Digital fabrication and parametric tools require not only digital dexterity but a robust material sensibility that precedes digital mediation. Developed through Gaston Bachelard’s concept of the graft, the material imagination acts as a reciprocal creative intelligence to today’s dominant formal imagination enabled through the fluid geometric precision in digital tools. This paper presents a series of “materials first” pedagogical approaches through which material constraints become operative design criteria in the development of digital skills. This intersection between analog and digital systems develops a parametric sensibility that is demonstrated through physical prototypes and full-scale installations. This approach is implicitly a critique of the disregard of material logic in many parametric approaches in particular, and digital design culture in general. Conversely, the development of a parametric sensibility through analog means enables the development of material primitives from which parametric tools can expand the material imagination while giving structure to it.
1 Introduction

Digital fabrication in association with the virtual prototype and parametric modeling are powerful tools for design development, but the growing conventions of use can thwart the material development these tools were meant to engender. Digital fabrication and parametric tools require not only digital dexterity but a robust material sensibility that precedes digital mediation. To this end, the pedagogical emphasis presented here focuses on a materials first approach to developing digital skills to excite the material imagination.

This material imagination is more than a pragmatic means to develop digital skills, but a more epistemic way of operating—a practice, if you will, for engaging with the world. My interest is to position the material imagination as a reciprocal creative intelligence to the dominant formal imagination enabled through the fluid geometric precision in digital tools. In the end, nurturing this material imagination in concert with the formal imagination may have a strong influence on the conceptual horizon that students draw from, and in so doing bridge the gap between conception and execution.

2 The Graft: Developing a Synthetic Sensibility

In Water and Dreams, Gaston Bachelard focuses on the imagination through the eyes and ears of poetry (Bachelard, 1999). Through poetry, Bachelard seeks to cultivate the projective image sprung from the material imagination. The material imagination is, then, the seed of intentionality.

Bachelard highlights two aspects of creative inspiration: the formal cause and the material cause, or the formal imagination and the material imagination in which he sought a “dual participation” between the two. For Bachelard, form gives structure, but material is the inspiration—the spring time.

To encourage the reciprocity between the formal and material imagination, Bachelard puts forward his concept of the graft:

“The graft seems to be a concept essential for understanding human psychology. In my opinion it is the human stamp, the specifying mark of the human imagination...

It is the graft which can truly provide the material imagination with an exuberance of forms, which can transmit the richness and density of matter to formal imagination. All metaphors aside, there needs to be a union of dream-producing and idea-forming activities for the creation of a poetic work. Art is grafted nature.”

While the graft develops a reciprocity between the material imagination and the formal imagination, Bachelard further decomposed the material imagination as a “paste” composed of earth and water giving fluidity to the matter that extends from the earth. Through the paste, he emphasized the experience of fluidity and pliability in creative development with the example of working geometry as a kind of kneading and modeling. Today, with the pliability of NURBS-based software, geometry is all too frequently kneaded without the paste of the material imagination grafted onto it. Perhaps something more literal like clay would be most akin to NURBS-based development but this would only extend the formal imagination with disregard for material constraints and the material imagination that can spring from these constraints. As distinct for example from the fluid geometry of small scale sculptures or industrial design objects, the material imagination in architecture continues through the rigorous configuration of material systems. Toward this end, material constraints become operative to focus the material imagination. Bringing this material execution into the conception of architecture is more than a practical matter, but grounds the nature of design conception into material experience. Bachelard's concepts of the graft and the paste are concepts rooted in the understanding of creative development and therefore an essential understanding for any design pedagogy. Materiality gives resistance to the geometrical flexibility of software, and yet material flexibility is needed to inspire the material imagination.

3 Parametric Sensibility

Digital fabrication is not a substitute for the material imagination, but rather sits at the opposite end of a spectrum, if not a totally different analytical and intellectual faculty that must be grafted onto the material imagination (Figure 1). This grafting requires translation that is at once both a projection and an abstraction of the material imagination. A give-and-take reciprocal development between form (order) and material (substance) is at the core of developing a parametric sensibility that co-evolves with parametric
tools. Sensibility, as the word implies, is the combination of sense + ability. Developing digital skills should not only focus on ability, but the senses cultivated in the learning process.

For this reason I take a materials first approach to developing digital skills. Rather than simply the development of digital skills, as if skills were isolated from the development of content, the approaches presented here are intended to cultivate a digital/material sensibility through the intersection between analog and digital systems.

Below I briefly present two pedagogical approaches, one beginning with the physical basswood spline and the other with the constraints of sheet material. A third design-build studio project is included which takes the best attributes of these two preliminary approaches into a permanent interior fit-out.

4 Material Primitives: the Forming of Form

In the eighteenth century, splines were drawn analogous to the material resistance of wood planks in ship-building (Farin, 1993). In other words, the tools developed were in relation to material properties. In the 1960s, mathematicians such as Pierre Bézier abstracted the geometry from these material splines but in the process abstracted out the material properties. Bézier’s intentions were not to develop a more efficient means of existing methods, but to create a bi-directional link between design and manufacture (Bézier, 1998).

Ironically in today’s design tools these material constraints must be brought back in by the designer.

The first pedagogical approach emphasizes a physical-digital-physical cycle which begins with the literal basswood spline discussing its capacity and tendency to take shape (Delanda, 2004). The capacity of materials includes its material composition, for example how the higher grain density in basswood is superior to the looser grain structure of balsa. The tendency of material to bend a certain way has to do with a material’s geometric cross section, such as the weak and strong bending axis (bi-axial versus uni-axial).

As a three-week introduction in a digital media seminar, through the development of a basic material primitive of about twelve basswood splines (Figure 2), a number of principles of NURBS-based geometry can be introduced including degree of curvature, surface development, and surface panelization through ruled surfaces completing the cycle from material primitive, to 3d form, to 2d cut files.
including degree of curvature, surface development, and surface panelization through ruled surfaces completing the cycle from material primitive, to digital geometry, to cut files, to return to a developed physical model.

5  Degree of Curvature

The technical understanding of curvature degree (1st, 2nd, and 3rd) is important to transcribe the physical analog model into digital splines through a basic, though not obvious understanding of digital splines: a minimum of input points creates a smoother curve. This develops the first principle of a parametric sensibility through a strategic economy of information from which a variable system is based.

6  Surface Development

Based on the network arrangement of the physical splines in the analog model, simply lofting doesn’t work. This requires selectively surfacing the model through a range of surface modeling approaches from lofting, railing, from boundary curves, etc. to construct a preliminary surface from which to extract isocurves to then develop a new surface, discarding or hiding the original surface. This introduces a second principal aspect of the parametric sensibility: to understand the surface as a jig, or the controlling geometry.

7  Surface Panelization

Surface panelization through ruled surfaces comes full-circle from physical input, digital development, to physical fabrication (Figure 3). The real world material and fabrication constraints balance the idealized non-material digital surfaces. Furthermore, the development of panelization requires the development of primary and secondary structural systems to support this panelization, which requires a further sophistication in understanding geometry through the surface normal to generate depth from the surface. This bottom-up materials first basswood spline-based approach creates a context for developing digital skills establishing a parametric sensibility between analog material systems and digital precision.
8 Material Constraint: Economy of Means

Despite the formal flexibility enabled through digital fabrication, little if any attention is paid to the sheet as a material in and of itself which results in a great deal of material waste. As a two-week introductory project in a third year undergraduate design studio, the moveable feast installations are a series of annual studio-based fabrication experiments which establish a bottom-up intensive material investigation into what sheet materials can do prior to establishing any architectural form. The mandate to eliminate waste through maximizing sheet goods became an operative design criteria to exploit the nature of the material through cutting, scoring, and folding while creating a self-enclosing material assembly.

By beginning with flexible paper, focus is placed on the material imagination through a quick series of collective sketch studies. Developed as full-scale installations, the initial material play required a scalar shift which also necessitated more rigid material such as cardboard which requires a translation from the initial material studies.

Moveable Feast 2008 employs folding as its material technique to develop a three-dimensional unit from a sheet of 24”x48” cardboard (Figures 4–5). Moveable Feast 2009 (Figures 6–8) developed through expanding pattern stretched across a plywood frame, which expands like expanded lath and can be seen in SANAA’s aluminum rainscreen for the New Museum of Contemporary Art (Verona, 2007). Both examples begin with material play which establishes a basic material system or assembly, which is then developed as a 2d cut file, and digitally fabricated on a Kongsberg Tangential Knife typically used for cardboard box prototyping. This developmental path is different than that shown in Figure 1, as there is no complete three-dimensional representation (Figure 9).

Both examples arrive at a solution that would not have been imagined if based on digital tools alone, and furthermore develop a surface articulation that is difficult to digitally model. In the first installation, the actual shape was not known until assembled, while in the second installation, the overall plywood frame was digitally modeled but the expanding infill surface panels could not be. While the complexity of surface affect is achieved through very minimal means and without material waste, and was also prototyped through more permanent materials such as water-jet cut aluminum (Figure 10).
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figure 9: This developmental path curtails three-dimensional representation with final shape of Moveable Feast 2008 not known until final assembly.

13: A developmental path of the graft diagram in a material-based parametric process.

figure 10: The Moveable Feast installations are developed in cardboard due to time and budget constraints, but aspects of these have also been prototyped in water-jet cut aluminum to test their real world viability.

Figure 11: The F-Stop student lounge and gallery completed in Spring 2011 by a third-year undergraduate design-build studio.

Figure 12: Studio in process with initial material primitives on back wall which established a sense of scale and a basic hexagon unit as a geometrical structure and with laser-cut prototype model of display wall and furnishing elements in foreground.
9 F-Stop: Design for Assembly

The first NURBS-based approach develops some principle aspects of a parametric sensibility, while the movable feast installations focus on the development of full-scale assemblies which ideally could become embedded in a parametric logic. In Fall 2010, these two approaches were combined in a design-build studio for a student lounge known as F-Stop (Figure 11). The design, fabrication, and installation of this project was 90% complete after this ten week immersive quarter studio, with the remainder of electrical work and final installation complete by Spring 2011. The third-year students entering this studio had little previous experience with digital design, and no previous experience with digital fabrication. To generalize, the majority of students' design proposals were based on what they knew they could build which led to conservative if awkward design proposals. On the other hand, a smaller minority of more digitally desirous students gathered references of rendered surfaces sketching out clay proposals that had little material awareness and far out of reach from what they could actually build.

As a balance between these two positions, the built design proposal makes a strong case for a parametric sensibility cultivated from the material imagination. While the concept of a vortex-like ceiling cloud was proposed, a parallel development focused on the material assembly of this non-uniform surface thus combining Bachelard's formal imagination with the material imagination. The breakthrough in this proposal developed from a series of material primitives sketched out through cardboard and tested out at multiple scales (Figure 12). From these material primitives, a basic hexagon geometry could be established to make the connection to the formal proposal through a parametric design approach using Grasshopper. This approach establishes a third version of the graft diagram in a parametric process from material play, to development of a material primitive and its associated analytical geometry from which the parametric variation is developed (Figure 13).

While a small student team was tasked with understanding the basics of Grasshopper, due to the fast-track nature of the project, I developed a series of Grasshopper definitions that were ultimately used. In a positive sense, these definitions gave consistency and certainty to the accurate geometrical development of a complex material assembly to a group of students with no prior experience with Rhino and digital fabrication.

While a single master definition was initially sought, instead a series of definitions were employed: first, a definition which established a single, well-ordered surface from the student's multiple trimmed surfaces and projected a hexagon pattern onto the surface; second, from each projected hexagon, a second definition was applied that developed each hexagon into twelve folded petals giving depth to the material

![Figure 14: Conversion from Master Surface at left to hexagon structure with 12 folded petals per hexagon.](image)

![Figure 15: Joint assembly parametrically defined to create joints and connector plates, including pre-drill holes and part labels.](image)

![Figure 16: Connector plate registers joints in exact locations, and engraving on back of petals allows for precise placement of each connector / joint assembly into a larger hexagon ceiling assembly which is hung in place.](image)

![Figure 17: Final ceiling vortex assembled](image)
assembly based on the initial material primitive (Figure 14); and finally, a third definition was applied to each folded petal which created a series of connector plates with valley, bridge, and ridge joints (Figure 15) to connect each petal to its nearest neighboring petal into a series of prefabricated hexagon assemblies (Figures 16-17). Instead of a single master parametric definition with global control, this series of definitions helped to coordinate the development of the complex ceiling assembly with other more conventionally designed components of the project while also creating a system of checks-and-balances in the design and fabrication process. Installed in three days from 1,000 unique parts, this parametric design process gave certainty and precision to a complex design proposal that could not have been executed without it, and at the same time, it was the basic material primitive that established the underlying geometry that was structured in the parametric definitions. In the end, developing a parametric sensibility is more than simply learning the software, but establishing a material sensibility that gives structure to the parametric geometry.

10 Conclusion: Translation and Abstraction

Bachelard captures the “image” within the imagination connecting the material imagination back to material experience. This image is not simply a reflection of how things appear, but a projection into the depths of experience. The development of a parametric sensibility through material constraints implicitly critiques the disregard of material logic in many parametric approaches furthering the disconnect between digital tools and material experience. As design culture inevitably becomes more of a digital culture, a more robust model of design conception grounded in material experience must be paired with the developing parametric sophistication in digital tools. Design “concepts” are not developed as abstract ideas, but rather develop from material experience as contemporary studies in embodied cognition show (Gallese & Lakoff, 2005).

The development of a parametric sensibility through analog means enables the development of material primitives from which parametric tools can further the material imagination while giving structure to it. This requires translation and abstraction from initial material play to the design of material systems enabled by the precision of digital fabrication and controlled through parametric tools. Digital fabrication and parametric techniques are not a substitute for the material imagination, nor necessarily do they inspire it. Rather, the material imagination is cultivated through the fluidity of material play and focused through constraints. Through a rigorous process of translation and abstraction, digital techniques enable the development of material systems derived from the material imagination. This process of translation and abstraction is a pedagogical opportunity to connect the material imagination with a disciplinary development of material systems through parametric means. Developing a designer's sensibility is, in part, a graft between the intuitive material senses pulled through the analytical development of digital skills through a process of translation and abstraction at the core of architectural thinking.

References