle; it melts and fuses on top of the previous layer. A special kind of bio-plastic can also be used in the form of filament. This material

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[241] http://www.stratasys.com/

[242] http://www.objet.com/

[243] Stratasys and Object have recently merged into one company.

is water-soluble[244] at temperatures of around 80° C. It is commonly used as support material in the 3d printing process in order to achieve even higher level of complexity in the object's form. It is also this kind of material and a similar fabrication process that is implied in François Roshe's "things which necrose" project[245] (Figure 113).

Figure 113: **R&Sie(n),** François Roche - Stéphanie Lavaux, *"things which necrose"*

Objet, with its *Connex* machines, pushes the multi-material technology a step further. According to their press release[246] from a selection of more than 100 different materials[247], the Connex 3D printer is able to spray "up to 14 different material properties in the same model". Materials range in their properties from elastic to rigid, from transparent to opaque; they come in different colors and chemical consistencies[248]. Regardless of the large pool of materials that can be used, there are a few characteristics that remain consistent. The pre-selected materials are sprayed from different nozzles one at a time. Like the Stratasys, here too one has to define regions of geometry (boundaries) where each preselected material is deposited.

The specific 3D printers, just like their bigger brothers, point towards construction without assembly. We can now imagine monolithic objects that can have regions of different materials, with different aesthetic and functional characteristics. But there is a catch! When materials meet, they meet at an edge. Although the joint between two materials is now chemical instead of

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[244] A chemical additive is needed.

[245] http://www.new-territories.com/twhichnecrose.htm

[246] press release from June, 20, 2012

[247] http://www.objet.com/Portals/0/docs2/PR32_Objet_107_Materials_20June2012-F.pdf

[248] The materials come in liquid form (mostly resins). The moment they are sprayed they are cured with Ultra Violet (UV) light. This material technology is very similar to the one used by dentists to make substitute teeth. Materials contain a chemical which stays inert before the exposure to UV light. Once they are exposed they instantly cure to become solids.

mechanical - a major shift on its own, some expressive characteristics stay the same. One material for one shape. Even if shapes are now glued together and not bolted, there is still a "trace" of assembly. If the mechanical failure in an assembly of parts means the breaking of the joint, here the mechanical failure results in the de-lamination of the members. Among other things, this last possibility of failure has since the early 90s become the object of investigation of MIT's 3D printing laboratory at even smaller scales.

Research started at MIT as early as 1989. With the Local Composition Control (LCC) MIT's 3D printing laboratory has initiated a research for creating Functionally Graded Material parts that essentially have composition variation within them.[249] According to the research group, "material composition can be tailored within a component to achieve local control of properties (e.g., index of refraction, electrical conductivity, formability, magnetic properties, corrosion resistance, hardness vs. toughness, etc.)"[250]. As they explain, the precise control of the spatial distribution of properties can allow for control of the state of the entire component.[251] In the case of mechanical de-lamination this would mean the following. When we have two materials with different mechanical properties joined or glued together- for example, they have different expansion rates or different elasticity - it is often the case that while temperature changes or movement is applied, they fail at the joint. We see this in buildings all the time. Brick walls most commonly crack at the point they meet a concrete beam. On the other hand, gradient transitions between two materials we basically have the ability to blend their mechanical properties within an area thus turning the joint into a gradient. This allows for the forces that produce the failures to not concentrate on a single point but instead dissipate within an area. As the LCC groups explains "By such local control, monolithic components can be created which integrate the function of multiple discrete components, saving part count, space and weight and enabling concepts that would be otherwise impractical."[252] This last argument pretty much echoes today's concerns in the discipline about energy efficiency, reduction of weight, minimization of material usage and so on, and promises the integration of new functionalities and performance characteristics in buildings. More importantly, it implies a mode of expression that fits between the traditional tectonic and the composite approach. While it adopts the continuity of the composite approach,

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[249] 3DPrinting Laboratory, MIT. See: www.mit.edu/~tdp/composite.html

[250] Liu, Hongye 'Feature-Based Design of solids with local Composition Control', MIT Thesis, (2004) p. 11

[251] ibid

[252] W. Cho E. M. Sachs N. M. Patrikalakis M. J. Cima T. R. Jackson, H. Liu J. Serdy C. C. Stratton H. Wu R. Resnick, *Methods for Distributed Design and Fabrication of Parts with Local Composition Control, in* Manufacturing Grantees Conference, Vancouver, BC, Canada, January 2000.

it allows for the full spectrum of expression of parts. It accommodates for the necessary change in material property, that the traditional tectonic approach does so well. The absence of such an expression at the scale of architectural production and the lack of methods that would allow it became an incentive for the development of a gradient material 3D printer.

2.10 Cast_it

Cast_it[253] is a multi-axis, computer numerically controlled (CNC) device that prints 3 dimensional objects by dynamically mixing at least two distinct but chemically compatible materials. Dynamic mixing allows for gradient transitions between two or more materials, resulting in an object with anisotropic material properties. Cast-it is still ongoing research[254]. Compared with existing 3d printing technologies and informed by the work of MIT's LCC group it aims to derive construction principles that can apply at the scale of architectural production. Furthermore, it is used in direct relationship with VSpace. Designs from VSpace can become physical products with the use of this machine.

Cast-it is a scaled-down prototype of a CNC machine that at 1:1 scale would fabricate architectural "chunks" of variable material composition (Figure 114). The machine and its subsequent technology suggest an alternative to the building industry's current reliance on producing multiple parts with distinct properties that are then assembled into larger structures. It develops methods that engage with Gregg Lynn's "composite approach" and aims to replace components with single, multi-material "chunks" that combine properties (structural, functional, optical, aesthetic, etc.) produced in a single process.

Cast_it is comprised of three distinct functional parts[255]. There is a reconfigurable mold on which materials would be laid, a 3 axis gantry that holds the printing head responsible for the material mixing, and two numerically controlled large capacity syringes the regulate the material flow.

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[253] Tsamis, Alexandros, *'Go Brown. Inner-disciplinary Conjectures'* in Architectural Design (AD) : Ecoredux. Design Remedies for an Ailing Planet, (Ed) Kallipoliti Lydia, John Wiley and Sons, London (June 2010).

[254] The project started in collaboration with Kaustuv DeBiswas. Alexandros Tsamis was responsible for determining the functional principles of the machine and also responsible for the fabrication and mechanical assembly of the parts, while DeBiswas was responsible for programming the interface between computer and machine. Thank you Kaustuv for your generosity. It is currently being developed at UAI, School of Design, Chile.

[255] It is amazing how many nuts and bolts and motors and belts and lead screws are necessary in order to fabricate gradient, non-assembled things!

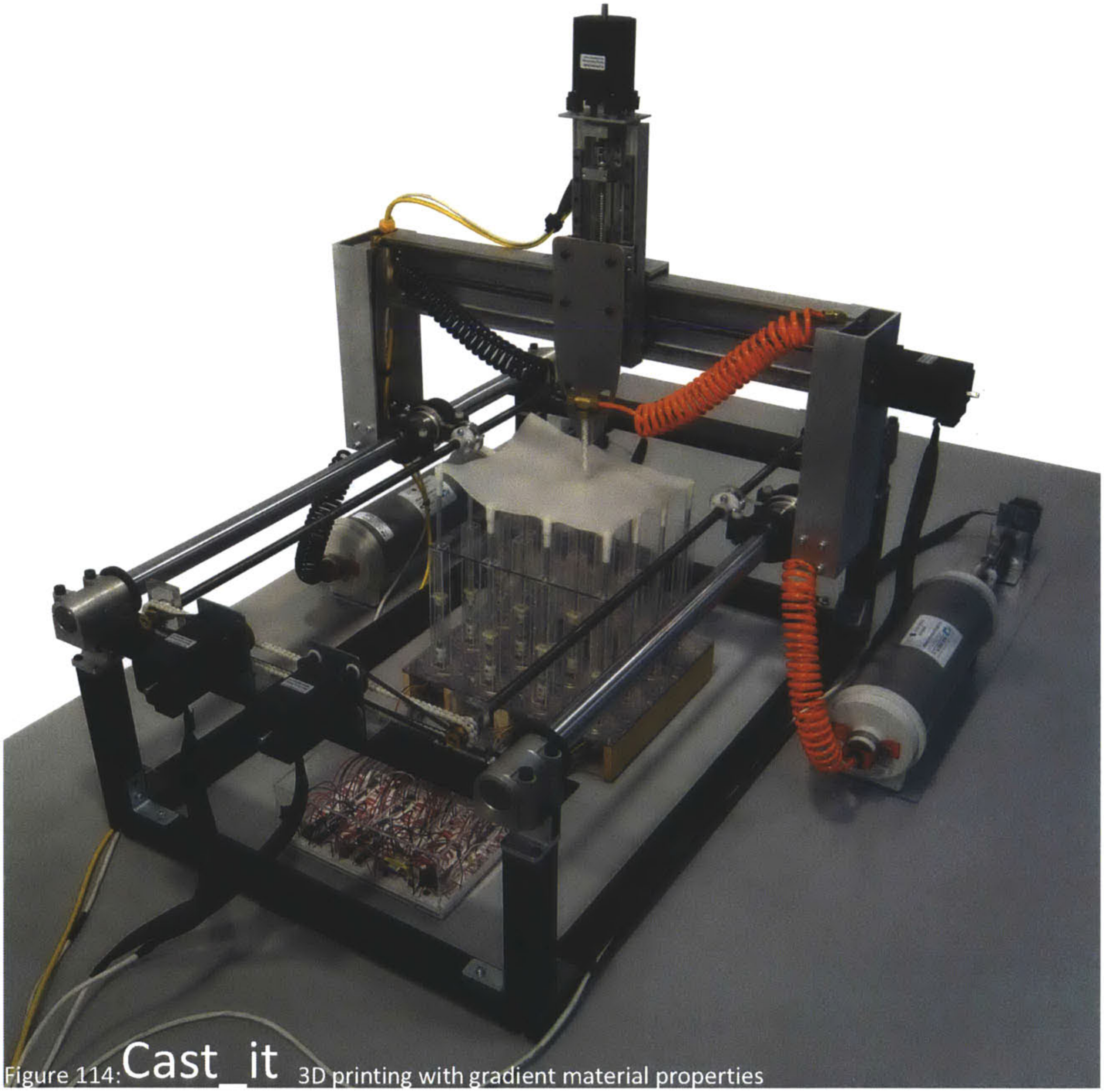

Figure 114: Cast_it 3D printing with gradient material properties

2.10.1 Reconfigurable mold

Cast_it uses a CNC reconfigurable bed[256] on which material is deposited (Figure 115). The purpose of the mold is to eliminate the need for excessive support material when printing objects with complex geometry. In some cases, it could eliminate support material completely. Furthermore, since this process is intended for large-scale production of surfaces, a reconfigurable mold would allow for the construction of surfaces with complex geometry.

The bed consists of a malleable silicone surface that is pushed by a 2-dimensional array of 16 computer numerically controlled (CNC) pistons that take instruction from a 3D CAD file and modulate accordingly. Essentially a boundary shape from VSpace, is sampled at 16 points in a grid that correspond to the 16 pistons. Each piston is operated by a single stepper motor. The difference in height between the points is converted to number of steps and given as instruction for the pistons to move up or down and assume their respective positions.

Like in any 3D printing process, although the bed is rectangular in shape, part of it can only be used each time in order to produce a chunk with limits that are specified by the design (Figure 116). The boundaries of each chunk are essentially limited by the total surface area of the bed and by the intended design.

An issue that arises from this process is that the boundary shape would never be exactly reproduced by the shape of the surface. An attempt was made to fabricate a silicon surface with variable thickness (denoted with a circle in Figure 116) so that it is less elastic at the points of attachment with the surface yet elastic enough in other areas to accommodate for the stretching that the deformation requires. The design of the mold surface is a design and engineering issue on its own. Some shapes are easier to approximate than others. Restrictions are imposed by the number of pistons available (sampling resolution) and the physical behavior of the silicone surface. A second approach to resolving the issue was also implemented. A laser distance sensor (Figure 117) attached to the machine gantry would scan the silicone surface once it has reached its final position. The results of the scan would then be compared with the original boundary design. A comparison as a feedback loop, between successive scans and the original digital shape

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[256] This device was developed in 2003 as part of Media Lab's "Learn How to do Almost Anything MAS 863" class. see Tsamis, Alexandros, '*Digital Graft. Towards a Non-Homogeneous Materiality*', MSc Thesis, MIT 2004. Programming interface was done by Stylianos Dritsas. Devises that should be mentioned here as precedents are: dECOi's Hyposurface project. Although the hyposurface was designed as a 3d physical display and the technology used is different, they share similar principles of operation. A second precedent is Axel Killian's and Kyle Steinfeld's smart molding device which was developed the same year a semester earlier. Although different in technical specification, they too developed a reconfigurable mold. (http://designexplorer.net/projectpages/mas863.html) If there is any contribution here, it is in its use as a bed in a 3d printing machine.

would allow for further compensation. In most cases however, this process could also prove imprecise. Further precision could be achieved if a support material was laid in areas of the mold that deviate from the original.

2.10.2 Printing Head

The printing head of Cast_it is mounted on a 3 axis CNC driven gantry[257]. The printing nozzle, which is responsible for mixing materials together, is essentially a hollow tube that contains along its axis two intersecting helixes that are spiraling in opposite directions[258] (Figure 118). This printing head is intended to be more like the printing head of "contour crafting" that we saw earlier in this section. Before they reach the nozzle, two distinct materials in liquid form flow through flexible pipes and reach a T section plumbing connector. As the two materials flow through the nozzle, the helixes force them to fold one into the other resulting in a homogeneous mixture.

This prototype was intended to be a scaled-down version of a machine that would print Architectural chunks. A larger-scale machine would require a large amount of material printed at a time. As a result, the containers of material are not mounted on the gantry so as to not hinder its movement and also lessen the amount of energy required for the machine's operation[259]. Part of this is since the two materials remain separate until they reach the nozzle, any material not used can be retrieved back to the container.

2.10.3 CNC Raw Material Containers

The control of material flow on the machine bed is achieved through to CNC syringes (Figure 119). Essentially, a stepper motor attached to a lead screw pushes the syringe pistons at a controlled rate. The faster the motor rotates the more material comes out of the nozzle. Since two syringes feed into the same nozzle, a coordinated control of the respective stepper motors, allows for a precise mix ratio between the two materials. The two syringes are intended to hold two distinct but chemically compatible materials. The method of control will be further analyzed in the section that follows.

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[257] The 3 axis motion is pretty much the same as a regular CNC milling machine.

[258] the nozzle in the prototype is used by dentists to mix a two component ceramic material. Nozzles come in different lengths and diameters.

[259] it would not be very practical to drag bulk of unused material while the machine was in operation. The weight of the moving parts play a crucial role in determining precision and energy consumption

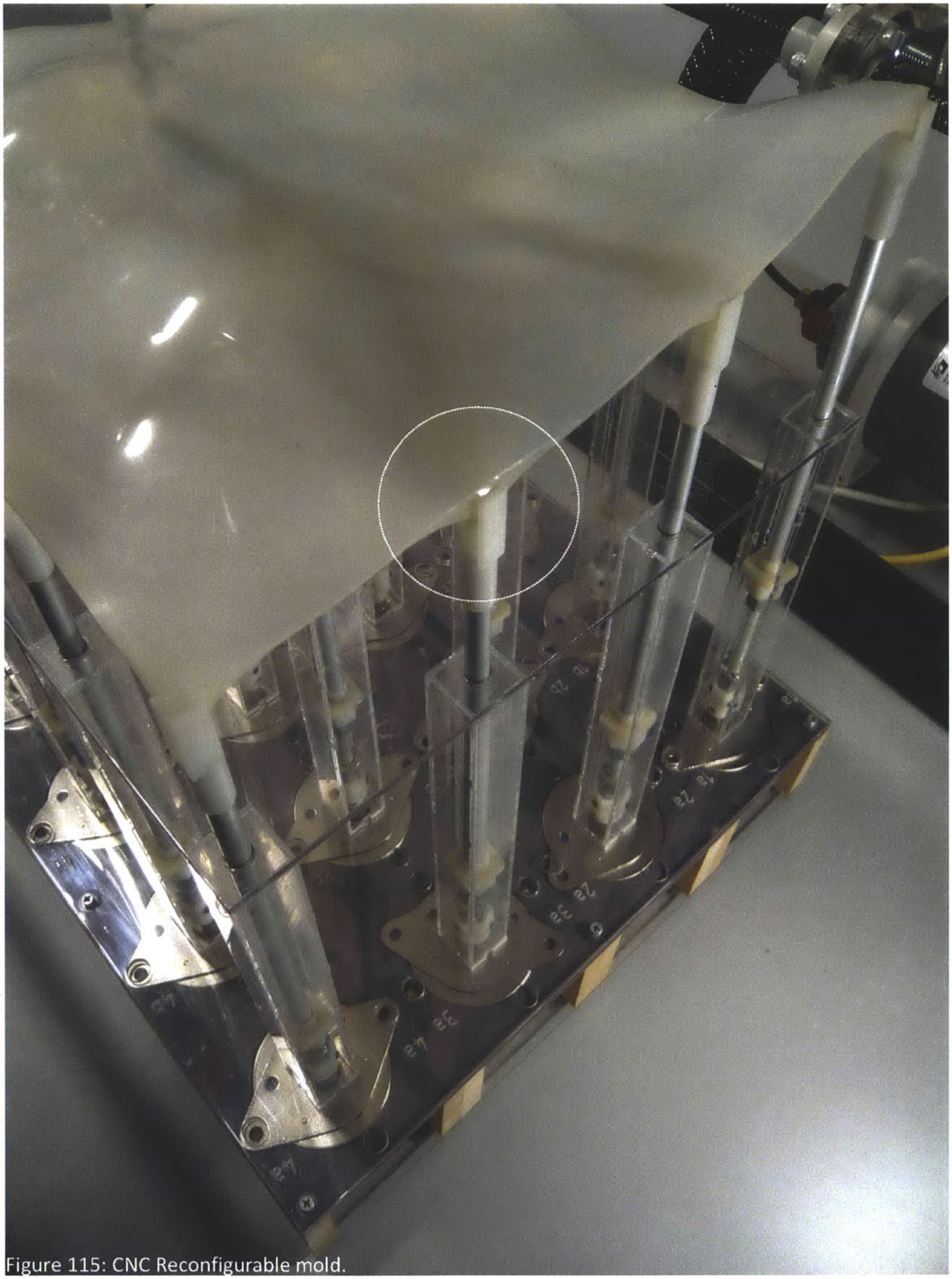

Figure 115: CNC Reconfigurable mold.

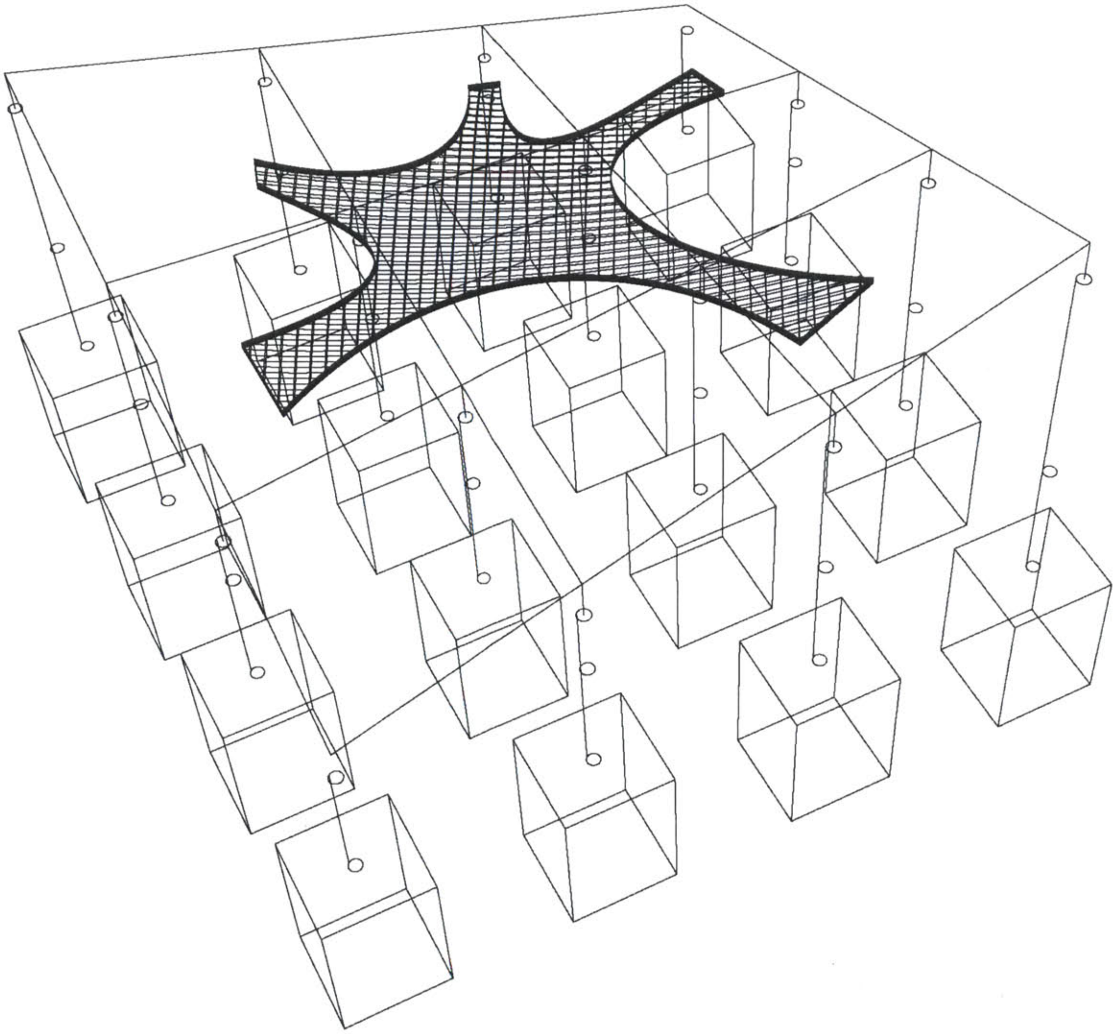

Figure 116: CNC Reconfigurable mold. Printed chunk location

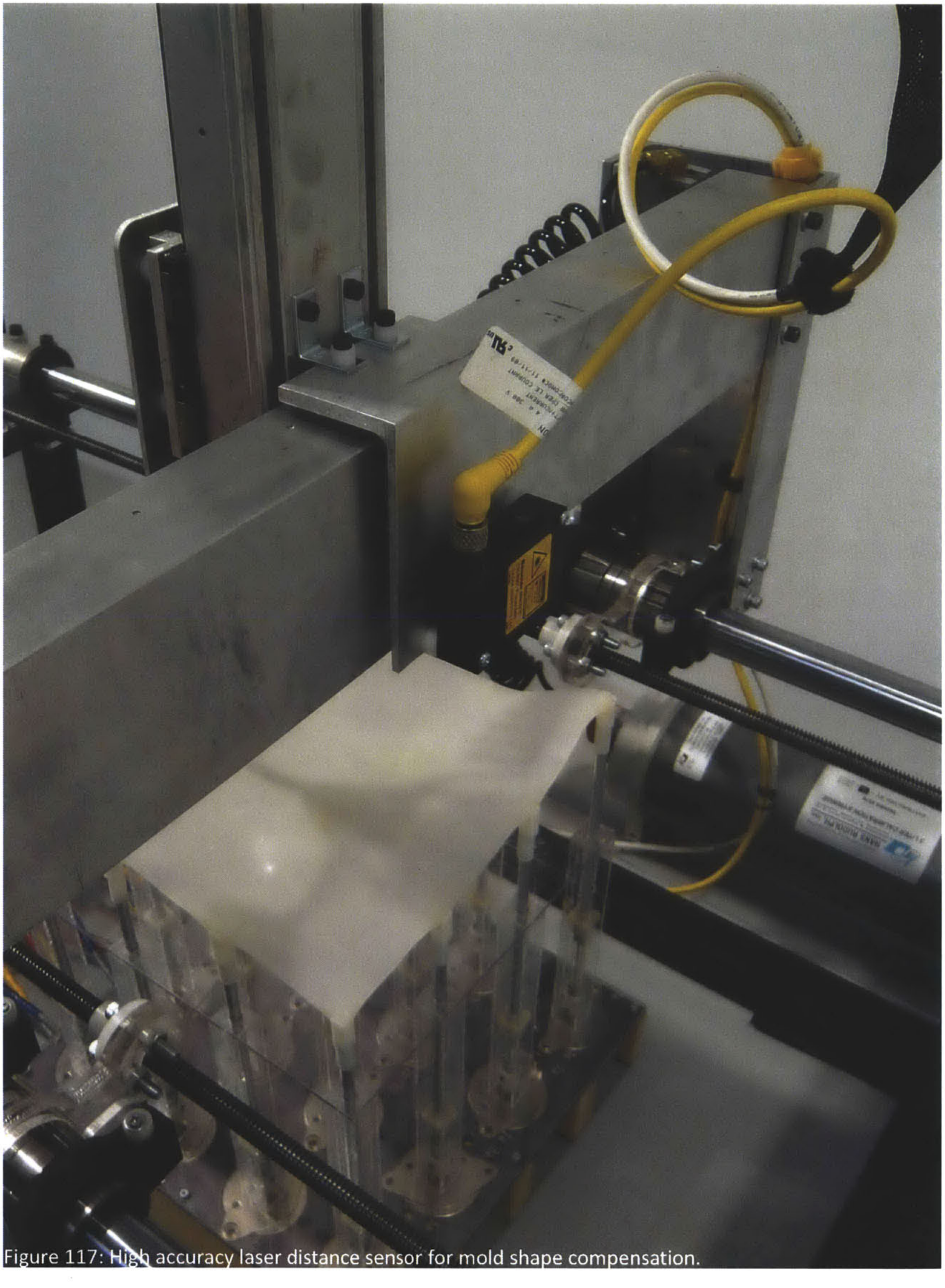

Figure 117: High accuracy laser distance sensor for mold shape compensation.

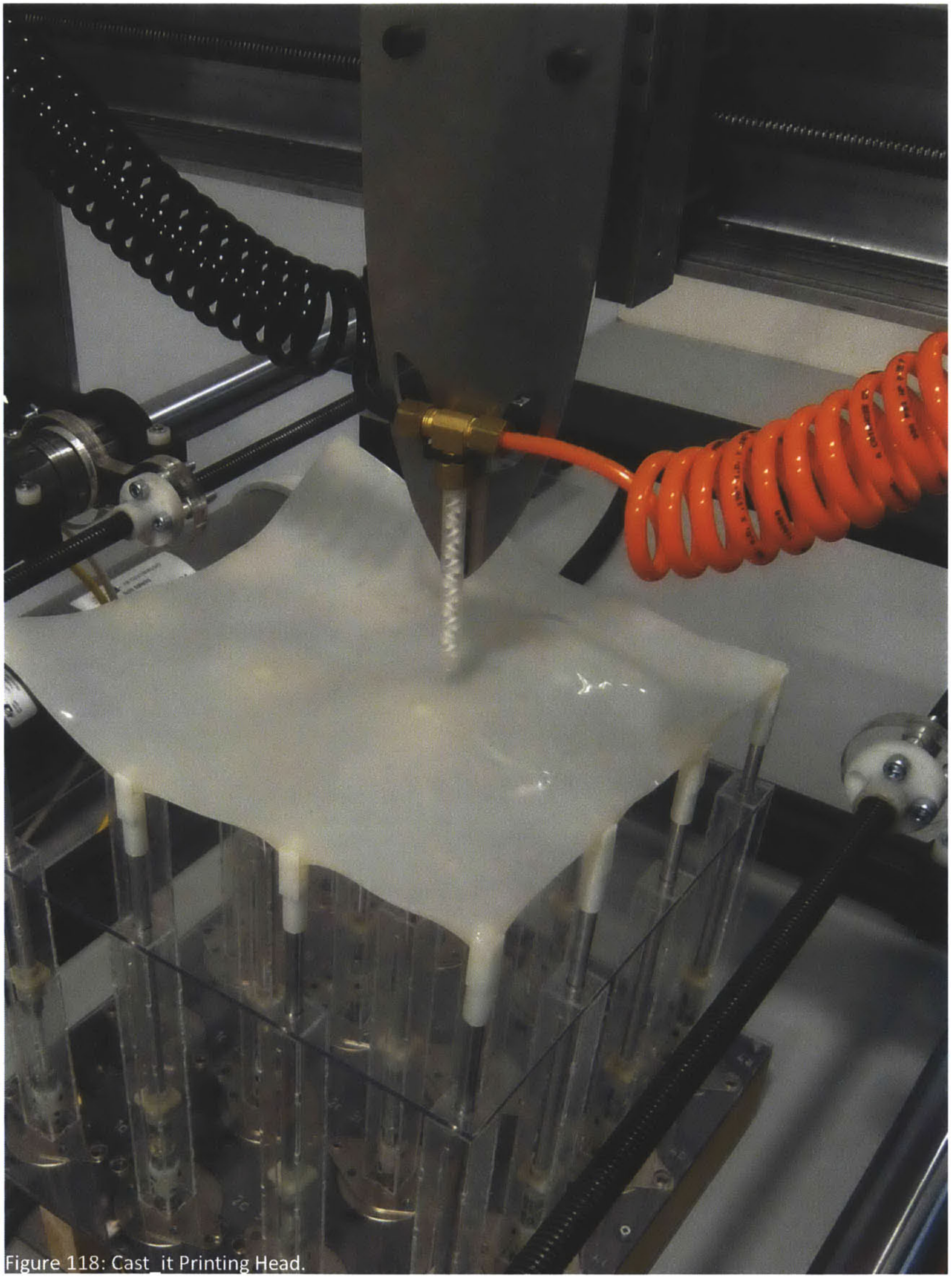

Figure 118: Cast_it Printing Head.

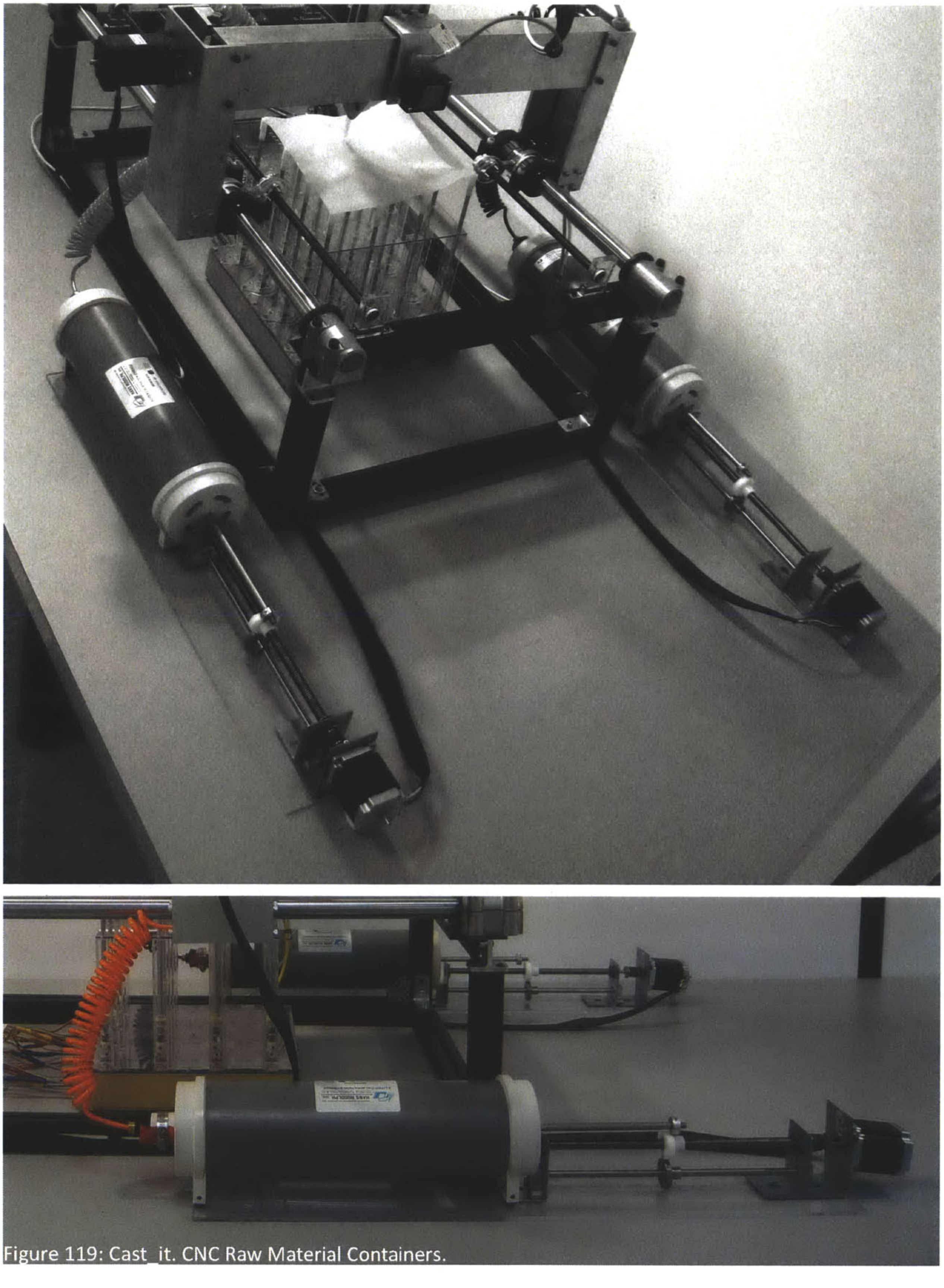

Figure 119: Cast_it. CNC Raw Material Containers.

2.10.4 Cast_it. Control Software and Method

MIT's 3d printing laboratory has made as its main focus of inquiry since the late 90's the methods and technologies that can be used to digitally represent objects with variable material properties[260] as well as how to translate those into instructions for a machine to fabricate them.

The group has identified two distinct methods of representation. The first method is the voxelized one. According to the group "a voxelized representation relying on the optimal volume dithering is used to serve as an intermediate representation scheme which converts the continuous-tone composition variation into printable, discrete information throughout the volume of an LCC object. As a result of such conversion, the transformed boundary may only approximate the boundary of the LCC object."[261] (Figure 120). This approach represents a solid object as a collection of voxels. Each voxel holds information about the material to be used for that voxel and also whether it is inside or outside the ideal solid. One of the issues that they raise is that voxels, because they are resolution dependent, cannot exactly describe the ideal solid. From the point of view of this thesis, this approach is not that much different than Albert Farwell Bemis' description of forms built from four-inch cubes. In this case Voxels are essentially treated as physical bricks at a tiny sub millimeter scale, each storing material information for the volume of space it occupies. They should not be confused with the voxels described in VSpace. The goal of the LCC group is to translate voxel information into a printing process that essentially works just like an inkjet printer. Voxel information is translated into droplets of material that are placed in their corresponding positions.

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[260] The LCC group has been concerned since the late 90's with digital representations of material properties. They too, for entirely different reasons, critique the hierarchical relationship between geometrical and material information within the digital.

[261] Cho, W., Sachs, E. M., Patrikalakis, N. M., Cima, M. J., Liu, H., Serdy, J., Stratton, C. C., Local *Composition Control in Solid Freeform Fabrication,* Massachusetts Institute of Technology. in http://www.mit.edu/~tdp/info-flow/publications/DMI-0100194.pdf

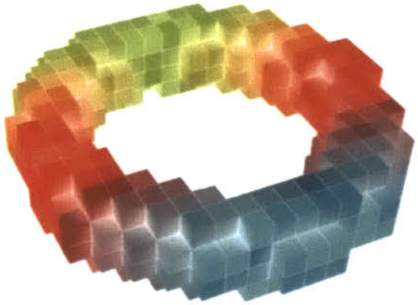

Figure 120: Voxelized torus with different material properties.

For the purpose of this thesis, especially since we are considering larger-scale production, I examine this process as it translates with current commercially available multi-material 3d printers. As we saw earlier the *Object Connex* technology requires as input a boundary representations of distinct objects each assigned with a material. We also saw that *Object* is now capable of printing in the same model 14 different materials. If we assume the voxelized approach as it is described by the LCC group, we could have a digital model that contains multiple voxels - **defined as boundary representations** - each assigned its own material. In the case that we have 1mm sized voxels and 14 different mixtures of two materials spaced equally along the range, the maximum gradient area we can achieve is 14mm long in all directions.

Figure 121 : The Voxelized Approach, linear gradient.

Larger voxels would make larger spans of gradient transition at the cost of resolution reduction. At the architectural scale, a 2.8 meter gradient would require 14, 20cm long bricks; pretty much the standard dimension. Although scale relative to the eyes perception is important, and it is possible if voxels (as bricks) are small enough to achieve a gradient transition, at larger scales especially if we are also tackling functional requirements, this could prove challenging.[262] This approach in terms of expressive and material performance requirements is scale-sensitive.

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[262] The risk of de-lamination increases as the physical dimension of the voxels increase.

What becomes important to me at this point, paraphrasing Antoine Picon[263], is to be able to surpass in the construction of gradients the unitary logic that the digital medium imposes. What has been Shape Grammars' primary concern since the 70ies for computation in design, can also find its application in the realm of construction. Although I find it impossible for this to happen inside a digital computer - after all, Zeros and Ones are non-negotiable unless we invent another kind of computer[264] - a translation of a unitary logic of description to mechanical continuous movement can make continuous gradient fabrication possible.

The second general method scheme that the LCC group suggests is one in which a boundary representation is first divided in regions of material along its surface and then blending algorithms produce material information for the object's surface as well as its thickness. The B-rep and its interior is then subdivided in distinct tetrahedral elements, the vertices of which store material information (Figure 122). According to the group, this general approach "advocates the decomposition of models into general regions over which material variations are mapped."[265]

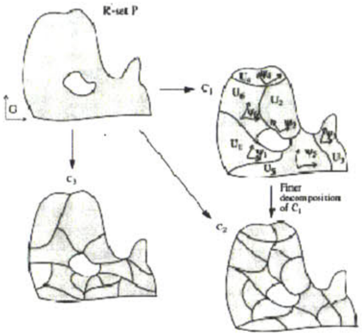

Figure 122 : LCC Group. General scheme for division of boundaries into regions of material.

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[263] Picon, Antoine *'Digital Culture in Architecture. An Introduction for the Design Professions'*, Birkhauser, Basel (2010).

[264] As we saw earlier, Alan Turing's "chemical basis of morphogenesis" as a physical phenomenon is a kind of non unitary material computation and has spawned speculation and research on a new kind of computer.

[265] Todd, Robert Jackson, *'Analysis of Functionally graded Material Object representation Methods'*. MIT Thesis (1997).

This method, with its blending functions, points towards the direction of continuous gradient deposition as in the digital representation there is no fixed dimension element and all regions and "blending" functions are designed in advance. In the scope of my work, again here the issue that arises is that since materials come pre-mixed and are deposited separately, continuous gradient transitions are not feasible.

Mostly along the lines of the LCC Group's second method of modeling and communication, **Cast_it** receives input directly from **VSpace** through a specified file format, in order to achieve continuous, scale independent, gradient transitions.

As we saw in the first section of this thesis, in VSpace we have the simultaneous representation of Properties and Boundaries. A **Property Shape (PS)** and a **Boundary Shape (BS)** are the flip-side of the same description of a digital shape. One can work with the distribution of properties and derive boundary representations. For the case of Cast_it, properties become Material Properties. For example one could be working with transparency as the blending of an opaque and a transparent resin material, or stiffness as the blending of a rigid and an elastic rubber (rubber).

We also saw that boundaries are derived by "asking the question", for example where in space is property A equal to 0.46. In the general case study from the previous section, we have three properties A, B, C. A Boundary MCa@0.47 has property A = 0.47 while properties B and C can vary with values between Zero and One. The varying concentration values of B and C can become material input for the boundary MCa@0.47. With the given mixing technology of Cast_it, the first restriction that needs to be applied is that at any given point in space the concentrations Cb and Cc added together need to equal one. Since it is true in all cases that $0 < Cb < 1$ and $0 < Cc < 1$, we have $0 < Ca + Cb < 2$. A scaling algorithm can convert the values of Cb and Cc so that $0 < Cb + Cc < 1$. Since the two syringes push material in the same nozzle and at any given point in space, we would require the total amount of material to be deposited to always be the same. We need to ensure that the total volume of the two materials added together remain constant. For example, for a total volume of 100% if Ca = 40% then Cb = 60%. Generally speaking, any queried point of any given boundary representation derived in VSpace, can have material properties associated with it, based on its relationship to the Voxel Space. In Figure 123 we see a section of the voxel space and multiple boundary representations derived from it.

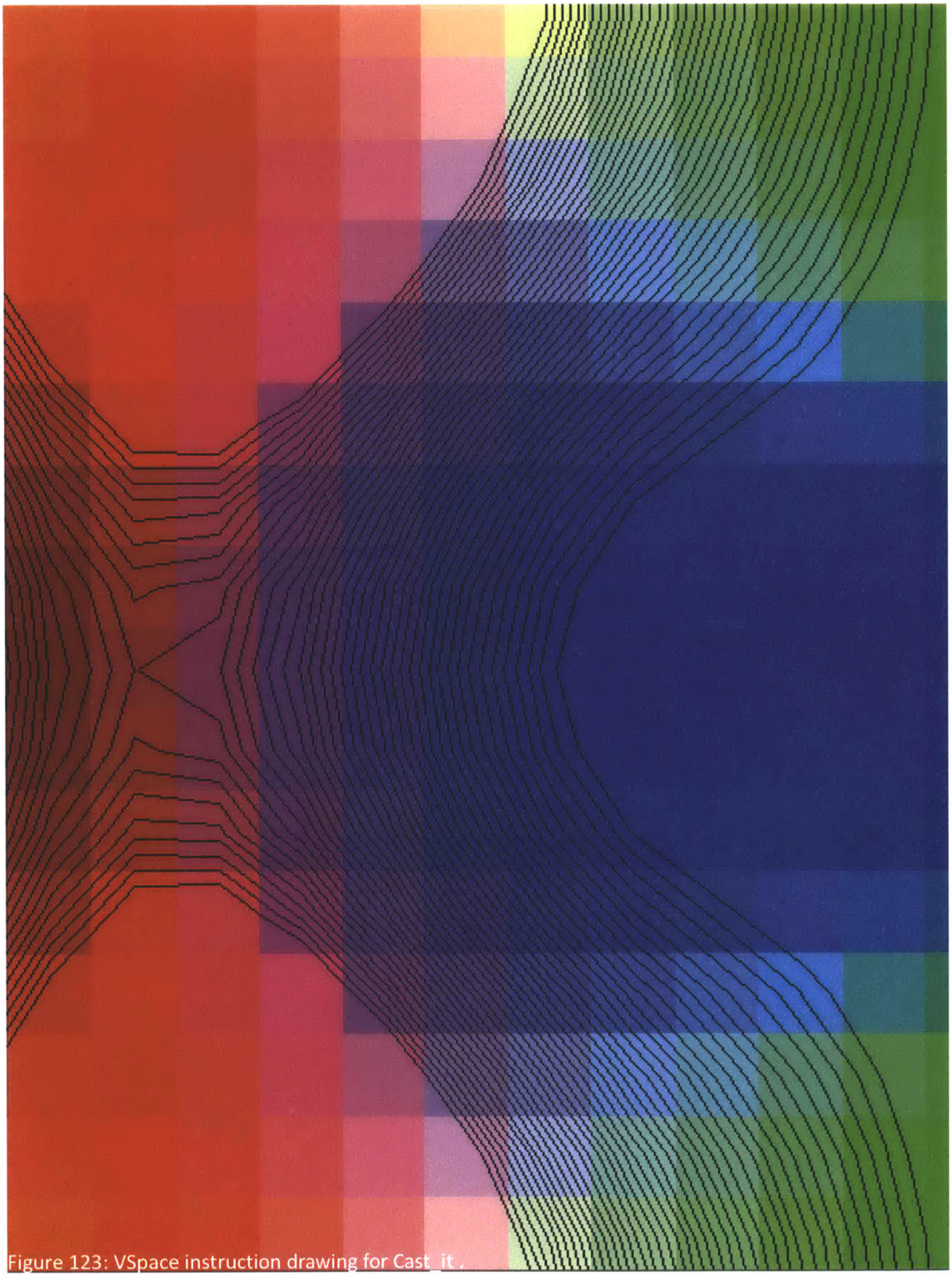

Figure 123: VSpace instruction drawing for Cast_it .

Typically in 3d printing the main mode of communication of the machine with a computer is through G-Code. An ordered set of points that describes the print-head's trajectory (Like in Stratasys or Contour Crafting) are fed into the machine sequentially. Generally, G-Code tells the print head to move from point a to point b at a fixed speed. In the case of the existing multi-material technologies a material is associated with the **line segment**, which in turn designates which print head will be depositing material along the trajectory. There are two general types of G-Code, the linear one where the movement between points a and b happens on a straight line, and a circular one where the movement between points a and b happens along an arc. In both cases the speed of the print-head is constant and can be associated with a specific line or arc segment.

As mentioned before, although existing 3D printers deposit multiple materials within the same model, they can only print one consistent material mixture at a time (per slice segment) and are therefore incapable of achieving gradient transitions between two or more materials. For example, in the case of two distinct materials (M1, M2), the existing technology deposits a fixed mixture of M1 and M2 from point A to point B. Hence, from point A (0, 0, 0) to point B (1, 2, 0), the mixture is 40% M1 and 60% M2 (Figure 124, upper). In other words, the material does not change consistency between point A and point B: it cannot achieve continuous gradient effects.

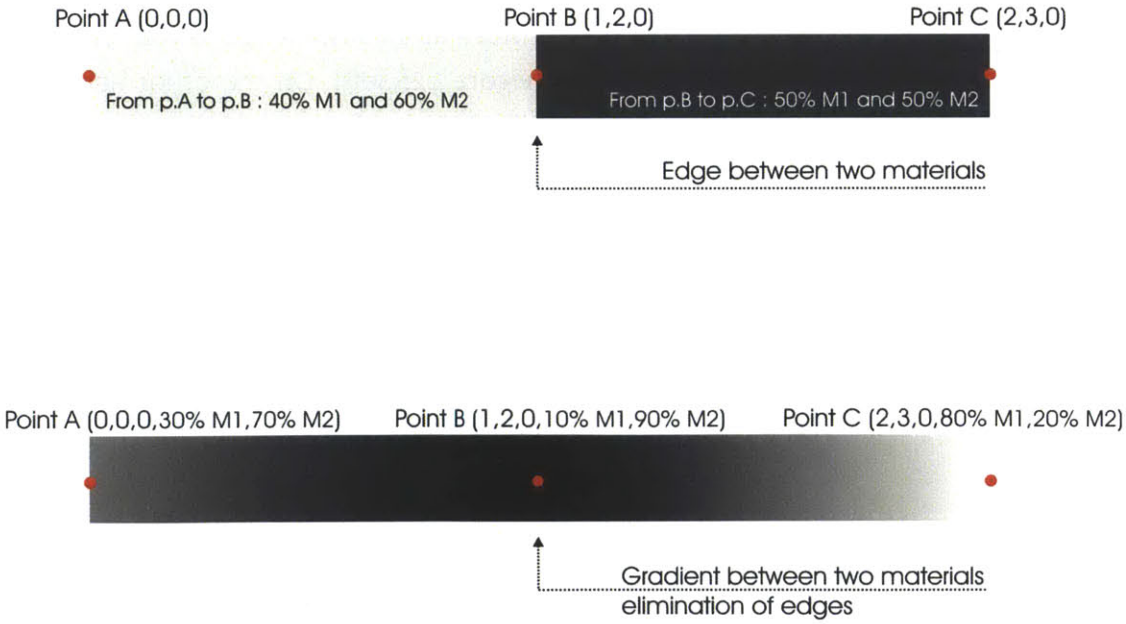

Figure 124 : comparison diagram between existing multi-material 3D printing technologies (upper) and **Cast_it** technology (lower).

With Cast_it there is a different approach. **Material is not associated with a line segment but instead is associated with a point.** Material associations to points are inherent in the VSpace software, since points are essentially derived from properties and not the other way around (Figure 124, lower). As an extension of G-Code this file format, stores along with the point coordinates, the concentrations for each material to be used. While the print head is moving from one point to the next, the flow of each material is accelerated or decelerated respectively to achieve the desired concentration at the target point. For example for two materials M1,M2 and two points A(0,0,0) and B(1,2,0) the information that is fed to the printer looks like this : Point A (0,0,0, 30% M1, 70% M2) and Point B (1,2,0, 10% M1, 90% M2). Essentially, this translates to the instruction that says: Go from point A to Point B at a constant speed in a linear or circular motion and while doing so decelerate the speed of extrusion of material M2 and accelerate the extrusion of material M2.

The acceleration and desecration of material can be precisely controlled to meet the desired volume amounts at each location. Although there might be other ways to do so, the method implemented in Cast_it is also using G-Code. In Cast-it, the flow of material from each syringe is controlled by a stepper motor. In general, the faster the motor turns, the more material comes out. If we carefully examine how G-Code translates in physical motion of the stepper motors we will see that: When in linear mode, in order for the print head to move from Point A to Point B at a constant speed each axis has to move at a constant speed too. This results in constant rotation speed for the stepper motors (Figure 125 left). On the other hand, when in circular mode, in order for the print head to move from point A to point B at a constant speed, one axis has to accelerate while the other has to decelerate at a constant rate (Figure 125 right).

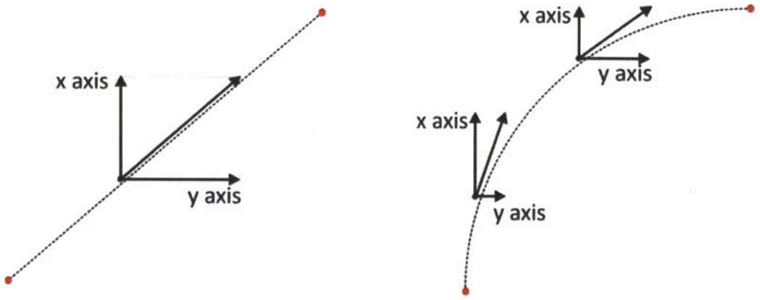

Figure 125. Linear (left) and circular (right) motion as it translates to respective motor speeds.

At the one end of an arch trajectory equal to a quarter of a circle, one motor starts with Zero speed and the other with speed equal to the desired total speed. At the other end the speeds are reversed. Any point in between has speeds proportional to the location. For any combination between material concentrations, an arc segment of the quarter circle can be specified.

G-code is sent to the machine sequentially point by point. Since the mixing nozzle has a specified length, it takes time for the mixed material to reach the mold after the mixing process starts. The specific file communication would have to have a build-in delay between material information and point coordinates. The delay is coordinated so that when the print head starts to move between two points the mixed material has already reached the tip of the nozzle. As speed of movement and total material volume are always fixed, this delay can also remain fixed throughout the fabrication process.

As we saw in the previous section, in VSpace we have what I called Diffusion Rate. It is an analysis tool that indicates how "fast" or how "slow" a gradient change happens. At its extremes, when the diffusion rates is Zero the material composition remains constant mirroring in construction essentially Greg Lynn's composite strategy. On the other hand when the diffusion rate is maximum edges appear. In construction, the operational model described above, can range between the two. In other words, in this model an **edge is a special case of a gradient**.

If there is one observation to make to engineers about all approaches to modeling and constructing gradient materials is that, the transition from the unitary logic of the computer, which causes so many problems with issues of approximation and so on (there could be plenty of those with Cast-it too), can be directly dealt with at the level of mechanical movement and chemical composition. We don't necessarily have to represent exactly the way something looks before we construct it. The complete computation of material can instead happen between a computer, a physical device with mechanical properties and materials with chemical properties. Instead of trying to make it work, we can instead work with it. This is a strategy always very familiar in architecture.

Cast_it is still an ongoing project. Actual materials have not been tested yet. So far it has allowed me to specify areas of investigation and derive principles for possible solutions. It is important here to say that this machine is not called "The Universal Building Machine 3000". This project is not claiming that buildings should be built with this machine. After all it is seeking a mode of expression. It understands a building's materiality as an environment of material properties. As a tectonic strategy, the principles of this machine allow us to detach the existence of an edge, with the functional requirement of material change. It does not claim to obliterate edges. Chunks can have edges in their interior and definitely have boundary edges. The design of an edge is still a design opportunity and will remain one for many years to come. But "Chunks" are not "components". They are designed as material environments. Edges can essentially be

embedded[266] as a design act within a continuous field of property. Edges are designed the same way the "jar" is designed around Thoreau's environment[267] (Figure 3). There is no single hierarchical system that determines the way "we put things together". Gravity or expression of structure does not come first. Cast-it with its gradient material distributions essentially sees edges in new light.

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[266] Embedding is borrowed here as a term used in Shape Grammars. See Stiny, George, *'Shape. Talking About Seeing and Doing'* MIT Press, Cambridge Mass (2006).

[267] Referring to the project "a piece of nature" in figure 3

2.11 CHUNK

CHUNK is a design project that is meant to exemplify how one would work from design to construction, using VSpace and its logics as a design tool and the principles of Cast_it as a fabrication method. It is meant to be seen as a material sample, a zooming in into the details of a software tectonic.

CHUNK is a project in building technology. As Cast-it is still an ongoing project and has not reached a level of completion that would allow it to be used for fabrication, I ended up doing what every architect with a sense of self-respect does in this case. I faked it. As a result certain restrictions where applied, which will see later on.

CHUNK is conceived as a detail of a building skin. Three functional characteristics, structure, insulation and transparency, where interrogated for their expressive potential as a material environment. The goal is to take different characteristics of a building skin and "put them together" in a way that does not privilege a singular hierarchy. In traditional tectonics these construction parts would necessarily imply distinct components put together in an assembly.

On the other hand, in the continuous composite paradigm "putting together" different functional requirements, would imply a continuous "super" material that can perform all the separate tasks homogeneously. Extending Jesse Rieser's tectonic logic in which "each element has no intrinsic and stable meaning outside of its contextual relationships"[268] CHUNK attempts to establish a non- intrinsic relationship between material property variation and a traditional construction element/characteristic. At the same time, although one material is not intended for one function, the logic of their interdependencies is expressed. Furthermore, CHUNK seeks to establish a dynamic relationship with its environment, a relationship that is found perpendicular to its surface. CHUNK is part of its environment. It forms it and it is formed by it. CHUNK uses materials to do the job of mechanical systems. Although, as a building skin it is specified to be able to support its own weight, allow light to come in and also provide insulation[269], this construction method allows for certain performance characteristics to be taken away from mechanical systems and incorporated into the material properties of the skin. CHUNK is designed as a Dynamic Insulation wall.

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[268] Reiser, Jesse and Umemoto, Nanako, *'Atlas of Novel Tectonics'*, Princeton Architectural Press, New York (2006), p.40.

[269] all curtain wall systems do that.

The CHUNK prototype was designed with two materials in mind. A white rigid polyurethane thermoset (plastic resin) and an amber translucent elastic polyurethane thermoset (rubber resin). Both materials use the same catalyst in order to set and therefore if used with Cast_it they could be mixed together at different ratios. The materials could be chosen through the CES software package that allows a designer to query thousands of materials in a database. Their physical characteristics could be compared and chosen according to functional and aesthetic requirements[270].

As a first-step structure, transparency and insulation where designed in VSpace 2D as a function of "stiffness". The bluer the voxels are the stiffer the material becomes (Figure 126). This drawing is essentially a Property Shape (PS) in which the white areas are trimmed from the property distribution. These areas will later become the points of attachment of the structural skin.

From the original drawing, again in VSpace 2D, Boundary Shapes (BS) were derived at "equidistant increments[271]" (Figure 127). The lines with color indicating their height in the direction perpendicular to the page, constitute another diagram of stiffness. Boundary Shapes and Property Shapes are the flip side of the digital Shape.

Although with Cast_it these two representations would become information for the Mold to take shape, since the issue was not resolved, using the information I constructed a surface that would later serve as a mold (Figure 128). The principle for height variation derives from the polyurethane physical properties. Both materials become more rigid the thicker they become. In addition, the rubber material becomes more elastic and more transparent the thinner it becomes[272].

Using a CNC milling machine a mold made out of plywood was carved out of a single block (Figure 129). In Figure 130 we see how an initial property distribution results in a physical object with variable geometry. For example here, the less transparent the property the deeper the mold gets (Figure 131).

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[270] This process of material selection was effectively shown in the "window-wall" plastic composite project designed in collaboration with Anas Alfaris and Lydia Kallipoliti. It was published in John Fernandez (2005)

[271] equidistant in terms of property not geometry. see "offset example in the VSpace description.

[272] these characteristics where effectively exploited my NaderTehrani and his students in a project called "a New Approach to Rubber". See Mori, Toshiko (ed.), '*Immaterial - Ultramaterial: Architecture, Design and Materials*', George Brazziller publisher and Harvard Design School. (2002), p.5

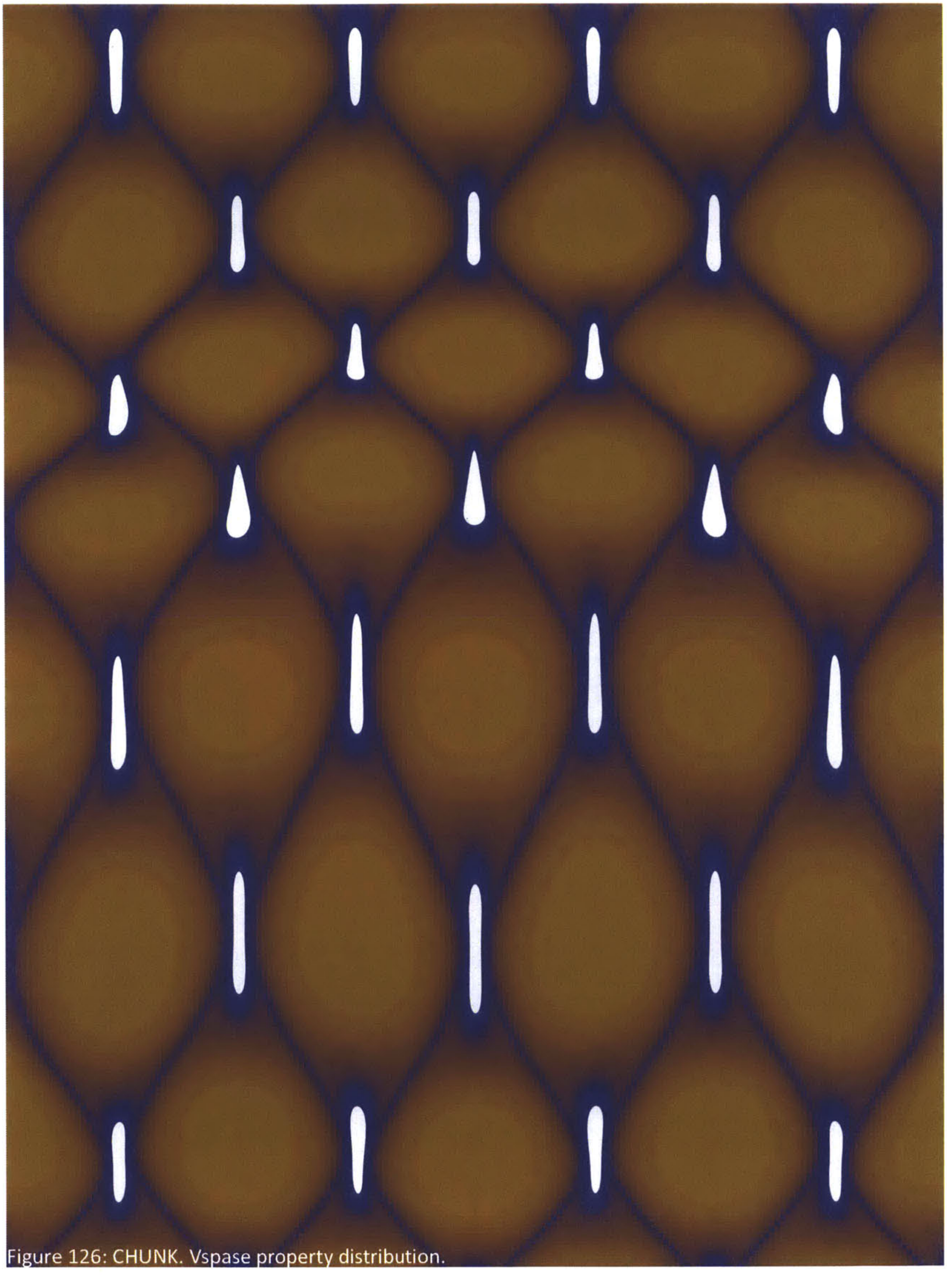

Figure 126: CHUNK. Vspase property distribution.

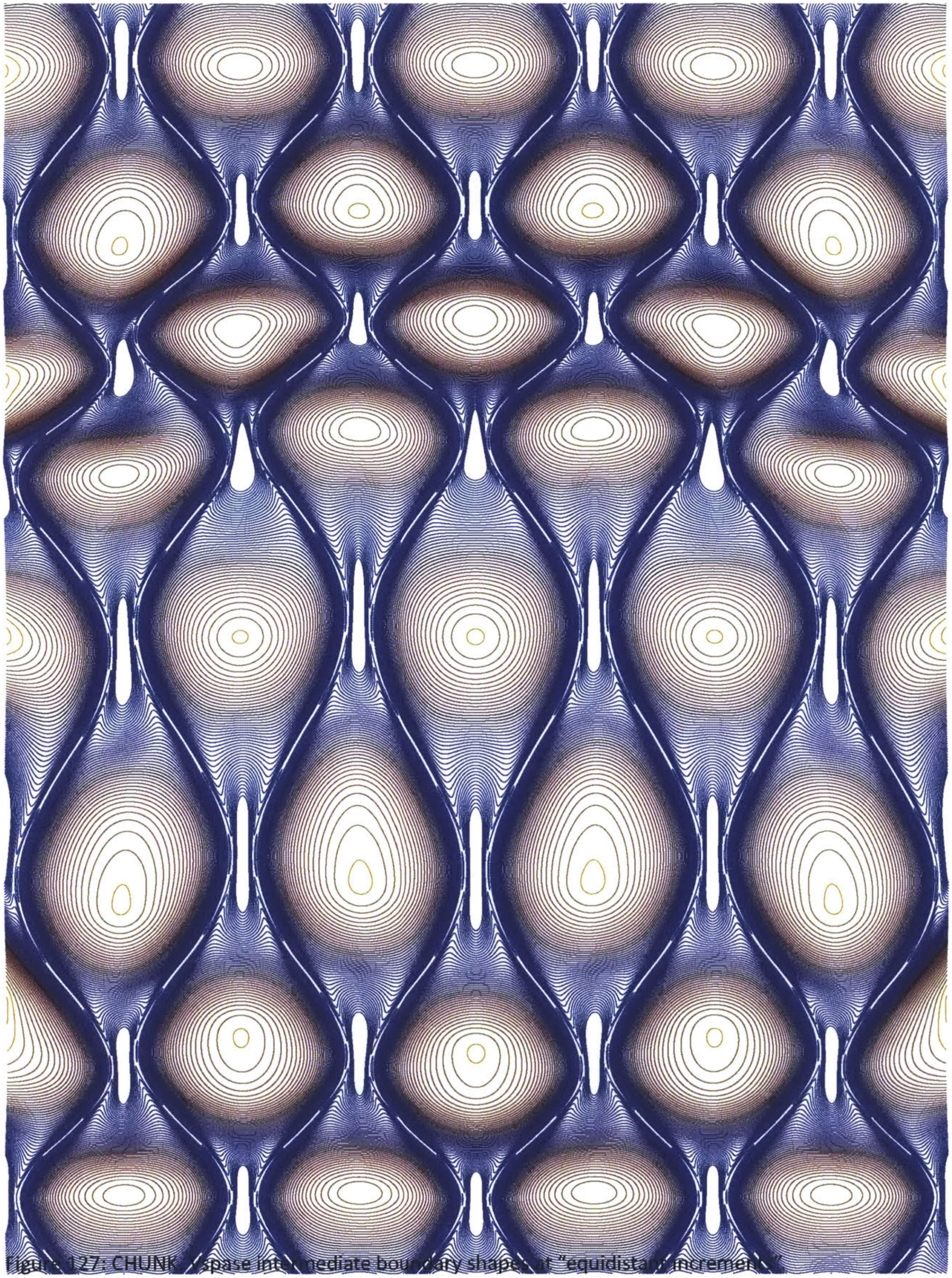

Figure 127: CHUNK. Vspase intermediate boundary shapes at "equidistant increments".

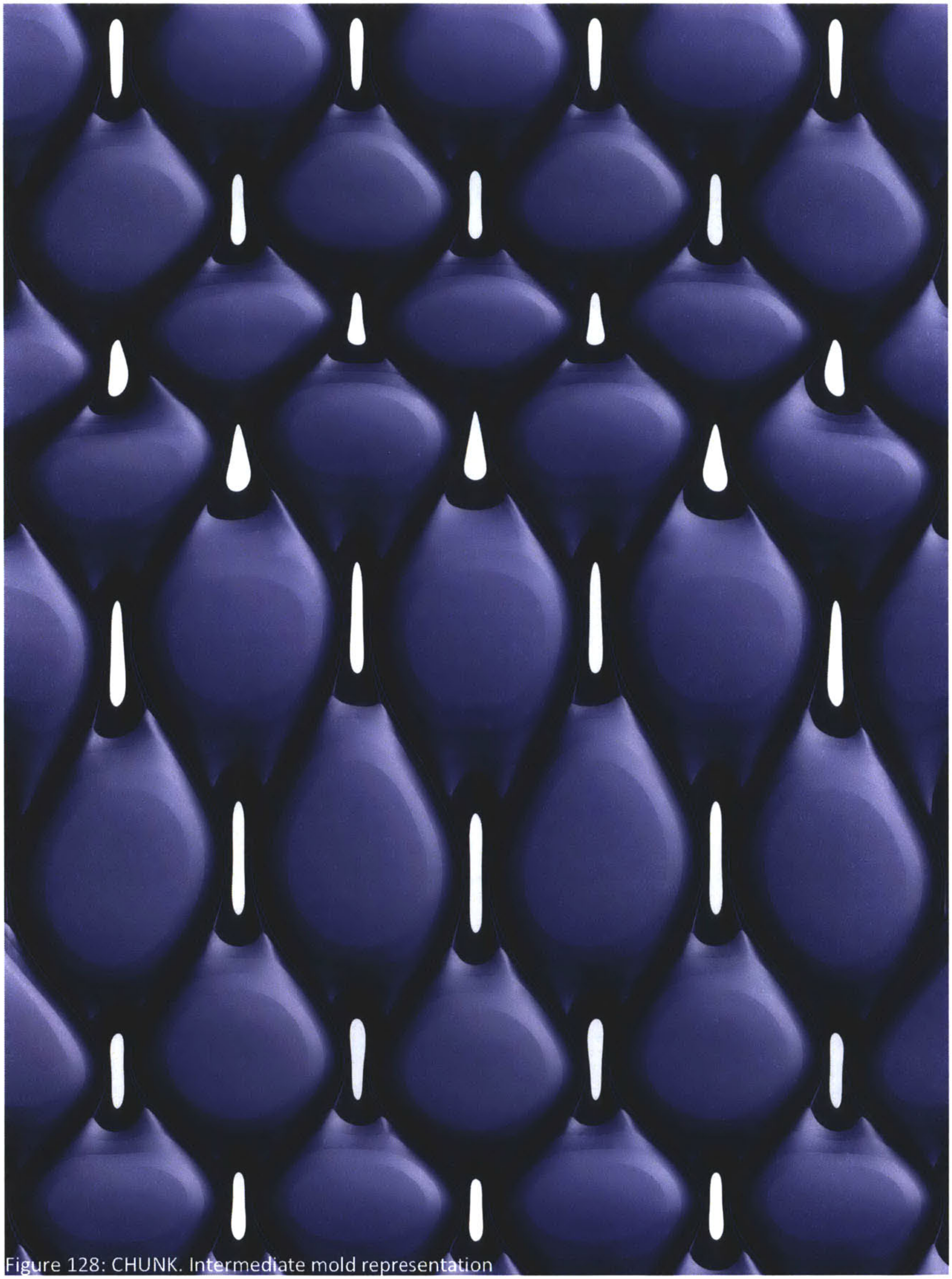

Figure 128: CHUNK. Intermediate mold representation

Figure 129: CHUNK. Plywood mold

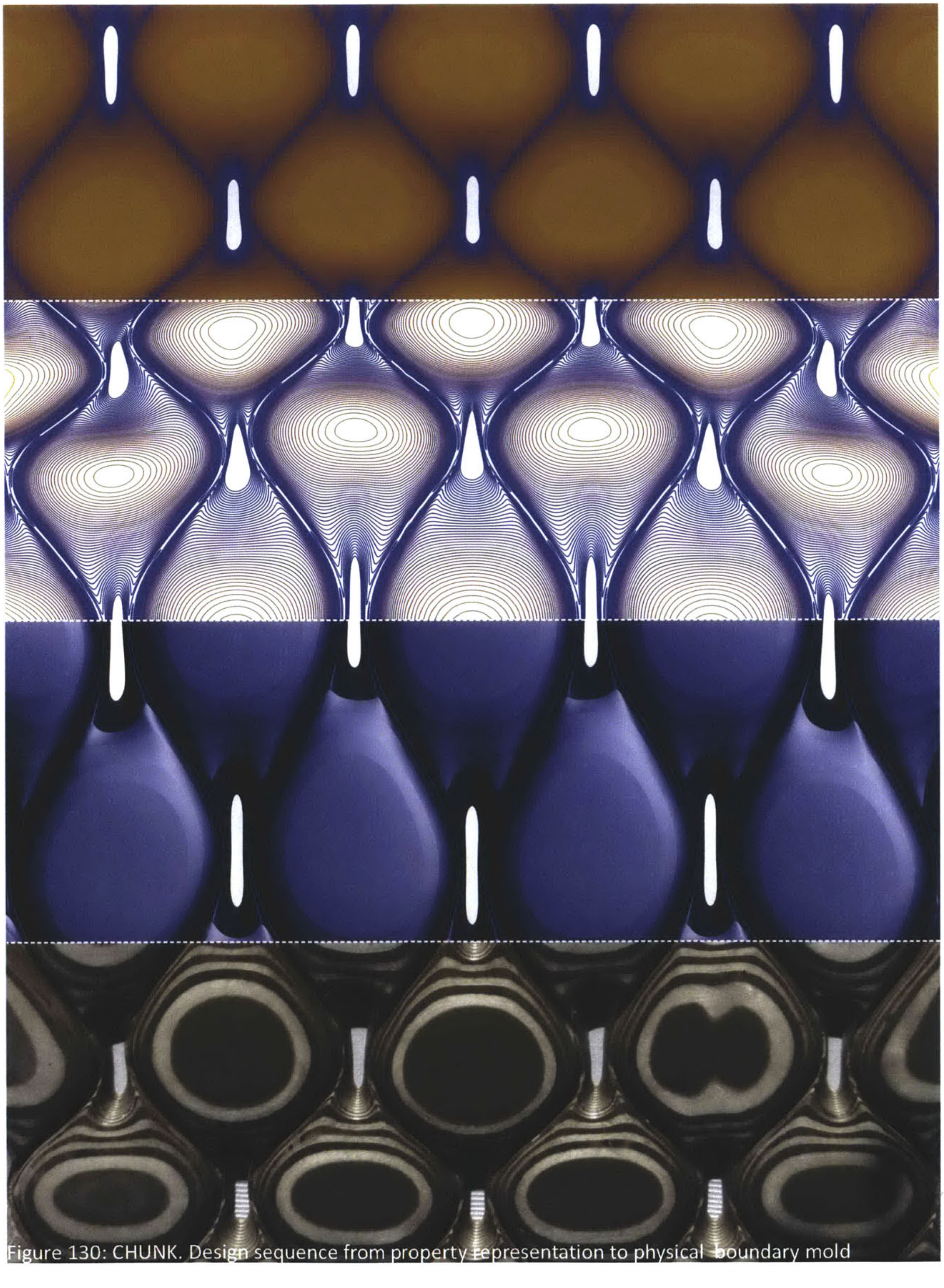

Figure 130: CHUNK. Design sequence from property representation to physical boundary mold

Figure 131: CHUNK. Geometric characteristics as a function of structure, transparency and insulation

This characteristic will in turn affect the property characteristics of the final material prototype[273]. The mold was designed to be used twice. The design is symmetrical in one axis.

The mold that is produced is then sequentially filled with the two materials. Because Cast_it is not fully functional, a manual casting process was introduced. Here materials cannot be mixed. First the white material is poured up to a certain level (Figure 132). The second material is poured on top (Figure 133). Since the two materials are chemically compatible, if the first material is still "tacky" ,while the second one is poured the two fuse together to form permanent bond. The construction procedure clearly produces an edge instead of a gradient between the two materials and the risk of de-lamination is still present. Gravity among other things made its mark.

The resultant piece (Figures 134 - 135) exhibits the following characteristics: where the white material is thick it is very rigid and while it gets thinner it becomes more flexible. Along the same lines the amber material, is more transparent and flexible in areas where it is thin and less transparent and rigid where it is thicker. Risk of de-lamination decreases in areas the two materials meet because, since the white becomes more flexible and the amber more rigid, their mechanical properties become more similar.

The two distinct pieces, mirrored to each other, are glued together in the areas of specified attachment. These are the areas where the pieces are most rigid (Figure 136). The final CHUNK is an air-tight object (Figure 137). It is imagined to be filled with a gas that has a high expansion ratio with temperature variation. In typical curtain walls, the air gap between interior and exterior skin acts as an insulator. Air is a good insulator. Since the CHUNK is air-tight and elastic, any temperature variation would result in change of its capacity to insulate. While the envelope thickness decreases, heat can be exchanged between inside and outside while when it increases the exchange rate drastically reduces. Rapid fluctuations in outside temperature would induce a parallel change in shape of the envelope, thus registering on the building skin its dynamic relationship with its environment. This **boundary** is only an instance of the **properties** of the dynamic environment that gave rise to it.

In CHUNK, gravity as a vector which runs along its surface is not more important than Heat which as a vector runs perpendicular to its surface. CHUNK, simultaneously serves the purposes of structure, surface, and insulation (Figures 138 - 140). Chunk is chemically composed. It is neither a "super" material nor a hierarchical assembly of parts. Although "parts" exist as intellections and functions they are not materialized as distinct assembled objects. Instead they are expressed as an environment of chemical material interaction.

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[273] The transition from material as property first to form second and back to physical material property was the object of investigation, in one of my early scripting studies included in my Master's Thesis. see Tsamis, Alexandros, '*Digital Graft. Towards a Non-Homogeneous Materiality*', MSc Thesis, MIT 2004.

Figure 132: CHUNK. Casting of first material

Figure 133: CHUNK. Casting of second material

Figure 134: CHUNK. resulting single piece

Figure 135: CHUNK. Resulting single piece. Detail

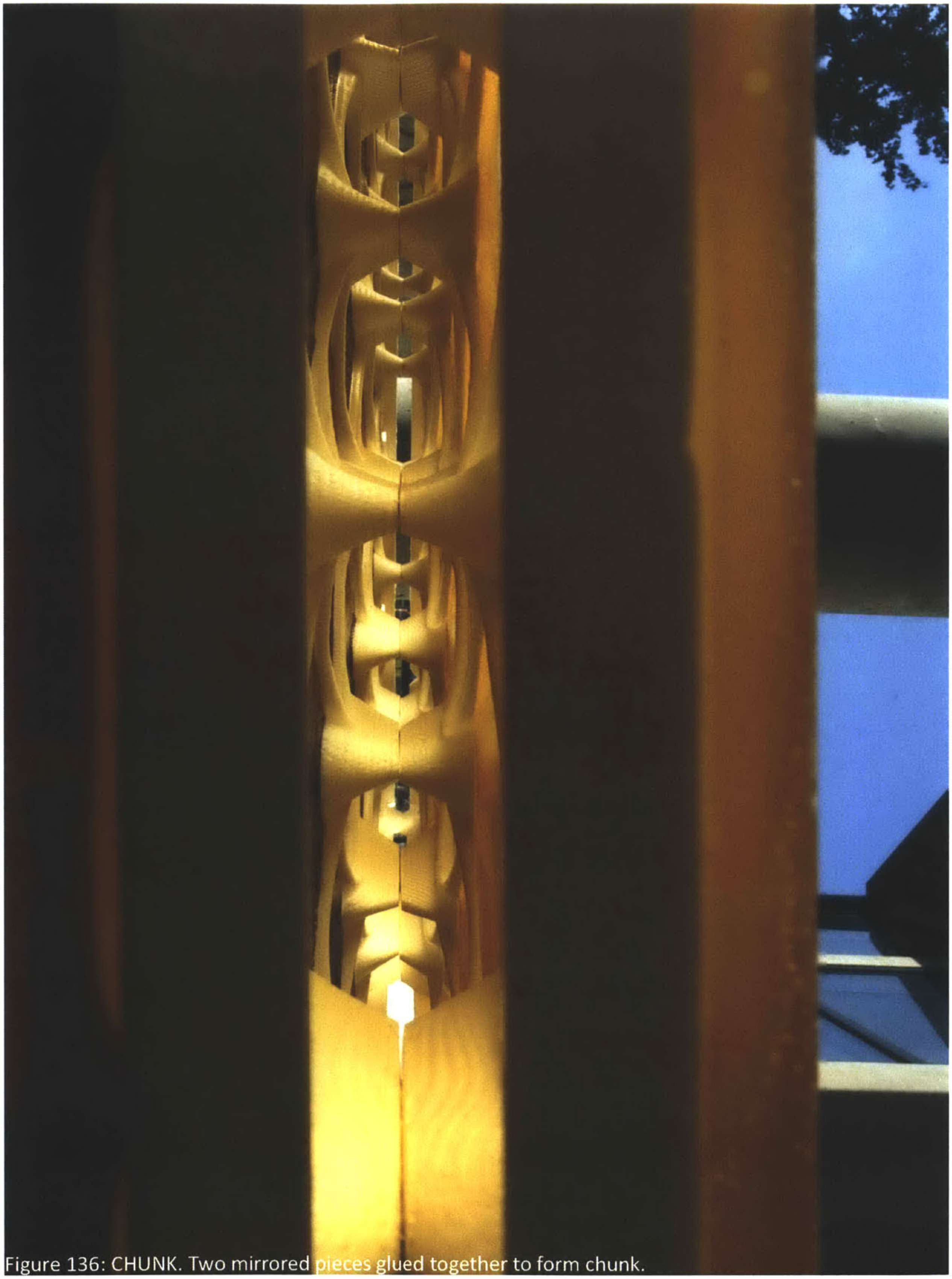

Figure 136: CHUNK. Two mirrored pieces glued together to form chunk.

Figure 137: CHUNK. inflation.

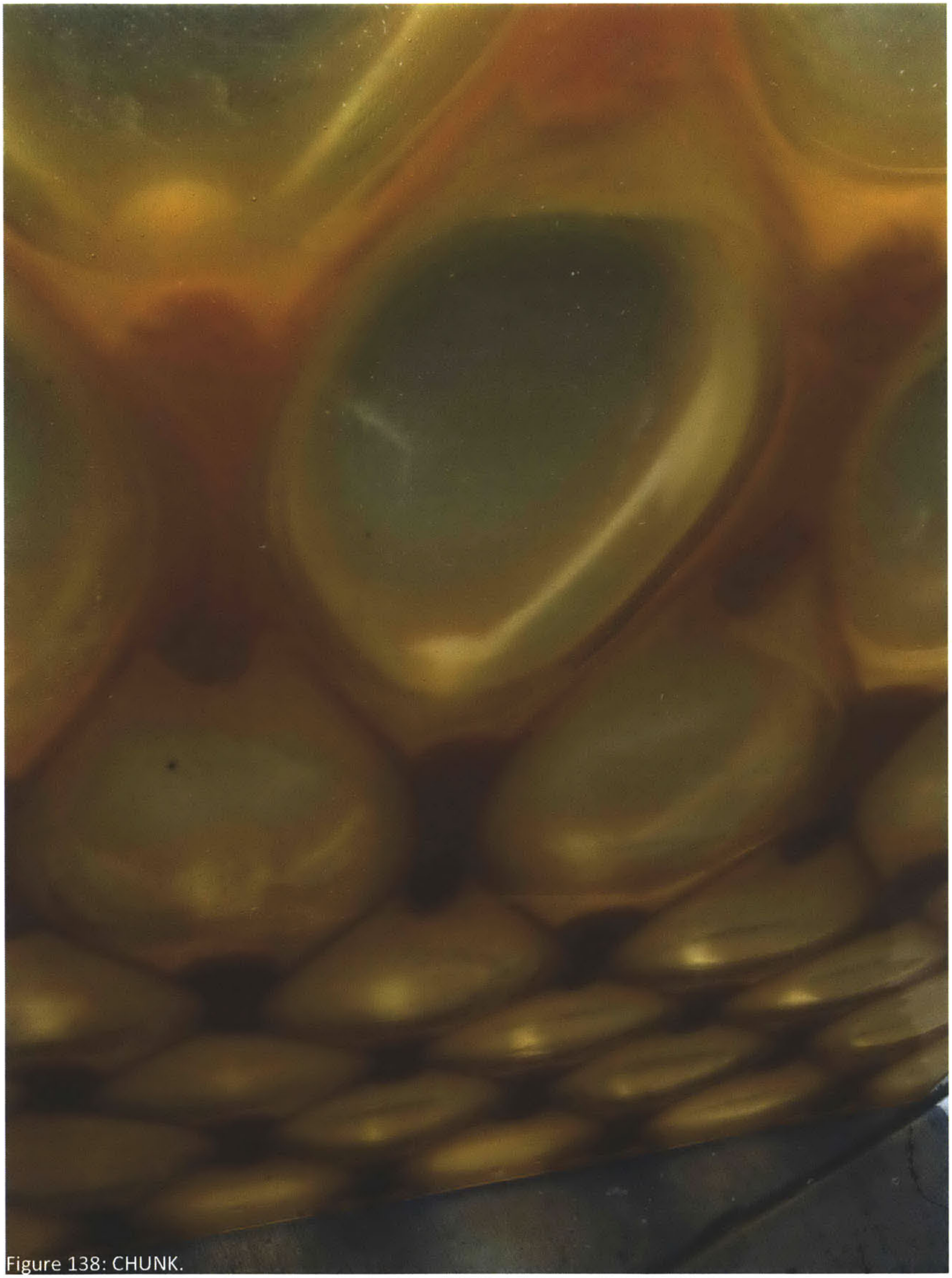

Figure 138: CHUNK.

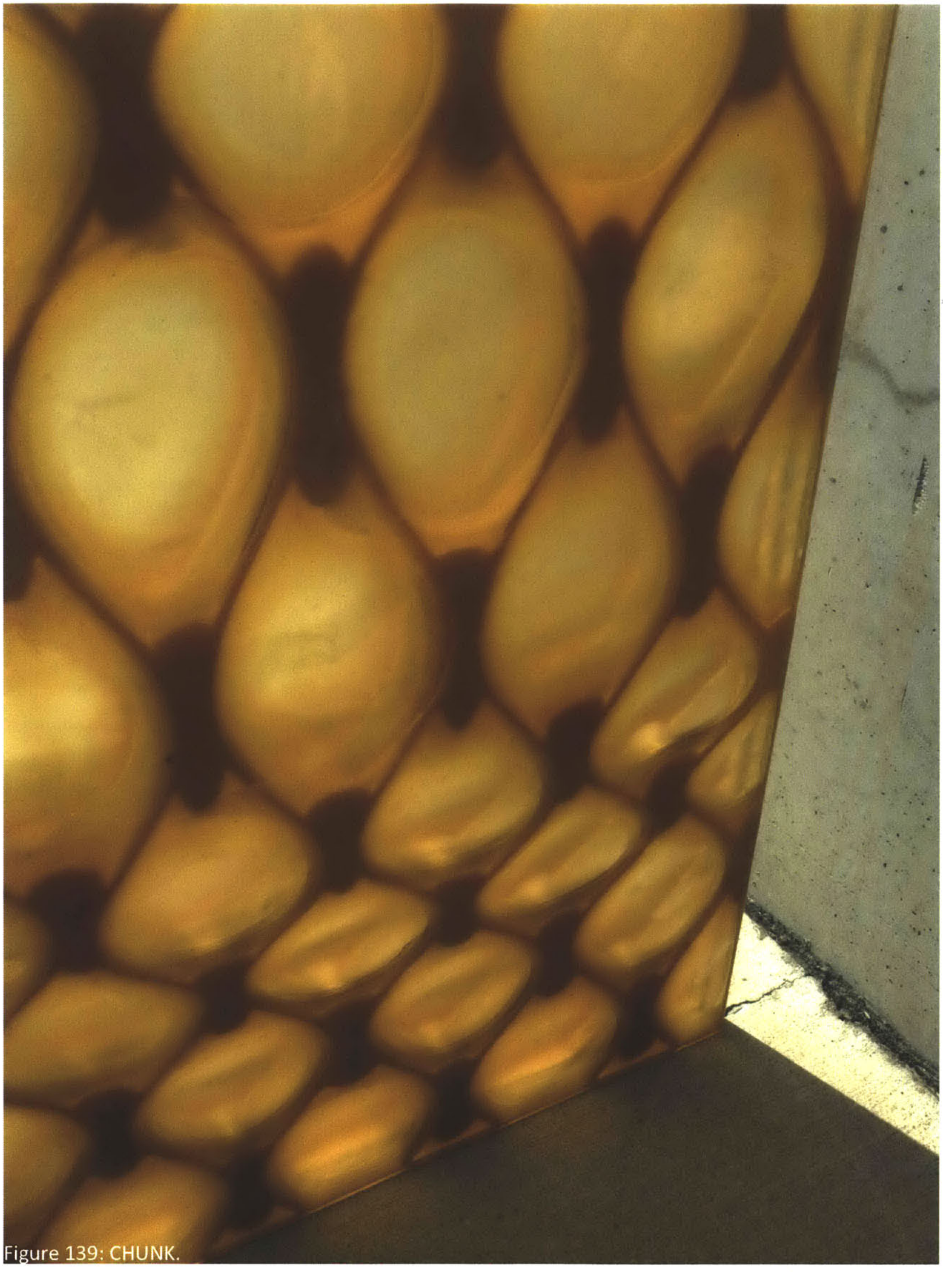

Figure 139: CHUNK.

Figure 140: CHUNK.

Conclusion

Beyond the technical pragmatics of clean, renewable, passive energy and all the performance anxieties they have induced, ecological design as a coherent cultural practice entails, as I have tried to discuss, the consideration of an artificial, composed, synthetic environment; an environment whose properties (matter, energy, and information) locally participate in a perpetual exchange. I have worked with a conjecture. An architectural environment today, has almost acquired the role of an interior. For software tectonics, any exterior envelope of a building is only an interior "partition" of an environment.

If matter energy and information coming together is to be thought of as a model for the production of space, Software Tectonics sought to make this model a MANIPULABLE entity for design practitioners. In other words, while the shift of attention from object to environment is already part of the theoretical vocabulary of the designer, in practice the technologies of design and construction still revolve around issues of object composition.

In the section entitled **Software,** I have developed *VSpace*; a computer application that reverses the hierarchy between Boundaries and Properties. Unlike current design software that privilege Boundary Representations, with *VSpace* I have derived principles for the development of CAD the work with Property Representations. We have seen how in *VSpace* properties become MANIPULABLE entities. We have seen distinct methods for selecting, instantiating and transforming properties. We have also seen how a Property Shape (PS), as a subset of a property distribution, allows a designer to query 3Dimensional space for its property characteristics. I have shown how Voxels can be used as *placeholders* of information rather than *bricks*. In *VSpace,* the process of property shape selection (PS) happens with properties in mind. Although form a computational point of view, a Voxel as a defined – represented entity inside a digital computer does not differ much if it is to be used as a *brick* or as a *placeholder*, from a designer's-practitioner's perspective it is significantly different. Departing from the additive space of combinations that Lionel March proposes, subsets of a Voxel grid are not a result of composition, based on principles of standardization. Instead, subsets are literally painted on top of a Voxel grid. Subsets are selected based on an inherent logic of property distribution. I have showed how Lionel March's additive logic can be extended to include painting and distributions as a driver for selection.

What is understood accepted in this thesis is that digital computers impose their inherent structure on modes of representation. Computer programs require fixed representations in order to compile. Perhaps one of the most important characteristics that digital computer bring to the surface of the design world is their unitary logic. VSpace does not remain unaffected by this. It was stated early on, that Voxels (in the shape of a cube) are used as space fillers to hold information in 3D space. Although other shapes of Voxels could be used, it was understood from the beginning that their characteristics would stay fixed. The reason why Lionel March's sets are countable and Property Shapes are countable is that the definition-representation of a single Voxel or a Voxel Space remains fixed. This issue constitutes an area for further investigation. Within the framework of VSpace, what would make Property Shapes uncountable and therefore more capable to absorb the full range of property distributions, would be to be able, at any step during the design process, to redefine the structure of the space filling elements. What is needed here is a logic of "embedding". The Shape Grammarian "ice-ray" space-filling strategy points to this direction.

We have also seen how Boundaries work in VSpace. Unlike Marche's approach which derives boundaries within a Voxel grid by choosing between fixed states of possible solutions (again, from a designer's perspective, here we have a logic of combinations), in VSpace Boundaries are directly derived from Properties. This is where the fixed hierarchy between Boundaries and Properties in CAD is reversed. In Marche's approach Boundaries within subsets of Voxel grids are also countable. In VSpace on the other hand, Boundaries are infinite but bound. And although this would actually pose a problem from the combinatorial perspective (when we don't have a fixed amount of states we have no way to select), in *VSpace* this issue is resolved. With painting, distributing and interpolating properties I have described a precise way that allows a designer, to derive Boundaries. I have shown how geometric topology (the kind that does not allow for the transformation of a torus to a sphere) is not an issue in *VSpace*. Nevertheless, although the hierarchy between Boundaries and Properties is reversed, it is always present and fixed. In VSpace, although we can derive Boundaries from Properties we cannot derive Properties from Boundaries. This is why I consider VSpace a complementary digital design application and not a universal computation for design. The question still remains open. Can we abandon the hierarchies altogether within the digital? I suspect that within a digital computer we cannot. I would be pleasantly surprised if we did. For sure it would make my life as a designer easier. Perhaps we need to abandon digital computers altogether.

In the second section of this thesis entitled **Tectonics** – the issue at stake was the translation of Design to Construction. If the current dilemma in the discipline is whether to abandon or redefine Tectonics I chose the latter. New technologies of design and construction pose a "threat" to the discipline only if they are uncritically adopted. Although historically inaccurate, I chose software tectonics, because I would rather not choose between technology and tradition.

What became important for this thesis was to take a stub at a resolution between the "digital tectonic" strategy and the "composite" strategy. I have argued that the first is a relic of the "ethos" of industrial production, while the second has become subservient to the logics of production that it utilizes.

Although still at a nascent stage, with Cast_it I attempted to find within 3d printing technology, a mode of expression in construction, that while it acknowledges for the need of material change, it promotes the fabrication of non-assembly.

From a technical perspective, I have shown how VSpace is set up in a way that it can be used directly as input for translating information from geometry to material. I have also shown how in order to be able to achieve gradient transitions between two distinct materials we have to let go of the unitary logics that the digital medium imposes and instead rely on the mechanical and chemical properties of materials. What I find impossible to achieve within the digital medium, I see possibly happening in the translation between digital information to physical material. For cast_it there is a lot of work ahead. Although a novel algorithm for dynamically mixing materials is already in place, actual physical materials have not been tested yet. For architectural applications this is an altogether different issue.

This issue I have partially attempted to tackle with the CHUNK project. Mass customization, as a conceptual edifice, offers a conduit for investigation into the possibilities of a new understanding of tectonics. My critique of its contemporary use is based on its adoption of a basic principle- the production of single-purpose parts- which is a relic from the period of mass production. I have suggest that we revisit Ruskin's notion of the "chunk". By using his interpretation of "changefulness" we can reconsider mass customization as, instead, the production of a single-variable purpose chunk that varies in its material composition.

The fabrication of non-assembly, reconsiders architectural tectonics, by attempting to derive an architectural expression of part to while adopting the composite strategy. The Ruskinian "chunk", which would be the outcome of this type of fabrication, would replace typical construction methods. Structure, infill, window, wall, insulation, ornament, etc. would be dealt with within a piece's variable material properties. We can always substitute the notion of structure and surface with the equivalent structural and non-structural body, the notion of the window and the wall with a relationship between transparent and non-transparent areas, changing the point of view from parts to properties. This endeavor would entail a new more open dialog between architects, computer and material scientists, robotic and structural engineers, hearkening back to Viollet-le-Duc and his desire to see engineering inform architecture and vice versa. A dialog that is very present in the discipline today.

Paraphrasing LeCorbusier, I would argue that within ecological concerns, I am arguing that today, the prime consequences of the information evolution in "building"...[are] the replacing of industrial materials by non-homogeneous ones, of fixed consistency and purpose by heterogeneous and artificial ones (tried and proved in the laboratory) and by products of variable properties.

The "ecological project" allows us to rethink basic architectural disciplinary assumptions and derive both an aesthetic and architectural ideology of first encoding and then manifesting the full spectrum of environmental tectonics. It is the germinal capacity of an environment to transform that may shed new light on the ecological discourse. Tweaking core disciplinary assumptions – such as the part-to-whole relationship to property of whole, and the notion of mechanical assembly to fabrication of non-assembly with anisotropic composite materials – is essential in order to surface a nuanced definition of ecological design. Advanced computation and fabrication methodologies allow us to understand and **practice** both the notion of environment and that of assembly as a kind of topology. This is what makes this body of work a thesis in design. It doesn't understand technologies as universal and it does not pretend to solve problems. It only seeks modes of expression.

Bibliography

Aspray, William, *'John Von Neumann and the Origins of Modern Computing'*, MIT Press, Cambridge Mass (1990).

Babbage, Charles, *'The Exposition of 1851 or Views of the Industry, the Science and the Government of England'*, John Murray, Albemarle Street, London (1851).

Bachelard, Gaston, *'The Poetics of Space',* Beacon Press, New York (1964).

Banham, Reyner, 'The Triumph of Software', New Society, Harrison Raison, London (October 31, Volume 12, No. 318, 1968).

Banham, Reyner *'The Architecture of the Well-tempered Environment'*, The University of Chicago Press, Chicago (1969).

Banham, Reynar *'Theory and Design in the First Machine Age'*, MIT Press, Cambridge Mass (1980).

Bamberger, Jeanne & Dissea, Andrea *'Music as Embodied Mathematics: A Study of a Mutually Informing Affinity'*, International Journal of Computers for Mathematical Learning 8, Kluwer Academic Publishers, Netherlands (2003).

Battle & McCarthy, 'Multi-Source Synthesis. *Atomic Architecture'*, in Architectural Design (AD), Vol.65, No.1/2, (London: Academy Group Ltd, 1995).

Baumgart, Bruce G., *'Geometric Modeling for Computer Vision'*, PhD Thesis, Stanford University, (1974).

Beukers, Adriaan & Hinte, Ed Van, 'Lightweight Structures', Architectural Design (AD), Vol.72 No.1, John Wiley & Sons Limited, London (2002).

Beukers, Adriaan & Hinte, Ed Van, *'Light-ness'*, 010 publishers, Rotterdam, (2005).

Braid Ian C., *Boundary Modeling,* in *Fundamental Developments of Computer-Aided Geometric Modeling,* edited by Les Piegl, Academic Press, London (1993).

Bressani, Martin, 'Notes on Violet-Le-*Duc's Philosophy of History: Dialectics and Technology',* The Journal of the Society of Architectural Historians, vol. 48, no.4. Chicago (December 1989).

Broadbent, Geoffrey, *'Emerging Concepts in Urban Space Design'*, VanNostrand Reinhold, London (1990).

Brooks R.A. and Dichiro G., *'Principles of Computer Assisted Tomography (CAT) in Radiographic and Radioisotope Imaging'* in Physics of Medical Biology (1976).

Burry, Mark, *'Beyond Animation'*, in Architectural Design (AD), Vol. 71, No.2, John Wiley & Sons Limited, London (April 2001).

Cache, Bernard, *'Earth Moves: the Furnishing of Territories',* MIT Press, Cambridge Mass (2006).

Casti, John L. 'Alternate Realities: Mathematical Models of Nature and Man', Wiley, New York (1989).

Colquhoun, Alan, *'Essays in Architectural Criticism',* MIT Press, Cambridge Mass (1985).

Coveney, Peter V., *'Self-Organization and Complexity: A New Age for Theory, Computation and Experiment',* Philosophical Transactions: Mathematical, Physical and Engineering Sciences, Vol. 361, No.1807, Self-Organization: The Quest for the Origin and Evolution of Structure. (Jun. 15, 2003).

Davidson, Mark 'Social sustainability: a potential for politics?', in Local Environment, 14: 7, (2009).

Derrida, Jacques, *'The Problem of Genesis in Husserl's Philosophy',* University of Chicago Press, Chicago (2003).

Di Christina, Giuseppa, *'The Topological Tendency in Architecture'* in Architectural Design*: Architecture and Science*, (ed) Giuseppa Di Christina, Willey Academy, Great Britain, (2001).

Dyson, Ann, 'Recombinant Assemblies', in Architectural Design (AD), Vol. 72. No 5, John Wiley & Sons Limited, London (2002), p.62

Evans, John, *'The Lamp of Beauty: Writing on Arts by John Ruskin',* Oxford, (1959).

Frampton, Kenneth, *'Botticher, Semper, and the Tectonic: Core Form and Art Form',* in What is Architecture, (ed.) Andrew Ballantyne, Routledge, London (2002).

Giedion, Sigfried, *'Space Time and Architecture: The growth of a new tradition',* Harvard University Press, Cambridge Mass (1967).

Goodwin, Brian C., *'Structuralist Research Program in Developmental Biology',* in Mark Rappolt (ed), Greg Lynn Form, Rizzoli, New York (2008).

Hight, Cristopher, 'Putting out the Fire with Gasoline: Parables of Entropy and Homeostasis from the Second *Machnine Age to the Information Age',* in Softspace, From a Representation of Form to a Simulation of Space (ed.) Sean Lally & Jessica Young, Routledge, London (2007).

Hobhouse, Hermione, *'The Crystal Palace and the Great Exhibition: Art Science and the Productive Industry. A History of the Royal Commission for the Exhibition of 1851',* Continuum, New York (2002).

Husserl, Edmund, *'Origin of Geometry: an Introduction',* University of Nebraska Press, (1989).

Ilachinski, Andrew, *'Cellular Automata: a Discrete Universe',* World Scientific Publishing Company, Singapore (2001).

Ingraham, Catherine, 'Why all these birds? *Birds in the sky, Birds in the Hand'*, in Antoine Picon and Alessandra Ponte Architecture and the Sciences: Exchanging Metaphors, Princeton Architectural Press, New York (2003).

Ingraham, Catherine, *'Architecture, Animal, Human: The Asymmetrical Condition'*, Routledge, New York (2006).
Jarzombek, Mark. *'Molecules, Money, and Design'* in Thresholds 18. Design and Money, editors: Andrew Miller, Garyfallia Katsavounidou, James P O;Brien. MIT Journal, Fall 1999.

Kallipoliti, Lydia 'EcoRedux: Environmental Architectures from Object to System to Cloud' in Praxis: Journal of Writing and Building, No.13 (Eco-Logics), (2012).

Khoshnevis, Behrokh 'Houses of the Future: Construction by Contour Crafting. Building Houses for Everyone', Viterbi School of Engineering, Information Sciences Institute, University of Southern California, 2004.

Kipnis, Jeffrey, *'Performance anxiety?'* in 2G no.16 (4) 2000.

Kipnis, Jeffrey, *A Family Affair*, in Mark Rappolt (ed) Greg Lynn Form, Rizzoli, New York (2008).

Knight, Terry W., *'Color grammars: The representation of Form and Color in Designs',* in Leonardo, Volume 26. No. 2 (1993).

Knight, Terry W., *'Color grammars: designing with lines and colors'*, Environment and Planning B, 16 (1989).

Kwinter, Sanford, *'Architectures of Time: Toward a Theory of the Event in Modernist Culture'*, MIT Press, Cambridge Mass (2002).

Lally, Sean, *'Eat Me Drink Me',* in Architectural Design (AD): Territory Architecture Beyond Environment, (ed.) David Gissen, John Wiley & Sons Limited, London (May/June 2010).

Langton, Christopher G., *'Artificial Life'*, MIT Press, Cambridge Mass (2000).

Lavin, Sylvia, *'Plasticity at Work'*, Mood River, Ohio: Wexner Centre for the Arts, (2002).

Laugier, Marc-Antoine, *'Essays on Architecture'*, Hennessey & Ingalls, Los Angeles (1977).

LeCorbusier, *Towards a New Architecture*, Dover Publications, New York (1986), Table of Contents.

Licht, Walter, *'The Rational Factory: Architecture, Technology, and Work in America's Age of Mass Production'*, in Journal of Social History, (September 1999).

Liu, Hongye 'Feature-Based Design of solids with local Composition Control', MIT Thesis, (2004).

Lorensen, William E. and Cline, Harvey E., *'Marching Cubes: A high resolution 3D surface construction algorithm',* in Computer Graphics', Vol. 21, Nr. 4, (July 1987).

Manetti, Antonio di Tuccio; Saalman, Howard, 'The Life or Brunelleschi', University Park (1970).

March, Lionel and Steadman, Philip, *'The geometry of Environment'*, RIBA Publications Limited, London (1971).

March, Lionel, *'The Architecture of Form',* Cambridge University Press, (1976).

Martino, Jacquelyn A., *'The Immediacy of the Artist's Mark in Shape Computation: From Visualization to Representation'*, PhD Dissertation, MIT (2006).

McLuhan, Marshall, *'Understanding Media: The Extensions of Man'*, Routledge (2006).

Meredith, Michael (Author, Editor), Aranda-lasch (Editor), Mutsuro Sasaki (Editor), *'From Control to Design: Parametric/Algorithmic Architecture',* Actar (2008).

Mitchell, William J., 'The Logic of Architecture', MIT Press, Cambridge Mass (1990).

Mori, Toshiko (ed.), *'Immaterial - Ultramaterial: Architecture, Design and Materials'*, George Brazziller publisher and Harvard Design School. (2002).

Payne, Jason, *'Heather Roberge, Matter and Sense'* in Softspace, From a Representation of Form to a Simulation of Space (ed.) Sean Lally & Jessica Young, Routledge, London (2007).

Pearce, Robert P., *'Meteorology at the Millennium'*, Academic Press, San Diego (2002).

Picon, Antoine *'Architecture and the Virtual: Towards a New Materiality'*, Praxis: Journal of Writing and Building, issue 6: New Technologies, New Architectures.

Picon, Antoine *'Digital Culture in Architecture. An Introduction for the Design Professions'*, Birkhauser, Basel (2010).

Pine, Joseph B. II, *'Mass Customization: The New Frontier in Business Competition'*, Harvard Business School Press, (1999).

Rabinow, Paul *'Artificiality and Enlightenment: From Sociobiology to Bio-Sociality'* in Incorporations (ed.) Jonathan Crary & Sanford Kwinter, *(Chapter 6),* Zone Books New York, MIT Press, 1992).

Reiser, Jesse and Umemoto, Nanako, *'Atlas of Novel Tectonics',* Princeton Architectural Press, New York (2006).

Rocker, Ingeborg M, *'When Code Matters'*, in Architectural Design (AD), vol. 76, issue 4, John Wiley & Sons Limited, London (10 Aug 2006).

Ruskin, John, *'The Stones of Venice'*, Smith, Elder and Co., London (1853).

Ruskin, John, *The Storm Clouds of the 19th Century*, J.W. Lovell co., New York (1885).

Ruskin, John, *'Prosperina, Ariadne Florentina and the Opening of the Crystal Palace'*, Kessinger Publishing, Whitefish (2005).

Scanlon, Jessie, 'Seamless', Wired Magazine: Break the Rules, (2004).

Sedgwick, Susan, 'The Young Emigrants, Madelaine Tube, the Boy and the Book, and Crystal Palace', Lightning Source Incorporated, (Jul 31, 2009).

Semper, Gottfried '*The Four Elements of Architecture and Other Writings*, Cambridge University Press (1989).

Sienko, Tanya and Adamtzky, Andrew and Rambidi, Nicholas G. and Conrad, Michael (ed.), *'Molecular Computing'*, MIT Press, Cambridge Mass (2003).

Stiny, George, *'Ice ray : a note on the generation of Chinese lattice designs',* Environment and Planning B, (1977), volume 4.

Stiny, George, '*Weights*', Environment and Planning B: Planning and Design 19 (1992).

Stiny, George, *'Shape. Talking About Seeing and Doing'* MIT Press, Cambridge Mass (2006).

Stiny, George and Gips James, *'Shape Grammars and the Generative Specification of Painting and Sculpture',* in Information Processing 71, (ed.) C.V. Friedman, Amsterdam: North Holand, (1972).

Testa, Peter, *'Carbon Tower'*, in M. McQuaid, *'Extreme Textiles: Designing for High Performance'*, Princeton Architectural Press, (2005).

Thomas, David, 'Beyond the Image Machine: a History of Visual Technologies' Continuum Books, New York (2004).

Thompson, D'Arcy, *'On Growth and Form'*, Cambridge University Press, Cambridge (1992).

Tsamis, Alexandros, *'Digital Graft. Towards a Non-Homogeneous Materiality'*, MSc Thesis, MIT 2004.

Tsamis, Alexandros, *'Go Brown. Inner-disciplinary Conjectures'* in Architectural Design (AD): Ecoredux. Design Remedies for an Ailing Planet, (Ed) Kallipoliti Lydia, John Wiley and Sons, London (June 2010).

Turing, Alan, *'The Chemical Basis of Morphogenesis'*, Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences, Vol. 237, No. 641. (August 14, 1952).

Viollet Le-Duc, Eugène-Emmanuel, *Lectures on Architecture, tr. by B. Bucknall, (1881).*

W. Cho E. M. Sachs N. M. Patrikalakis M. J. Cima T. R. Jackson, H. Liu J. Serdy C. C. Stratton H. Wu R. Resnick, *Methods for Distributed Design and Fabrication of Parts with Local Composition Control, in* Manufacturing Grantees Conference, Vancouver, BC, Canada, (January 2000).

Weathers, Sean Lally, 'Potential Energies', in Softspace, From a Representation of Form to a Simulation of Space (ed.) Sean Lally & Jessica Young, Routledge, London (2007).

Wolfram, Stephen, *'A New Kind of Science'*, Wolfram Media Inc., Champaign IL (2002).

Wright, Lawrence, *'Perspective in Perspective'*, Routledge & Kegan Paul, London (1983).

Online References

http://usa.autodesk.com/ecotect-analysis Ecotect brochure.

http://www.3d-coat.com

http://www.Voxelogic.com

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.15.5208&rep=rep1&type=pdf

http://en.wikipedia.org/wiki/Voxel on March 24, 2011

http://mathworld.wolfram.com/Space-FillingPolyhedron.html

http://www.kinecthacks.com/kinect-3d-finger-painting

http://www.youtube.com/watch?v=C12UHwONh2M

http://www.fhwa.dot.gov/bridge/frp/frp197.htm Benjamin Tang, *"Fiber Reinforced Polymer Composites. Applications in the United States"*

http://www.centennialofflight.gov/essay/Evolution_of_Technology/composites/Tech40.htm Dwayne A. Day, "Composites and Advanced Materials"

http://www.d-shape.com Dini, Enrico 'D-shape'

http://www.stratasys.com

http://www.objet.com/Portals/0/docs2/PR32_Objet_107_Materials_20June2012-F.pdf

http://www.mit.edu/~tdp/composite.html 3DPrinting Laboratory, MIT.

http://www.mit.edu/~tdp/info-flow/publications/DMI-0100194.pdf Cho, W., Sachs, E. M., Patrikalakis, N. M., Cima, M. J., Liu, H., Serdy, J., Stratton, C. C., Local *Composition Control in Solid Freeform Fabrication,* Massachusetts Institute of Technology.

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