

Pixels in the Material World: Making Marching Cubes

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Abstract

In 1987, researchers at General Electric pioneered a method for generating computer graphics from medical scan data that featured an underlying language of faceted cubes. Widely adopted, *Marching Cubes: A High Resolution 3D Surface Construction Algorithm* has become a seminal visual language for virtual environments. We wanted to make this computational procedure tangible, into something people could build with. We translated the algorithm into 3D printed construction units that permit users to act out its logic. We also created a user's guide: input any object—a 3D scan or model—and a custom computer script outputs assembly instructions. Every one of these *Marching Cubes* interactive performances and installations are unique; the units can make anything. Assemblies are created in collaboration with the audience: together, we perform the computer's process. Sometimes, we simply play: with humans doing the work, the procedure's strict logic is optional. By enacting a ubiquitous algorithm in the real world, this project generates dialogue about how information technologies create the building blocks of contemporary culture.

Keywords

Art, Design, Architecture, CAD/CAM, Algorithms, Graphics, 3D Printing, Parametric Modeling, Modularity.

Introduction

Marching Cubes (MC) is an algorithm that constructs a continuous three-dimensional surface from a collection of points in space. First presented in 1986 and later refined for the purpose of generating high-resolution renderings of medical scan data, MC and its descendants have become some of the most widely adopted graphics algorithms ever created. [1,2,3] Vestiges of this algorithm's geometric signature remain present in many screen-based representations of three-dimensional information: it is part of the visual language that defines our virtual environments.

Marching Cubes are interactive performances and installation that permit participants to directly experience the MC algorithm and the visual language it represents. These projects are the culmination of ten years of research, experimentation, and built work focused on deploying this language in the architectural and sculptural realms, by interpreting the algorithm as a tool for provocative form-making at a variety of scales.

Precedent Projects

Marching Cubes extends some earlier creative work which began with an examination of Frank Lloyd Wright's Usonian Automatic projects, a significant historical example of unit-based construction. We then explored how the MC algorithm might be interpreted to create a more contemporary set of architectural units. Finally, we created the first physical instantiation of the MC algorithm, designed in close conversation with Wright's precedent. This research trajectory has been described previously but, given its enduring influence, is summarized below in order to provide context for the *Marching Cubes* projects that follow. [4]

Automatic

One of Frank Lloyd Wright late projects was his vision for Usonia, a new American landscape characterized by a diffuse agrarian urbanism. Usonian refers to a series of modest family homes designed for this new landscape. Early Usonian homes used wood construction techniques, but faced with rising labor costs in the 1950s, Wright turned to concrete. The suffix Automatic was added because the revised design created the potential for economy via end-user self-assembly, facilitated by a strict grid that determined the dimensions and relative positions of the constituent concrete units. Deconstruction, reconstruction, and replication of the Usonian Automatic system (Figure 1) provided a point of departure for our subsequent research. [5]

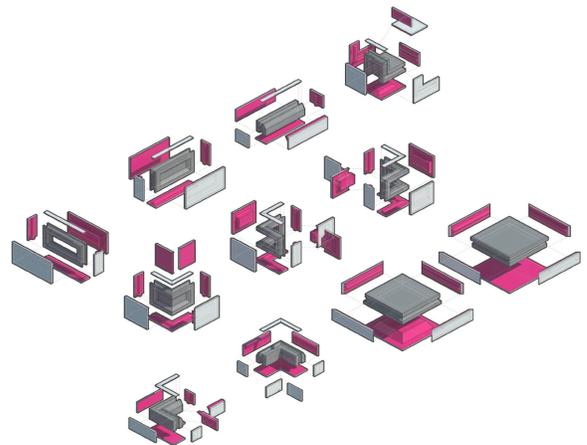


Figure 1: Frank Lloyd Wright's eleven Usonian Automatic units

Marching Cubes

The computational procedure originally published as *Marching Cubes: A High Resolution 3D Surface Construction Algorithm* provides a first order refinement of a voxel grid approximation of a volume. A voxel grid is a cubic subdivision of space, and can be understood as the three-dimensional analogue of a pixel grid. The pixel grid also provides a means to illustrate the computational logic of MC, by way of its two-dimensional cousin *Marching Squares*.

Given a plane containing a closed region of any size and shape, *Marching Squares* divides the plane into pixels, and further divides each pixel into quadrants. The procedure evaluates each pixel, identifying intersection with any portion of the closed region, and outputs an approximation of this portion (Figure 2). The specific approximation is determined by which quadrants the portion intersects. There are six possible intersection approximations, which can be reassembled to simulate the entire closed region (Figure 3). The resolution of the simulation is dependent on the size of the pixels: smaller pixels provide higher resolution.



Figure 2: One *Marching Squares* intersection approximation

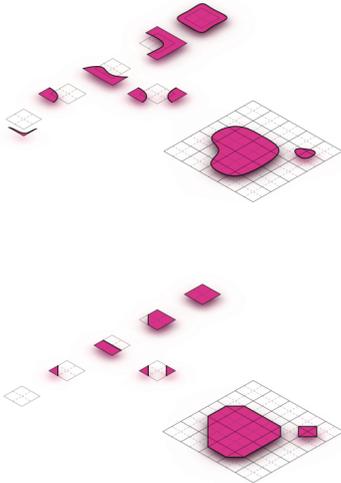


Figure 3: All *Marching Squares* intersection approximations

MC applies this same logic in three dimensions. Given a volume containing a closed surface of any size and shape, MC divides the volume into voxels, and further divides each voxel into octants. The algorithm evaluates each voxel, identifying intersection with any portion of the closed surface, and outputs an approximation of this portion (Figure 4). There are fifteen possible intersection approximations (Figure 5). As with *Marching Squares*, the specific intersection approximations are determined by which octants the

portion intersects, these approximations can be reassembled to simulate the entire closed surface, and the resolution of this simulation is inversely proportional to the voxel size.

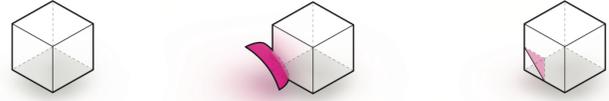


Figure 4: One *Marching Cubes* (MC) intersection approximation

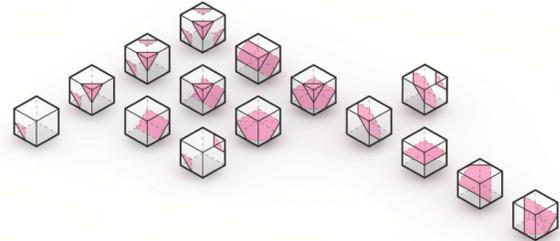


Figure 5: All MC intersection approximations

Automatic/Revisited

In spite of their disparate origins, we observed some interesting common characteristics between *Automatic* and MC. Both are motivated by efficiency: material and labor in the first case, computational in the second. Both provide a rule-based means to provide a formal language for the highly regularized subdivision of space. These observations led to iterative attempts to develop a more contemporary unit-based construction system derived from MC.

The fifteen intersection approximations, combined with their bounding voxels, can be interpreted as reciprocal pairs of positive and negative three-dimensional forms (Figure 6). When translational and rotational duplicates are eliminated, these forms reduce to a set of eighteen unique elements.

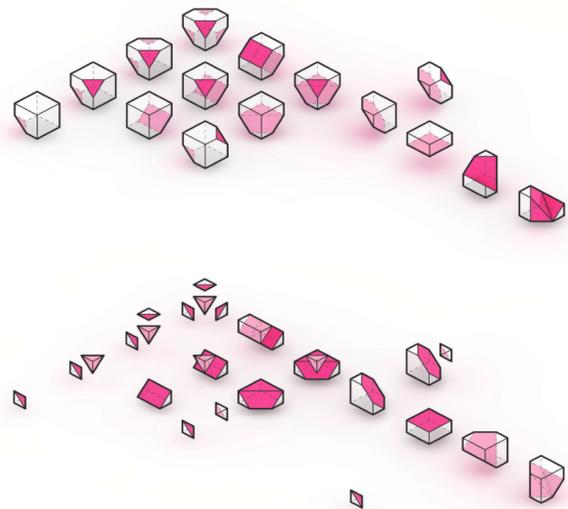


Figure 6: MC intersection approximations, interpreted as forms

Just as the MC algorithm can be used to simulate any surface, the eighteen unique elements can be aggregated to create any form, including architectural configurations such as the intersections of walls, floors and roofs. Sixty-four architectural aggregations, ranging from normative orthogonal configurations to more complex kinked and curved configurations were designed (Figure 7) and 3D printed (Figure 8). These new construction elements, like Wright's Automatic units, encode a strong formal vocabulary and character on any design to which they are applied.

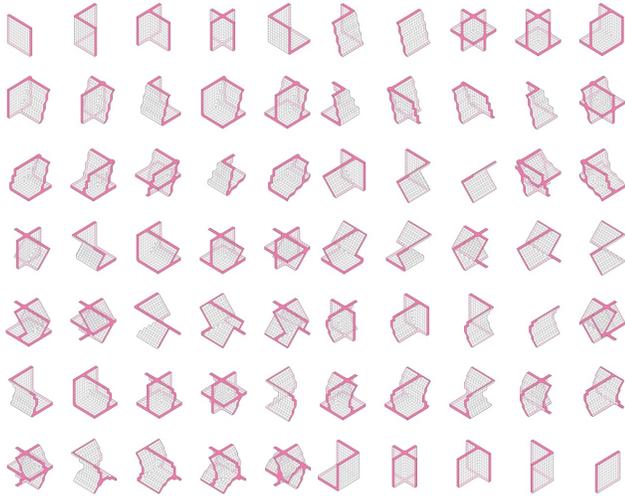


Figure 7: Sixty-four aggregations of Automatic/Revisited elements



Figure 8: 3D printed prototypes of the aggregations (2009)

In order to remain in conversation with Wright's system, we elected to pursue fabrication of these new elements—which came to be known as *Automatic/Revisited*—in concrete. We observed that if one half of a reciprocal pair is interpreted as a concrete object, the other half can be interpreted as this object's casting apparatus. We also observed that it was possible to reduce the required set to eleven elements—a curious albeit coincidental parallel with Wright's system—at the expense of the resolution of some kinked and curved configurations. In considering how to use these elements to create an architectural enclosure made of concrete, we arrived at two variations: a formwork system for cast-in-place construction, and a system of pre-cast units.

In the cast-in-place variant, the architectural enclosure is created when concrete is poured between two assemblies of modular formwork elements. As with existing cast-in-place methods, an offset grid of reinforcing steel, determined by the enclosure's loading and orientation, is required to resist

tensile forces. The formwork elements are re-useable, permitting a small number of them to be used to create a large quantity and variety of enclosures without the wasteful one-off customization normally required when creating complex geometry with cast-in-place methods.

In the pre-cast variant, the elements become the concrete directly. These modular units require a system of connection rods and couplings which provides tri-axial post-tensioning. This hardware also facilitates the one-by-one assembly of the units and eliminates the need for elaborate shoring. Unlike the cast-in-place variant, the development of tensile capacity is orientation-independent and reversible. The pre-cast system can be disassembled and reassembled into new configurations as desired.

In an architectural context, the enclosure permitted by either variant provides a flexible structural armature upon which surface components (cladding) can be affixed: slating, insulation, glazing, and paneling. The armature's resolution can either be expressed directly, or it can be used as a substructure and hidden from view. The eleven-unit pre-cast variant (Figure 9) was ultimately selected as the most suitable system for a temporary installation as it could be disassembled and reconfigured differently at a later time.

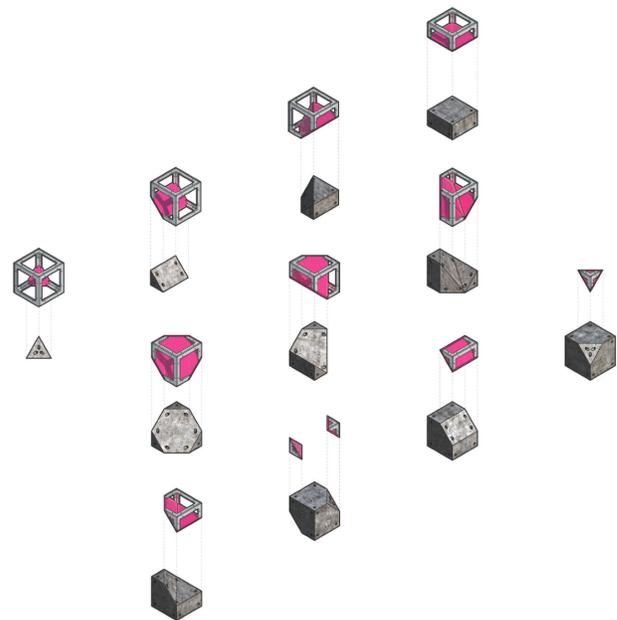


Figure 9: The eleven Automatic/Revisited pre-cast units

Seventy-five of the pre-cast units were fabricated using a combination of conventional artisanal techniques and 3-axis CNC machining and exhibited in two different configurations (Figure 10), demonstrating that the units could be flexibly assembled at an architectural scale while consistently retaining the aesthetic imprint of their algorithmic origin. Pursued as both a novel contribution to architectural knowledge and as a meditation on sculptural modularity, *Automatic/Revisited* made MC physical for the first time. [6]

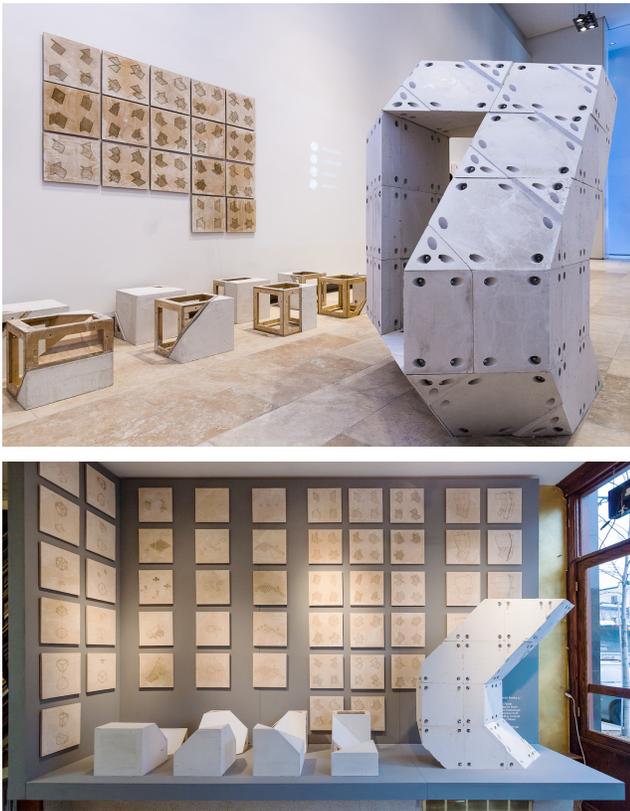


Figure 10: Automatic/Revisited exhibition views (2009/2013)

Making Marching Cubes Physical

Stimulated by the playful interactive qualities recognized in 3D printed prototypes of the architectural aggregations created during the *Automatic/Revisited* design process, we next created and exhibited a new toy-like interpretation of MC made from 3D printed plastic (Figure 11). [7]

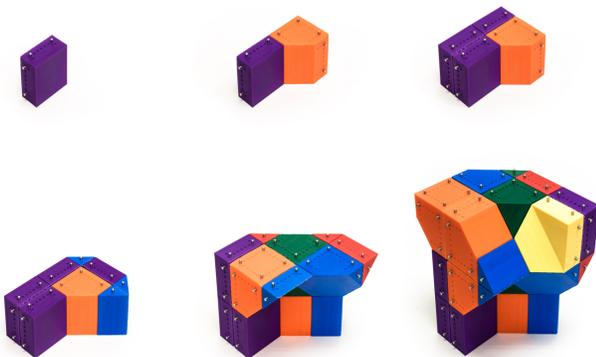


Figure 11: A new toy-like interpretation (2013)

Another key inspiration leading towards the interactive turn in *Marching Cubes* is the work of David Rokeby. Beginning with the seminal *Very Nervous System* and continuing in later projects such as *Dark Matter*, for Rokeby, the voxel

grid is an invisible instrument for which he provides a navigable structure, “an articulation of a space, either real, virtual, or conceptual”. [8,9,10] Taking up Rokeby’s challenge, *Marching Cubes* provides a navigable structure for algorithmic space by articulating it both literally, as a virtual space made real, physical, and tactile, as well as conceptually, by mapping a computational procedure onto the agency of human interaction.

In its ultimate form, described below, *Marching Cubes* projects are interactive performances and installations that permit direct physical engagement with the MC algorithm. The 3D printed construction units are sized to fit in the hand, and the installations contain enough units to allow participants to freely play, assisted by custom modeling software. This software generates real-time assembly instructions that help participants translate their experimentation into human-scale sculptural assemblies. The units are sufficiently robust to be assembled repeatedly, in near-limitless configurations; the interaction with them is sufficiently intuitive to encourage fluid creativity.

Two specific aspects of these new results that have broader implications for computational creativity and, as such, warrant more extended elaboration, are the novel adaptations to the original MC procedure required to facilitate interactivity at this new scale, and the design and fabrication innovations that helped bring *Marching Cubes* to physical fruition.

The Physical Marching Cubes Algorithm

Automatic/Revisited and the subsequent prototype systems featured less than one hundred total units, making it relatively straightforward to aggregate them manually and interactively without referring back to the MC procedure. *Marching Cubes*, on the other hand, consists of thousands of units, and while it is still possible to assemble them free-form, it was anticipated that large and complex aggregations would benefit from assembly instructions. Our Physical MC (PMC) algorithm adapts Lorenzen and Cline’s original procedure in support of this need.

MC was designed to produce polygonal meshes from any scalar field. These meshes delineate the boundaries of a volume within a given range of scalar field values, in the same way that the contours on a topographical map delineate the boundaries of an area within a given range of elevations. This ability made MC extremely popular for graphically rendering incremental scalar contours of non-visible characteristic such as temperature, concentration, or intensity. In the general case, these scalar fields can exhibit value gradients resulting in multiple concentric polygonal boundary meshes, like the layers of an onion.

Producing a single polygonal boundary mesh of the closed outer surface of a single object—analogue to isolating one topographic contour, or one onion layer—is a limited application of MC that corresponds with what we required in order to provide assembly instructions. We developed and optimized our PMC algorithm for this special case. The scalar field is Boolean, in that it has only two possible values: the inside condition (true) and the outside condition

(false) of a sampled voxel octant. Only computing Boolean scalar fields permits PMC to efficiently make use of the MC algorithm's look-up table procedure in support of a user's desire to experiment with different input geometries. A PMC solution is guaranteed, because every MC topological solution has a corresponding *Marching Cubes* unit.

PMC, implemented as a custom Grasshopper routine within the 3D modeling program Rhinoceros, facilitates the construction of *Marching Cubes* assemblies as follows. First, it permits the user to dynamically visualize what an assembly generated from a given virtual reference input—a 3D model or scan—might look like. If this visualization is deemed satisfactory, the routine can then create assembly instructions. The instructions consist of an illustrated manifest that documents the type, location, and orientation of the *Marching Cubes* units required to aggregate a physical approximation of the virtual reference input. For ease of use, the manifest is divided into vertical layers so that the approximation can be built incrementally from bottom to top. (Figure 12).

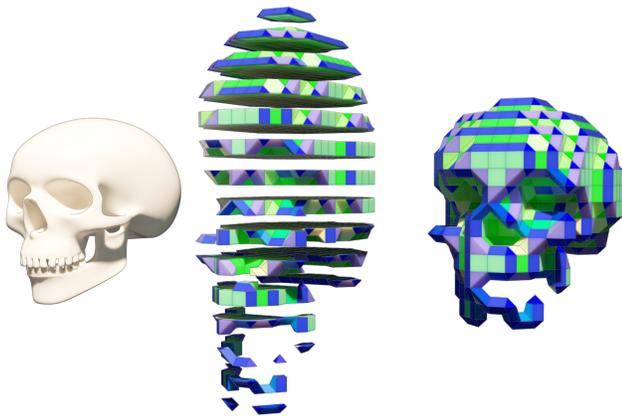


Figure 12: Virtual reference input (left), PMC assembly instruction layers (middle), aggregated PMC approximation (right).

PMC provides user control over the coordinate origin, axial orientation, and unit resolution so that these attributes can be dynamically and iteratively refined to facilitate the selection of an optimal approximation of the reference input. For example, a user can consider how the approximation of a virtual reference input varies with changes to the coordinate grid orientation about any of the three axes (Figure 13). They can also consider the impact of changes to the coordinate system grid size (Figure 14). This key parameter corresponds directly with the resolution of the aggregation.

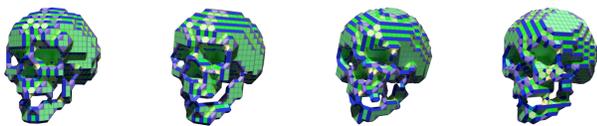


Figure 13: PMC approximation with the coordinate system rotated about the y-axis in 22.5 degree increments left to right

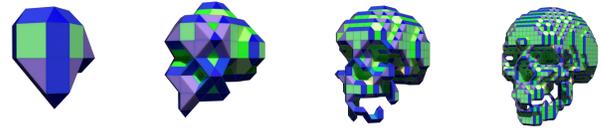


Figure 14: PMC approximation with the coordinate system grid size doubled in each increment left to right

The original MC algorithm suffers from a solution ambiguity in that multiple boundary surfaces can be attributed to a single Boolean condition within a sample voxel. In fact, the boundary surface is computationally arbitrary as long as its perimeter is consistent with its Boolean conditions; PMC optimizes this surface in service of maximizing the viability, utility, and continuity of the *Marching Cubes* units.

Several future improvements are being investigated. The first is the ability to calculate approximations for a reference input where the solution is constrained to use no more than a user-specified number of each particular *Marching Cubes* unit type. This feature would allow users to build complex aggregations with a limited number of units. The second is a fidelity setting, which will compare approximations with different coordinate grid rotations and determine which solution has the least deviation from the reference input. Finally, we are investigating integration of a structural analysis package that would permit users to predict whether a given aggregation is stable.

The Making of Marching Cubes

The desire for playful interactivity motivated the design of a new connection mechanism. The connection rods and couplings used in *Automatic/Revisited* provided the stability necessary to erect architectural-scale assemblies. However, this system is complicated and time-consuming to assemble, uses many small parts, and requires the precise application of a torque wrench. The pins designed for the first 3D printed plastic prototype are a simpler mechanism, but these continue to require precision assembly of small parts and provide nearly no tensile strength. Worse, this mechanism only permits stacked assemblies along one axis at a time due to interference between the pins and the units when they are brought together off-axis.

Several iterations of connection mechanisms using embedded magnets were explored. This approach promised hardware-free self-alignment and tensile strength proportional to the attraction between the magnets. Because each unit has six degrees of freedom, magnets with fixed polarities relative to the units proved impossible, as this prohibited connections between units in opposing orientations. The final design makes use of spherical magnets that rotate within cavities. These magnets and cavities are positioned on the voxel grid surfaces of the units at a position that balances magnetic field interference between adjacent magnets with the proximity of the magnets to the boundary surface.

The magnets are contained by a glued-in-place end cap with a unique color and shape for each of the five different voxel grid surfaces. This coding encourages intuitive

interaction by helping users understand which surfaces are connectible: the one-magnet face is coded with a pink triangle, the two-magnets-on-opposite-corners face with a magenta irregular hexagon, the two-magnets-on-the-same-edge face with a light blue rectangle, the three-magnets face with a purple irregular pentagon, and the four magnets face with a dark blue square. Filleted corners near the voxel grid vertices signal the correct orientation of each face. Put more simply, users are told that “units are correctly connected by matching the colored faces.” The colors themselves were selected on an aesthetic basis, heavily constrained by the need to acquire large quantities of inexpensive 3D printer filament in each color.

The decision to 3D print the units was not taken lightly as previous experience suggested that the precision required would be difficult to achieve using this technology. A number of factors conspired to motivate fabrication using consumer-grade fused-deposition 3D printers. First was the realization that injection molding, the most conventional method for creating repeated plastic objects, would prove impractically expensive due to the cavities required to contain the magnets: the requisite molds would need to incorporate removable slides along two axes. Moreover, the target count for each unit—on the order of fifty to two hundred pieces—did not justify the tooling costs for even simple molds. Second, the opportunity arose to make use of a newly purchased array of 3D printers, which provided a learning opportunity for future projects that might make use of a printer farm.

Ultimately, over a three-year period, forty-two 3D printers from three different manufacturers were operated to produce the components required for over 5000 *Marching Cubes* units. While the trials and tribulations of this process are beyond the scope of this paper, it bears mentioning that this means of production is not recommended. However, the choice to 3D print proved conceptually fortuitous because the actions taken by the user in aggregating the units into assemblies, layer by layer, mimics that of the printer in aggregating each unit from deposited plastic.

The making of *Marching Cubes* was made possible by: thirty-two Printbot brand 3D printers (for the natural plastic main unit), eight Airwolf brand 3D printers (for the pink, magenta, purple, and dark blue colored plastic end caps), two Dremel brand 3D printers (for the light blue colored plastic end caps), 600kg of PLA filament, 50,000 N42 grade 6.4mm diameter neodymium spherical magnets, at least 50,000 hours of 3D printing and 2500 hours of post-production, and the invaluable help of fifteen studio assistants.

Making Marching Cubes Tangible

The first units fabricated (Figure 15) permitted the beginning of an ongoing sequence of interactive performances and installations designed to publicly demonstrate the tangibility and the expressive potential of *Marching Cubes*. Through the end of 2018 we have explored architectural and anthropomorphic themes, two extremes of the form-making opportunity this project provides.

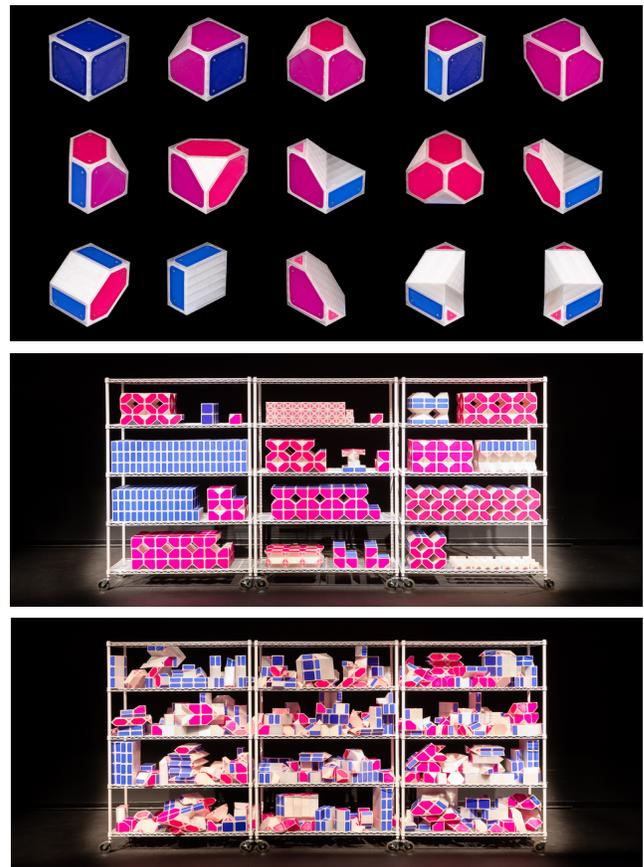


Figure 15: The first *Marching Cubes* units fabricated (2016)

The First Interactive Performance

The first opportunity to publicly demonstrate *Marching Cubes* took place in the Experimental Media Performance Lab (xMPL) in Irvine, California. The xMPL is a black-box performance space for interdisciplinary, interactive, and experimental media performance projects. This unique venue provided an optimal opportunity to deploy the construction units as part of an interactive performance.

Approximately 1500 units were located in the xMPL for three days. Volunteers were trained to facilitate public interaction with the construction units. The custom modeling software was used to generate instructions for a series of nine sculptural assemblies with architectural characteristics, derived from *Automatic/Revisited* (e.g. Figure 16). Participants were given the opportunity to work with the volunteers as a team, acting out the instructions as if they themselves were 3D printers, locating material in space from bottom to top. We also observed participants take advantage of the opportunity to ignore the instructions and design novel assemblies as they saw fit. This hybrid of expert and inexperienced participants deliberately evoked a historic performance previously reenacted in the xMPL: Yvonne Rainer’s *Trio A*, in which rhythmic movements, structured like tasks, are enacted without pause or climax. [11] In this case, the regular rhythmic movements of the participants echo those of the algorithm’s procedural calculations.

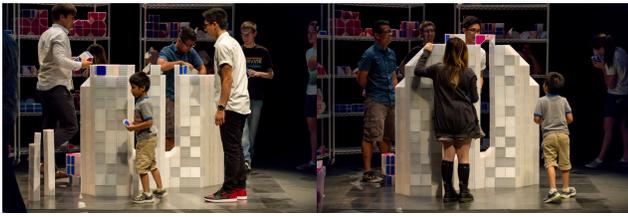


Figure 16: Marching Cubes Assembly #7 (2016)

Time-lapse photography was used to record the performances as well as generate documentary material required for the next phase.

The First Gallery Installation

The second opportunity to publicly demonstrate *Marching Cubes* took place at Pari Nadimi Gallery in Toronto, Canada. A final evolution of the architectonic sculptural assemblies was installed along with a complete set of units and video documentation of the xMPL interactive performances (Figure 17). The documentation was curated to illustrate both the original systematic intentions of the algorithmic procedure and any unanticipated results generated by the participant confusion, communication failure, or (in at least one case) deliberate and aesthetically intriguing subterfuge.



Figure 17: Marching Cubes Assembly #17 (2016)

Further Performances and Installations

Through 2018, one further pure installation and one further pure interactive performance have taken place, at the Arts Brookfield Grace Building in New York City, USA (Figure 18) and at the Patkau Project Space in Vancouver, Canada (Figure 19), respectively. The latter featured the first assemblies derived from 3D scans of a human figure.



Figure 18: Marching Cubes Assembly #19 (2017)



Figure 19: Marching Cubes: Boris (2017)

Three further hybrid performance/installation events have taken place to date, at Platform 28 for Art & Architecture in Tehran, Iran, at Kulturhuset Stadsteatern in Stockholm, Sweden, and at Open Gallery in Toronto, Canada. These opportunities presented logistical and financial constraints that precipitated the design of new assemblies that, when collapsed, could be transported by plane as checked baggage. These venues also featured video documentation of previous *Marching Cubes* performances and installations. Further demonstration opportunities are anticipated through 2020.

Reflection

An algorithm is nothing more than a step-by-step procedure. Conceptual artists have a long-standing engagement with

step-by-step procedures as generators of form: per Sol Lewitt, the “idea becomes a machine that makes the art.” [12] In this case the machine is an algorithm appropriated from one of the most transformative cultural forces in history: information technology. By inverting the normal application of this machine—from a procedure for converting form into computer-digestible units, to a procedure for converting computer-digestible units into form—*Marching Cubes* allows the audience to, through tangible interaction, directly experience the algorithm’s procedure and the visual language this procedure imposes on the world. Extended interaction begins to reveal the syntax patterns of this language and its representational limitations.

Embodying the algorithm in a construction unit—a traditional vehicle for open-ended play and experimentation—places MC at our fingertips, extracted from its usual background position within the inner workings of screen-based visualization technologies. Enabling the algorithm in this way requires physical movement on the part of the user, which, released from the error-correcting mechanisms present in a virtual instantiation, permits them to exploit the potential of glitches or other unintended consequences. Put another way: while assembly instructions are provided, they need not be followed; per Huizinga, “all play means something.” [13]

Conclusion

The algorithm that drives *Marching Cubes* is not new, and its applicability to physical form has been established and explored by our previous work. However, the new materiality and enhanced tangibility of the construction unit variant, enabled by the universally familiar and culturally primal act of play, has rendered the abstract idea of the algorithm accessible. This project provides a way in which one of our foundational computational procedures can be touched and manipulated, generating dialogue about the ways in which information technologies can be used to both literally and metaphorically create the building blocks of contemporary culture. Anything can be digitized: *Marching Cubes* asks us to reflect on what is lost and what is gained in this normally hidden process.

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Authors Biographies

Jesse Colin Jackson is a Canadian artist based in Southern California. His creative practice focuses on object- and image-making as alternative modes of architectural production. He manipulates the forms and ideas found in virtual and built environments through the expressive opportunities provided by digital visualization and fabrication technologies. His interactive *Marching Cubes* installations and performances (2016—present) have been featured in Toronto, Vancouver, New York, Los Angeles, Tehran, and Stockholm. Past solo exhibitions include *Skip Stop* (Pari Nadimi Gallery, 2019), *Radiant City* (Pari Nadimi Gallery, 2014), *Usonia Road* (Larry Wayne Richards Gallery, 2009), and *Automatic* (Larry Wayne Richards Gallery, 2009). Jackson was a 2014-2015 Hellman Fellow at the University of California and a 2008-2010 Howarth-Wright Fellow at the University of Toronto. Jackson is Associate Professor of Electronic Art & Design at the University of California, Irvine. He taught previously at OCAD University and the University of Toronto.

Luke Stern was a Senior Design Researcher at Patkau Architects in Vancouver, Canada, where he was the project architect for the Temple of Light, a project of ambitious structural complexity. He is now retired from professional practice.