Tactile, Spatial Interfaces for Computer-Aided Design
Superimposing Physical Media and Computation

by
Dorothy J. Shamonsky

Bachelor of Fine Arts, Rhode Island School of Design, 1977
Master of Science in Visual Studies, Massachusetts Institute of Technology, 1984

Submitted to the Department of Architecture
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Signature of Author

Dorothy J. Shamonsky
Department of Architecture
August 8, 2003

Certified by

William J. Mitchell
Dean, School of Architecture and Planning
Academic Head, Program in Media Arts and Sciences
Thesis Supervisor

Accepted by

Stanford Anderson
Chairman, Committee on Graduate Students
Head, Department of Architecture

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Dissertation Committee Members:

William J. Mitchell
Dean, School of Architecture and Planning
Academic Head, Program in Media Arts and Sciences
Thesis Supervisor

Glorianna Davenport
Principal Research Associate, Interactive Cinema
Media Laboratory
Thesis Reader

Joseph Paradiso
Associate Professor of Media Arts and Sciences
Co-Director, Things That Think
Media Laboratory
Thesis Reader

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ABSTRACT

Computer-aided design (CAD) systems have become invaluable in three-dimensional creative design fields such as architecture and landscape architecture. However, these digital tools have not replaced the use of physical tools and materials as envisioned by the early developers of CAD. Instead, most designers have added digital media to their suite of physical media, gaining the benefits of both realms and using each where it is most advantageous.

Given current CAD systems and how they are being used, two significant problems are apparent. First, the side-by-side physical/digital work environment has resulted in the need to frequently digitize and print in order to switch between physical and digital representations. This process is often time-consuming, costly, and frustrating. Second and more fundamental, the standard graphical user interface (GUI), although appropriate to some tasks, is restrictive as the only interface to CAD, because it lacks tactile and spatial qualities. Interacting with physical media such as paper, cardboard, and clay is a multisensory, spatial experience. Interacting in a GUI may be visual, but our other senses and spatial abilities remain underutilized. Recent interface design research includes embedding or augmenting physical artifacts with computation as one remedy to the limitations of the GUI.

This dissertation investigates whether superimposing physical and digital media to create new interfaces for CAD has merit. Findings are presented from experiments performed with Illuminating Clay, a prototype interface that superimposes modeling clay and topographic analysis. The objective was to discover whether these new kinds of interfaces could successfully combine the cognitive, motor, and emotional advantages of physical media with the capabilities of computation. Findings indicate that Illuminating Clay can indeed supplement a designer's eyeball analysis with more-accurate feedback while retaining the tactile and spatial advantages of working with a physical material. Salient issues pertaining to the design of tangible, and augmented-reality user interfaces were raised by these experiments: what the appropriate scale limitations should be, what the appropriate type of feedback is from computation, and whether real-time feedback is necessary.

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Cambridge, Massachusetts, USA
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To my parents, Matthew and Anne Shamonsky

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PREFACE

As I worked toward this doctoral degree, I periodically received e-mail messages that began "That degree you always wanted may be closer than you think!" After a momentary glimmer of hope that a higher power was delivering me from a lot of hard work, I realized that this was spam from a place that sells college degrees. Receiving these messages was a blunt reminder that although cheap fixes can be had instantly, significant achievements of creativity, skill, and learning are the result of a long process of applied, focused effort. Fortunately, a good tool can increase efficiency to a great degree. For example, word processing enabled me to write this dissertation faster than my predecessors on typewriters, because I didn't have to retype the manuscript every time I wanted to make changes.

Ironically, with their promise of "smarter-faster-better," computers have brought confusion to ideas of efficiency, skill, achievement, and quick fixes. A couple years ago, veteran interface designer Bill Verplanck taught a week-long seminar at the MIT Media Lab on sketching for interface designers. Although I felt comfortable with my sketching skills—I spent many hours in drawing classes as an art school undergraduate—I took the class to glean some of Verplanck's wisdom. Students in the class energetically participated in the exercises, but as I chatted with some of them during breaks, I was surprised to discover how many of these students were hoping to learn a few easy techniques that would leapfrog them into becoming competent drawers or, better yet, hoping to find out what software could instantly improve the look of their drawings.

The opposite reality became evident to me as I was conducting the research for this dissertation: *Good designers design well no matter what tools or materials they have access to. Also, skilled, experienced designers use tools and materials more efficiently and effectively than novices do.* I acknowledge that this may change in the future when and if computation achieves significantly more intelligence than it has now.

I have to admit that in the past I, too, have indulged in fantasies of quick fixes, which is how I eventually came to write this dissertation. As an undergraduate sculpture major, I can recall sitting in my studio overwhelmed by the cost of materials, and exhausted by tools that weren't working properly as end-of-semester deadlines loomed. I wondered, "Wouldn't it be great if I could simply visualize a sculpture and have it materialize instantly?" I'm sure that others, tired and working late, have shared this fantasy. I wished that I could work directly with my visualizations, as if they were shimmering life-size, three-dimensional holograms floating in space. I imagined that I could control my creation with gestures, like a conductor directing an orchestra. My baton would be a handy pointer or magical pencil. If the piece was not quite right, I would wave my wand like a wizard to rearrange the parts. Once satisfied, *poof!* The hologram would be changed into a material form.

When I first started working with computer graphics, it felt a bit like my fantasy. But my shimmering hologram of a virtual sculpture was, instead, a crude line drawing on a small screen. I could control it only by typing complicated, time-consuming commands on a keyboard. No gestures. No instant solutions. Yet I could see the potential of computer technology as well as the next person could, and became involved with digital media whole-heartedly.

What I did not see coming was how my work environment would change over the next couple of decades as computers became common design tools. I experienced what I think of as the "office-ication" of my studio. As an undergraduate, my sculpture studio was filled with natural light, texturally rich materials, and musty, invigorating smells. My tools required a variety of muscle/motor control skills and reverberated with a range of sounds, from the ping of a small hammer to the screaming of a skill saw. A decade later, working as an interface designer, my studio was considerably more sterile, with the shades pulled low and the dominant sounds being the whir of the CPU and the clicking of keys. I often would sit for hours, barely moving except for sliding the mouse around and typing. My studio had transformed from sensory-rich and playful to efficient and rote. My body—senses and muscle/motor control skills—were considerably less engaged by my new tools and materials. Although I wanted the capabilities of computation, the reality was not satisfactory.

My motivation for this dissertation is simple and comes from my experience as a designer. I want the fluid, fast, ephemeral qualities of the digital medium—something much like our thoughts—but with interfaces that are more embodied, like my old-fashioned textured tools and materials. I believe that these kinds of interfaces can better serve the needs and desires of designers.

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Chapter 1:
Introduction

1.1 Overview

The history of computer-aided design (CAD) for architects is like the life of a child's balloon. Initially, there were inflated notions of "all-virtual" work environments and even "designing machines." Over time, the air slowly seeped out of those high-blown expectations and they drifted back to Earth. Designers have, for the most part, embraced computation. And as predicted by early researchers, CAD has proven to be invaluable to the practice of architecture. However, rather than replacing physical media, as also predicted by early researchers, designers have incorporated CAD into current practice in ways that make sense to them—right alongside pencils, paper, cardboard, and clay.

After a decade of extensive use in professional practice, two significant shortcomings to CAD are now apparent. The first is practical: The frequent need to digitize and print in order to switch between the two realms, physical and digital is often disruptive, time-consuming, costly, and frustrating. The second shortcoming is more fundamental: Although the graphical user interface (GUI) was a major advancement at its invention over previous text-only interfaces, it is too limiting as the only interface to CAD because it lacks tactile and spatial qualities, which are so important for designers.

In this thesis, I propose that superimposing physical media and computation to create new smart modeling materials and augmented-reality interfaces for CAD would go a long way to remedy the shortcomings of current systems. In doing so, I draw upon a range of topics, including design media, human sense perception, human motor-skill acquisition, knowing-in-action, human-computer interface design, and constructionist learning. The fundamental principle explored here is whether these new interfaces can successfully combine the advantages of physical media with the new capabilities of computation.

The locus of this thesis is physical media and the designer, two things that early CAD researchers predicted would someday be replaced by computers. We now know that old-fashioned physical media, such as pencil and paper, cardboard, and clay, possess qualities valuable to the design process unique from the qualities of digital design media. We also know that replacing experienced designers with software applications is far more complex than originally anticipated.

1.2 Designers Are Visual *and* Tactile

Architects are visual people—no argument here, because they are in the business of making attractive-looking structures and environments as well as visual representations of them such as plans and renderings. Architects are tactile people—perhaps less obvious, but if you were to observe them firsthand, you would find that their hands are never idle. Their work requires drawing with various types of pencils and pens, cutting and gluing chipboard and Fome-Cor, and modeling with clay. Even when they are merely contemplating rough ideas or partially completed designs, they lightly touch models as if to better comprehend them, smooth out drawings with their whole hand, and trace lines with their fingertips. When discussing a project with other designers, they describe shapes with their hands and gesture at drawings and models. Some designers even experience a virtual sensation of weight and texture, like a perceptual overlay, just by the sketching process. They "feel" construction materials, such as wood and concrete, just by creating representations of them with pencil and paper [1].

Observation alone suggests that touch and vision play an important role in the design process, but science verifies that touch and vision, when used together, enable efficient and effective comprehension and manipulation of tools and materials in three-dimensional space [2]. The sense of touch, or cutaneous sensation, is based on the stimulation of receptors in the skin. The term *haptic,* derived from the Greek word *haptesta*, which means "to touch," is often used in the context of computer-generated tactile feedback. Touch usually includes the somatic senses, which consist of *proprioception,* the sense of the position of the limbs, and *kinesthesis,* the sense of the movement of the limbs. The somatosensory system is responsible for most of our sense of space (supplemented by vision and hearing, and our sense of balance centered in the inner ear) [3]. This is why looking at *representations* of space is not the same experience as that of a *real*, physical space; orientation, distance, proximity, enclosure, and so on, create powerful body sensations.

For the task of design, both touch and vision provide crucial information to the brain; it is arguable which sense is more important or dominant. Hands sense shape, surface, weight, temperature, texture, malleability, and position in space. Eyes sense shape, surface, color, texture, and position in space. Fingertips can feel anomalies that are too small to see. Vision senses objects both in close proximity and at a distance, out of range of the tactile sense [4].

1.3 Current CAD Interfaces

What happens when you give architects, these visual/tactile designers, one of today's CAD systems with a standard GUI (assuming a mouse or tablet input device)? It is as if a single, simplified mechanical hand has replaced the two intricately sensitive natural hands. The mechanical hand can make uniform marks, and move freely within a two-dimensional plane. However, the mechanical hand has limited expressive qualities, lacking the ability to use pressure or gesture. It cannot turn in the-dimensional space or vary the speed of drawing to create different types and shapes of lines, as a natural hand can with a pencil. Also, tactile feedback from the mechanical hand is limited to two-dimensional location, and several on/off buttons which signify point, select, and grab. In addition, a designer must look at a separate screen to know what the mechanical hand is doing and to be able to draw effectively with it. Where two human hands can work together or even do separate tasks simultaneously, the mechanical hand works alone and must do one task at a time.

However, the mechanical hand *does* have functionality unique from the human hand. It can draw perfectly straight lines, lines at any specified angle, lines of specific length, and lines in precise relationship with each other, such as perpendicular, parallel, intersecting, midpoint, endpoint, centerpoint, and projected combinations of these. The mechanical hand can identify an element's Cartesian coordinates, define areas and volumes, and precisely dimension relationships. It can extrude three-dimensional representations from two-dimensional ones, create perfect perspective, and change the size of a representation in one or both directions. The mechanical hand can also respond to input, including numbers, letters, and equations, to create representations; and it can do the opposite, extracting data from a drawing and transfering that data to another of its kind.

But CAD is not a mechanical hand, and the metaphor may push the reality of current CAD systems a bit far. It does make clear that current systems do not work in a way that is natural to designers—does not use their refined tactile skills, with two hands in three-dimensional space. Yet the powerful capabilities that CAD provides *are* highly desirable.

1.4 The Digital Medium

CAD is often referred to as a design *tool.* But it is not just a tool, it is a medium of expression—one of the many digital media, which also encompasses digital video, computer animation, digital publishing, digital music, and so on. A tool increases efficiency; think of a hammer or a straightedge. A medium allows a feeling or idea to be manifested; think of paint, clay, or video. So in addition to acting as a tool, making it far more efficient to create precise schematic drawings for large projects than can be with physical media, it also makes it possible to express ideas that would otherwise be difficult or impossible.

A medium provides scaffolding that enables a designer to explore and develop ideas, both creatively and analytically. It does this by facilitating the building of representations. Types of representations and the ways they can be modified vary from one medium to another [5]. The inherent qualities of a medium frame and determine how a task is approached, influencing the efficiency and success of its accomplishment. Therefore, choosing the appropriate medium for a design task is important. For instance, a physical pencil on paper enables suggestive lines that carry emotional weight and, may have multiple interpretations. Drawings can be layered (if on trace) or juxtaposed for comparison. Another physical medium, clay, enables fast, rough, suggestive three-dimensional forms.

CAD, on the other hand, makes numerically defined virtual representations possible. These representations can be saved, replicated, collaged, or transformed. The time required to create complex digital models can be justified by using the completed model for other purposes as well. Once a model exists, the model's data can be searched to create specification lists, cost-estimate spreadsheets, and so on. Detailed analysis and simulations also can be performed on digital models, making dynamic, abstract systems, such as heat loss in a building, more accessible and concrete for the designer.

1.5 Using the Appropriate Medium for a Task

Typically, architects create three types of representations. Sketches are used toward the beginning of the design process, renderings toward the middle, and schematics at the end [6].

> Sketch—fast, fluid, suggestive, makes ideas visible, allows ideas to be layered
> Rendering—representational, realistic, conveys a mood and style
> Schematic—informational, accurate, measured

What is the appropriate medium to use for each of these types of representations? For sketching, physical media excel. Current CAD systems lack drawing fluidity and are far too literal and explicit to be effective here. For rendering, physical media enable the designer to convey a certain mood and personality. CAD systems have the ability to produce realistically though emotionlessly rendered representations. For schematic drawing, where detail, accuracy, and the ability to make numerous, ongoing alterations is required, physical media can be tedious, but CAD clearly excels.

1.6 Comparing Physical Media and Digital Media

Each realm—the physical and the digital—has its own inherent advantages and disadvantages. Below is a table that compares the qualities of physical design media with those of digital design media. (I use *physical design media* to refer to media that can be experienced directly by at least one sense, without any aid of electronic technology, e.g., computers and video. I am generally referring to the design media that architects use such as pencil, pens, paper, cardboard and clay. I use *digital design media* to refer to current CAD systems.)

PHYSICAL DESIGN MEDIA	DIGITAL DESIGN MEDIA
tactile	nontactile
visual	2-D visual
aural	recorded, synthesized aural
olfactory	nonolfactory
spatial	representative of space
ambiguous	explicit
physically transformable	logically transformable
persistent	ephemeral
real time	faster than real time
not intelligent	intelligent
inexact	precise
moderately copyable	infinitely copyable
moderately reworkable	infinitely reworkable

The digital medium, which includes CAD, is evolving as computer technology becomes more sophisticated. In the above table I am considering current CAD systems. But one needs to be cognizant of the distinction between the inherent qualities of this medium, such as intelligent, and the temporary qualities of the current interface, such as nontactile. The original vision of CAD as an all-digital studio—slick workstations where designers sat staring at screens and manipulating input devices in pristine rooms—took into consideration the inherent qualities of the digital medium yet misjudged how much the interface mattered to the user, and might impact the design process. Developers at that time had little understanding of the value of physical media and how they support the design process so naturally by engaging all our senses in a real, three-dimensional space.

1.7 Physical Media and Knowing-in-Action

When architects design, they often progress through the process, performing actions without thinking about or deciding to do those actions. Some describe this as "feeling" their way through a design problem. Schon coined the term *knowing-in-action* to describe the process of a skilled practitioner:

Although we sometimes think before acting, it is also true that in much of the spontaneous behavior of skillful practice, we reveal a kind of knowing which does not

> *stem from a prior intellectual operation.... It seems right to say that our knowing is in our action [7].*

"Muscle memory" is a phrase used by athletes to describe their ability to respond skillfully without prior thought. Polanyi used the phrase "tacit knowing" to describe the adept use of a tool [8]. Think of how effortlessly you can write your signature with a pen. Compare that to the few times that you have needed to write your signature with a mouse; it is almost impossible. Theories of manual skill acquisition can, in part, explain this kind of "knowledge." Discrete learned motor abilities can become "chunked" into "motor programs" that can then be performed without conscious attention. For example, once we learn to balance, peddle, and stop a bicycle, we can ride without thinking about our every move.

But motor skill makes up only part of the equation of a skilled practice such as architecture. (And motor skill can be acquired even for badly designed interfaces.) Designing is a process that requires idea-generation and choice-making. Past experiences with projects, knowledge of history, materials and techniques, motivation, and point of view all come into play in the design process. Artists and designers often suggest that they enter an "intuitive/feeling" state during the process of solving a creative problem. Csikszentmihalyi [9] describes a similar state that he calls flow, as "thoughts, intentions, feelings, and all the senses are focused on the same goal." A temporary "loss of self" also accompanies this state of deep immersion.

Historically, artists have used sensory stimulation to encourage an intuitive/feeling state. "Great artists feel at home in the luminous spill of sensation." [10] For example, the poet Schiller used to keep rotting apples under the lid of his desk and would open it and inhale their pungent, musty smell when he needed to find the right word. Picasso walked in the forests of Fontainbleau, where he got an overwhelming "indigestion of greenness," which he then felt the urge to empty unto canvas [11].

Physical design media such as clay and paint correspond well with the human sensorimotor system because they engage us wholly, body and mind. Physical media have mass, weight, resistance, texture, color, sound, and aroma. We humans are adapted to function well in the three-dimensional space that physical media inhabit.

We can experiment with them and learn from the results, because the logic of cause and effect in the physical world is something we learned at a young age.

1.8 Limitations of the GUI

In contrast to physical media, working with a GUI is a disembodied, conceptual activity with limited sensory feedback. The "direct manipulation" of a GUI is primarily one-handed for drawing, which eliminates the two-handed control that can be used with physical media. Add to this the need to input text commands and command sequences, including complex combinations of mouse, icon, text, and keystrokes—activities that demand additional mental processing—and you are required to move into a logical/thinking state, away from a feeling/intuitive state. As one landscape designer says,

> *The big frustration of using Form-Z or 3-D Studio is that you want to make changes, but it's not a simple operation to drag your finger and change the height of a ridge. You have to go through all these different processes [12].*

GUIs are tactilely impoverished, providing feedback related only to mouse location and button clicking. The GUI provides limited visual information, with representations of three dimensions as merely illusions of three-dimensional space on a two-dimensional plane. Designers are asked to comprehend forms in three-dimensional space using only their visual sense, contemplating two-dimensional representations on a screen. Greater mental processing is required, compared with the easier cognitive sensing of real forms in real three-dimensional space. In other words, when feedback is missing to one sense (tactile, spatial), another sense (visual) must continually mentally compensate, resulting in cognitive overload.

Cooper explains the limitations of the GUI along similar lines, characterizing most electronic interfaces as having "behavior unconnected to physical forces," and labeling it "cognitive friction."

> *It's the resistance encountered by a human intellect when it engages with a complex system of rules that change as the problem permutes. Software interaction is very high in cognitive friction. Interaction with physical devices, however complex, tends to be low in cognitive friction because mechanical devices tend to stay in a narrow range of states comparable to their inputs.... Playing a violin is extremely difficult but low in cognitive friction, because—although a violinist manipulates it in very complex and sophisticated ways—the violin never enters a "meta" state where*

various inputs make it sound like a tuba or bell. The violin's behavior is always predictable—though complex—and obeys physical laws, even while being quite difficult to control. In contrast, a microwave oven has a lot of cognitive friction, because the ten number keys on the control panel can be put into one or two contexts, or modes. In one mode, they control the intensity, or radiation, and in the other, they control the duration. This dramatic change, along with the lack of sensory feedback about the oven's changed state, results in high cognitive friction [13].

Although the effects of cognitive overload or friction may seem insignificant, it is the persistence of the effect over time that becomes toxic. Designers spend many hours every day, for years, working on a computer. The tediousness and exhaustion that one feels using a GUI is incalculable, difficult to define, and usually accepted as a necessary hassle to gain the advantages of computation.

1.9 An Uneasy Marriage of Physical and Digital Realms

Today, we have the benefit of a decade of substantial use of CAD in practice. Computer tools have proved to be invaluable to the practice of architecture, but so have physical media. Rather than digital media replacing physical media, an uneasy marriage has occurred between the two. They are used side-by-side, each one where most appropriate. Physical materials remain invaluable to sketching, creative exploration, and presentation. CAD offers the analysis and accuracy most applicable to design development and implementation. For example, internationally renowned architect Frank Gehry persists in using physical models for design exploration but utilizes three-dimensional modeling software for design development, construction documentation, and fabrication data [14].

The domains of physical drawings and models, and digital drawings and models, remain very separate. Each medium offers unique capability, yet each resides within its own realm. The barrier between physical and digital representations can be crossed only by a tedious series of digitizing and printing processes. A designer works in one domain to a certain point, suspends work, does the necessary steps to transfer content to the other domain, and then resumes work in the new domain. These steps require special hardware and software to digitize and print. They can also include importing, exporting, translating, and transporting files in order to achieve the appropriate file format and/or location of the file to do the transfers. These transfers often disrupt the design process and can be time-consuming, costly, and frustrating. One landscape designer describes it like this:

A lot of what we do is about the purposeful manipulation of the land. We use clay to create those landforms. We've worked back and forth between clay and digital representations of them—contour maps, Form-Z studies, and those sorts of things—but there's a gap in those two things. You play with the physical model in clay, and then you try to interpret in Form-Z or in contour mapping to approximate it, but there's no direct dialogue between the two. At the moment, we build clay models and we photograph them, and then measure them and translate them into contour lines. It's very tedious. Feedback between altering it and changing the drawings is difficult. We do it, but it's time-consuming [15].

1.10 Problems with Current CAD Interfaces and Possible Solutions

Two problems exist with the current CAD environment. The first is practical; the second is fundamental:

1. Designers spend much tedious and frustrating time digitizing physical representations or printing digital representations in order to utilize the capabilities of both realms.
2. The GUI is limiting when it is the only interface to CAD. Interacting in GUI environments with today's computers is visual but lacks tactile feedback and spatial orientation, which is so crucial to the design process.

Possible remedies to these problems are the following:

1. Improve physical to digital conversion; work toward better printing and scanning capabilities, which will make the transferring back and forth from physical to digital representations less time-consuming and frustrating.
2. Expand input device options and add computer-generated tactile feedback capabilities to the GUI.
3. Superimpose computation and physical tools and materials to achieve new smart modeling material and augmented reality interfaces.

1.11 Superimposing

I propose that the third alternative, superimposing, offers the most benefit to the designer. By superimposing, I mean embedding computation into physical tools and materials, or using computation to respond to the surface of physical media using scanning and projection technologies. I acknowledge that the other two alternatives, improved conversion and an enhanced GUI, will hold a place in future design environments. But superimposing has the potential to combine the most advantages of both realms, while reducing the frequent need to transfer between realms.

Paramount in the design of new interfaces to CAD is the designer and the design process. Ideally, an interface should be transparent, to the task at hand and unobtrusive, or minimal. Design—and many creative activities—require a deep, intuitive mental state which must be fostered or at least not interrupted, disturbed, or defocused by the studio, materials, and tools of the designer.

1.12 Background to Superimposing

Superimposing builds upon the work of many others. As early as the 1970s, some researchers began experimenting with physical interfaces to CAD. Aish and Noakes [16] implemented a rigid "building block system," and Frazer [17] produced **Universal Constructor,** which consisted of sensor-augmented smart blocks.

For nearly two decades, Buxton, at the University of Toronto and at Alias | Wavefront Inc., Toronto, has worked on such projects as two handed interfaces [18][19], gesture input devices, shape tape input devices [20], and large visual displays for CAD [21]. In 1994, Fitzmaurice, Ishii, and Buxton [22] introduced an idea they called **Graspable User Interfaces**, which allows direct control of electronic or virtual objects through physical handles for control.

Shortly after **Graspable User Interfaces** was introduced, Ishii formed the Tangible Media research group at MIT. The group has prototyped tangible user interfaces (TUIs), which employ physical objects, surfaces, and spaces as physical embodiments of digital information and processes. Of significance here is **Urp** [23], ongoing since 1997, which is a tangible workbench for urban planning. Building upon Urp, **Illuminating Clay** [24], created in 2002, is a prototype interface that superimposes clay with topographic analysis software. It was used in a series of experiments for this thesis.

1.13 A Prototype: Illuminating Clay

Illuminating Clay utilizes continuous three-dimensional scanning with one scanner from a fixed location. The scanner reads the surface shape of the clay model and creates a digital model from the data. Topographic analysis algorithms are then performed using the data, and the results are projected back onto the surface of the clay. Because Illuminating Clay provides low-resolution feedback, it is particularly appropriate during early stages of design, or the roughing-out stage, before detailed analysis becomes necessary.

The Illuminating Clay interface offers something simple yet profound to support this early, more intuitive state of creativity. It provides computational feedback in response to the physical manipulation of physical material. When working on the initial forms of a design, designers rely on experience and mental visualization analysis to meet the technical constraints of a project. Illuminating Clay provides rough computer analysis that supplements and extends the designer's own mental analysis.

1.14 The Experiments

To test the principle of whether these new superimposed interfaces can successfully combine the advantages of physical media with the capabilities of computation, I devised a series of user experiments using Illuminating Clay. Subjects ranging in skill levels from novice to seasoned professional were asked to solve a discrete design problem, some using Illuminating Clay, some using the tools of current practice. I also observed a site-planning course that incorporated Illuminating Clay into a six-week-long project. Through these experiments, I was able to discern that Illuminating Clay can successfully combine the advantages of physical and digital media. The experiments also revealed significant issues regarding the design of superimposed interfaces: what the appropriate scale limitations should be, what the appropriate type of feedback is from computation, and whether real-time feedback is necessary.

1.15 Summary

Physical media and digital media both contribute valuable qualities to a creative design process. If we can better understand what those qualities are, when and why designers choose to work with each medium, and how it supports their design process, then we will be better able to design new interfaces that support creative human activity.

1.16 How This Thesis Is Organized

In Chapter 2, **The Practice,** a typical landscape design process is examined to discover when and how physical and digital media are used in current practice. From this examination, it is evident that the qualities of each medium determine how that medium is best applied.

In Chapter 3, **A Medium of Expression,** *medium* is defined as a combination of properties, usability, and appeal.

In Chapter 4, **The Qualities of Physical Media Compared with the Digital Medium,** qualities of physical and digital media are compared from the perspective of the designer.

In Chapter 5, **The Experience of Physical Media,** the experience of using physical media is described from the perspective of the designer.

In Chapter 6, **Superimposing,** the hypothesis of superimposing physical media and computation is presented. Because ideas for new tools can be gleaned by noting how users bootstrap existing tools, some observations on this are presented. Suggestions are made as to what is important to consider in future design tools.

In Chapter 7, **Related Prototypes,** prototype projects are reviewed that have a correlation to superimposed interfaces.

In Chapter 8, **Experiments with a New Prototype—Illuminating Clay,** how the experiments were devised is explained.

In Chapter 9, **Findings from the Experiments,** protocols from the experiments are presented as summaries and analyses. Findings encompassing all the protocols are then presented.

In Chapter 10, **Conclusions,** findings are summarized, issues raised by this research are discussed, and proposals for future work are made.

Chapter 2:

The Practice: Vision vs. Reality

Figure 1. ARK2, a computer drawing system, 1972.

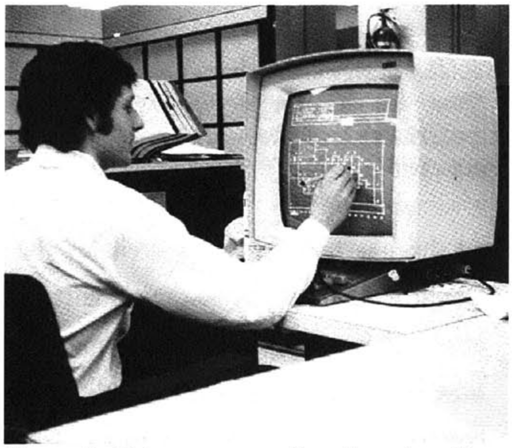


Figure 2. Using a space allocation algorithm.

2.1 The Vision: An All-Virtual Work Environment

Imagine a room, clean and clutter-free. Specialized tables hold monitors and keyboards, as large CPUs hum off to the side, filling the room with the constant whirring of fans. Shades filter out most of the natural light so that the designers can see the CRT screens at which they work. They sit, using electronic styluses to draw directly on the screen or on electronic tablets.

This early 1970's vision describes an all-virtual work environment for the architect of the future. He or she would draw with an electronic stylus on a CRT screen or tablet, eliminating the need for pencil, pen, paper, or physical mockups of any kind. This paradigm was set into motion in 1963 by computer graphics pioneer Ivan Sutherland. His seminal prototype, Sketchpad, was a computer-aided mechanical engineering drawing system that introduced the idea of virtual paper and pencil; it was the first GUI. The significant advantage of such a system was that the drawing was not just "dirty marks on paper," as Sutherland [1] referred to them, but a set of coordinates that could be saved, scaled, edited, and reused an infinite number of times.

Many CAD researchers and developers believed that computers would liberate designers from the restrictions of dumb, slow, physical media. Computers might even act as intelligent design assistants. At one end of the spectrum were those suggesting that "a symbiosis of designer and computer" [2] will someday be achieved, or even that "designing machines" might someday replace the need for architects altogether. Sutherland was more practical in his viewpoint:

> *... the designer of the future will be able to derive much more complete information from his design decisions. Information concerning cost, delivery schedule of materials, and the adequacy and appearance of the design will all be more easily accessible [3].*

At the heart of CAD research lay the problem of understanding the design process. Could it be demystified, systematized, and codified? Influenced by Simon's work in artificial intelligence and information processing [4], the dominant thinking at the time was that design was a highly visual and conceptual activity, and not particularly connected to our bodies or to tactile/spatial interaction with tools and materials.

Those enthralled by the new technology suggested that automating the design process with computer applications would liberate the designer from "distracting and unproductive activities," such as searching for appropriate references or building physical models, and thus allow more time for pure design [5]. These early adopters also tended to label those who were skeptical of the new tools as "stodgy" and "old-fashioned." But often the skepticism emerged after large investments of effort to develop and apply these new tools to real projects, as an early developer found:

> *Writing programs of value to architects is much more difficult than people expected.... It turns out that things toward the end of the process are fairly easy to "computerize": construction schedules, CPM.... Things in the middle of the process are a bit more difficult: automated floor-plan layout, interactive computer graphics.... At the beginning of the design process, things are in chaos [6].*

Some who became skeptical even questioned the dominant assumptions about the designer and the design process:

> *The notion that the designer is wasting time while doing repetitive or noncreative tasks (like drafting details) is potentially very damaging.... I suspect that while the designer is performing a task automatically (without concentrating on it), something else quite valuable is happening in his subconscious; he may be getting prepared to consider the forthcoming problem [7].*

What have the last 30 years of development and practice with CAD revealed about the all-virtual vision of the future?

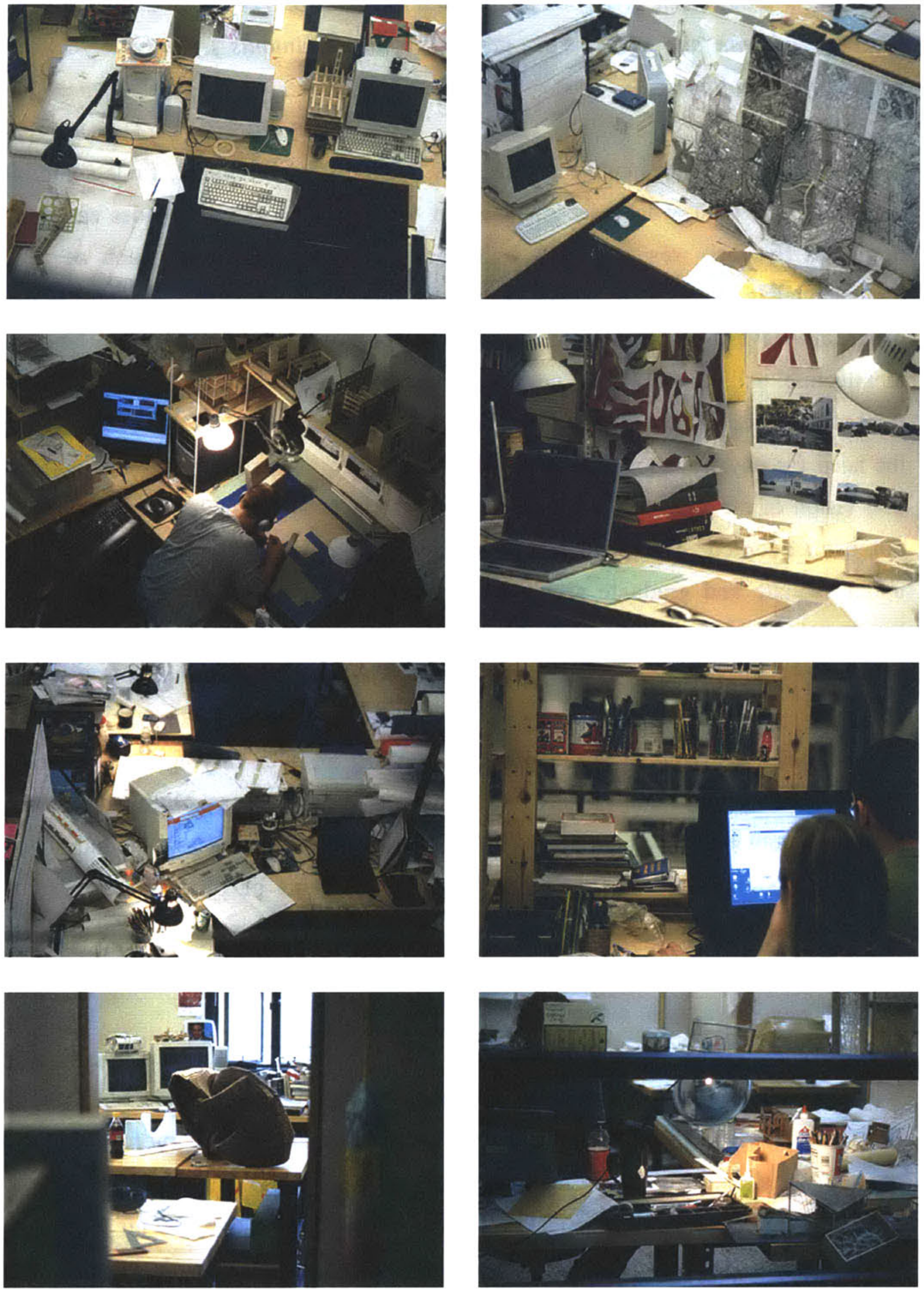


Figure 3. Architecture and landscape architecture students and professionals at work, 2002-03.

2.2 The Reality: Side-by-Side

A cluttered desk holds a laptop computer sitting next to several layers of drawings and models made from Styrofoam, clay, and cardboard. The walls next to the table are covered with site maps, trace-paper sketches, printouts from CAD files, and photographic collages.

In 2003, a visit to a designer's studio, such as that of an architect, finds something very different than what was imagined in research labs three decades earlier. As predicted by early research and developers, CAD environments such as three-dimensional modelers and renderers, image processors, and topographic analysis programs have become invaluable to the practice of architecture, landscape architecture, and planning. It is now inconceivable to do even small projects without the assistance of CAD software. Yet these software environments have not replaced the need for physical tools and materials such as pencils, paper, cardboard, and clay. The vision of the "paperless architect," or the completely "virtual design studio," has not been adopted. The persistence of that vision, however, is still evident, as undergraduate and graduate architecture students today express embarrassment at liking "old-fashioned" design media and at not having yet achieved "paperless design." [8]

Instead, what has evolved is the practice of using an ever-varying combination of digital software tools and physical media side-by-side. It is a solution that works because it provides designers access to both realms, the physical and digital, but it is not ideal, as explained in Chapter 1. First, the domains of physical drawings and models, and digital drawings and models, remain separate and can be crossed only by a tedious series of digitizing and printing processes. Second, the GUI is limiting as the designer's only access to computation.

Where do we go from here? Designers have not given up physical tools and materials. Does the all-virtual vision of the future of architecture require more time to be enacted? Or should we modify the vision of the virtual studio to let the physical world back in? What qualities do physical tools and materials have that are not replaceable by digital environments? A better understanding of when and why designers work in each realm, the digital and the physical, could shed light on these questions.

2.2.1 *When* Designers Use Specific Tools and Materials

When considering the use of digital vs. traditional tools, the design process of a typical landscape design firm might be something like the following [9] [10].

1. **Site Evaluation and Referencing.** Available documentation is examined, both physical and digital, including maps (topographic, GIS, aerial), history, zoning, and other regulatory requirements. Similar projects are referenced, and inherited data is utilized where needed.

2. **Concept Design.** Idiosyncratic methods of exposing creative possibilities are utilized, including frequent use of physical tools and materials, such as sketching with pencil on paper or "sketching" with three-dimensional clay models. Occasionally, software such as a parametric modeler is used for novel form-generation. Photography or image-processing software may be used to create two-dimensional collages to better understand an existing site or to propose new ideas.

3. **Schematic Design.** The most-promising design concepts are selected, and constraints such as drainage, zoning code, and the requirements of "best practice" are applied. These constraints may be applied in various ways: by eye, by hand, or by using analysis software. For instance, a digital model may be subjected to analysis software to evaluate topographic features such as slope, drainage, and sun/shade. The schematic design phase is characterized by the most-frequent interplay back and forth between physical and digital environments. Two-dimensional drawings may be printed from the CAD file and drawn upon, working directly on paper or, alternatively, modified directly within the virtual environment of the CAD software. Any refinements made on paper must be updated in the digital model by hand.

4. **Design Development.** Refined digital models are created from schematic designs, and far more details are added. CAD drawings are generated for engineers and other consultants to evaluate.

5. **Presentation.** Software tools used to generate two- and three-dimensional "prints" are often used to make attractive, information-rich presentations to collaborators and clients in order to gain consensus on a design and/or approval from clients. Physical drawings and models—whether created by hand or by outputting digital files—more fully communicate the design to all parties involved.

6. **Contract Documents.** The CAD files are finalized and printed to create construction drawings for use by contractors and permitting authorities. These files define the relationships between architectural design, construction systems, mechanical/electrical/plumbing systems, and regulatory requirements. Changes and corrections continue to be made to the CAD files throughout the construction process.

The interplay between physical and digital techniques described in the design process above is not unique to landscape architects. Consider the office of internationally renowned architect Frank Gehry, where the team's process follows a similar scenario. Physical models are used for design exploration and development. At a certain point, these models are digitized, and design development continues in CATIA, a sophisticated surface three-dimensional modeling software. New physical models, possessing progressively more detail, are periodically produced from the CATIA data by a milling process. These models are used for evaluation and further design development.

In another example, the head of design at Fiat motor vehicles, Michael Robinson, spends much of his time in the company's "virtual room" reviewing CAD models blown up to wall-size proportions. Throughout the design process, however, precise physical clay models are constructed for reference and presentation. As the last step before sending CAD drawings off to create a full-scale prototype, a physical model is milled from the CAD model, and designers use their hands to search for flaws in the CAD model. "It is the only way to know if it's right," says Robinson [11].

A peek into cutting-edge design schools, such as Harvard's Graduate School of Design, MIT's School of Architecture, and the MIT Media Lab, should be enough to convince anyone that physical materials still play an important role in the creative process. Amid scores of computers and the latest prototype tools, students continue to produce a myriad of cardboard, Styrofoam, clay, and even Lego models.

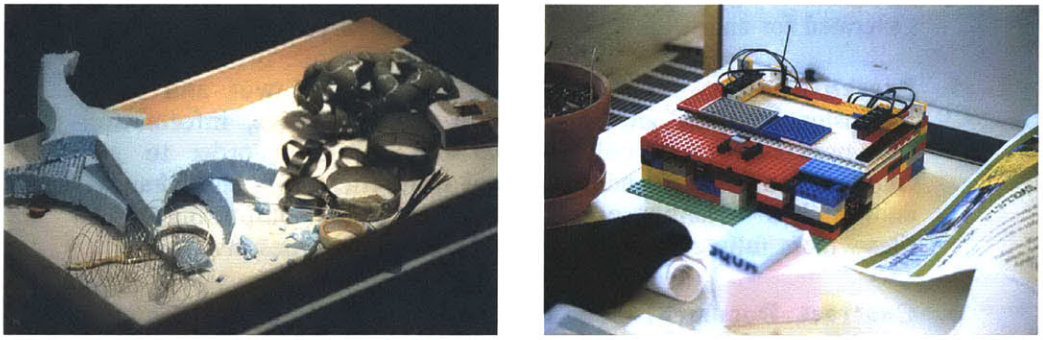


Figure 4. Models in progress at the Harvard GSD and the MIT Media Lab.

So far, we can extrapolate that the following practices are typical for architects:

1. Early design phases incorporate sketching on paper or with physical three-dimensional models.
2. When sufficiently developed, design ideas are converted to digital form via digital scanning or by re-creating the design digitally.
3. Once in digital form, analyses are performed on the model.
4. Based on the results of analysis, modifications are made to the digital model. If changes are substantial, work may go back to physical materials, with conversion to digital form recurring at a later date.
5. Presentation drawings and a model of the final design proposal are created and communicated to clients and other concerned parties.
6. Construction documents are derived from the CAD files.

2.2.2 *Why* Designers Choose Specific Tools and Materials

Digital design tools have proved to be particularly effective at certain tasks and at certain steps of the landscape design process. CAD software, such as AutoCAD, Form-Z, and Microstation, allows for the creation of digital three-dimensional models that can be flexibly applied to many purposes. They can be used to create drawings of multiple views of a proposed site design. They can be used in combination with analysis software to evaluate slope, drainage, sun/shade, and so forth more quickly and thoroughly than can be done by hand. CAD models can be modified and corrected and can contain an enormous amount of detail. They provide a highly accurate and complete set of working drawings for use in implementing a design. (CAD drawings can even be used to drive robotic earthmovers.) Thus, analysis and implementation tasks have benefited the most from digital tools.

Computer-based models, though limited to being two-dimensional visual representations of three-dimensional space, offer many advantages over physical models. They offer the ability to work directly with numeric data and at accuracies that far surpass the tolerances of most physical models. They offer a vast increase in the efficiency of correction, reproduction, and distribution of construction documents. And they can be used as data for analysis software that can represent entities or forces that change over time.

By contrast, software tools are noticeably absent from the beginning phases of the design process, where most of the idea generation, or creativity, happens. Although some designers utilize CAD software such as parametric modelers for idea generation, physical environments such as paper, pencil, clay, and cardboard are more common. The explanation may be that sketching is highly important at early design phases and is not adequately supported by CAD software. CAD and other computer systems are designed to produce precisely accurate drawings that minimize ambiguity in representation. Allowing for only a single interpretation reduces the risk of errors when these representations are used for building or manufacturing specifications.

2.2.3 Best Practice

This examination reveals that the tools, materials, and processes designers use are not arbitrary choices. How best to apply specific tools to a design practice is something that evolves over time through experience and communication with peers. The notion of "best practice" may embody designers' use of tried-and-true professional methods and resources, appropriate and effective technology, and historically successful solutions.

The above description of the landscape design process can be analyzed to extrapolate this skeletal framework of general design processes:

1. understanding the problem
2. generating ideas
3. roughing out solutions
4. progressively refining solutions
5. finalizing a solution

The landscape design process, like much creative design, proceeds as a series of trial-and-error steps from the abstract, haphazard, and unorganized to the specific, deliberate, and organized. Real-world constraints—which in landscape design include weather, zoning ordinances, environmental law, citizen/neighborhood concerns, and budget and market conditions—impact the process of idea generation and aesthetics. The skeletal design framework continues to function regardless of which tools or materials designers select. However, the framework demands particular qualities from available tools or materials, and new tools must find a place in this fundamental structure in order to be adopted. Designers have found advantageous and appropriate applications for CAD as it exists in its present form.

The human-computer interface profession uses the adage "the user is always right," meaning that if a tool or interface to a tool isn't usable for someone, then it is the fault of the tool or interface, not the person [12]. This adage supports the validity of best practice, which evolves from the collective experiences of the architecture community. Advocates for the adoption of new computer tools often suggest that designers are resistant to change and not innovative enough to incorporate CAD into their early design processes. Some have assumed that once a generation of designers becomes fluent with computers from a young age, they will fully adopt computer as design tools and discard the use of physical media. The evidence suggests otherwise. I believe that the problem of not utilizing computers in all the design phased lies *not* with humans but in the design of the tools themselves.

2.3 Summary

The original vision early developers had in the 1970s of CAD was of an all-virtual work environment. By examining current practice, it is evident that CAD, although universally adopted for some purposes, has not replaced the need for physical media in the design process. Instead, it has been added into the mix of physical tools and materials, and each medium is applied where it is most advantageous to the design process. This has, however, created the problem of converting back and forth between physical and digital representations. More fundamentally, the GUI is limiting because it lacks tactile feedback and spatiality. A deeper understanding of the nature of each realm, the physical and digital, would help to clarify how to remedy these shortcomings.

Chapter 3:

A Medium of Expression

Computer technology can act like a tool, but it is also a medium of expression—the digital medium. Now, I define *medium* and put the digital medium within the larger context of all media.

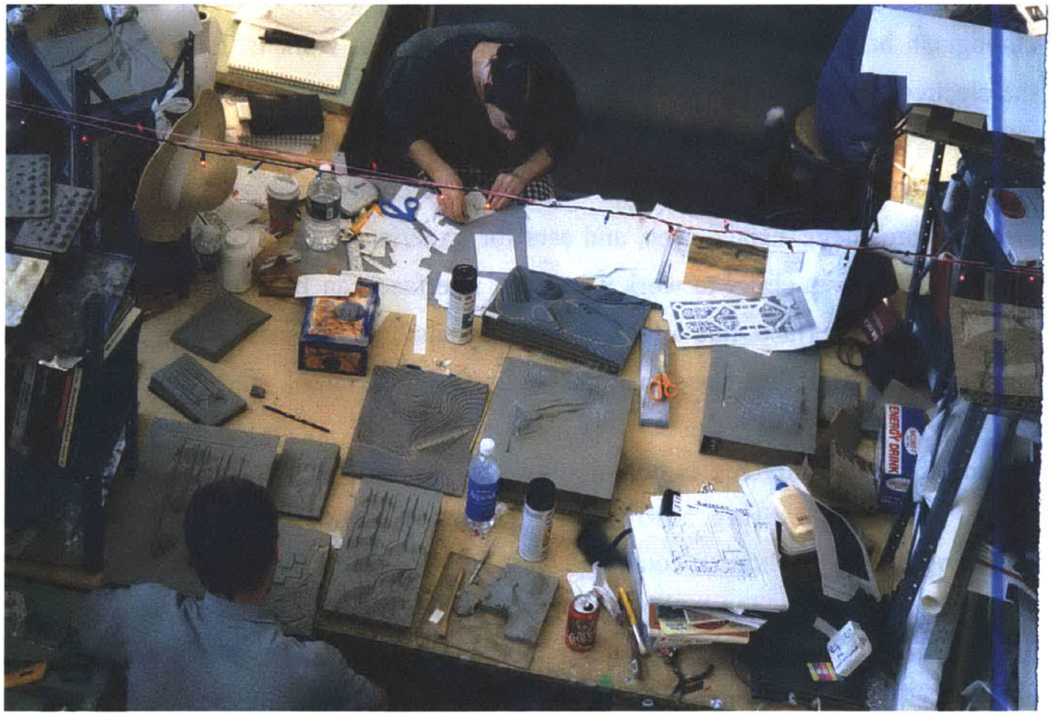


Figure 5. Students making clay models at the Harvard Graduate School of Design.

3.1 Defining a Medium

What defines a medium? A medium is an intervening substance through which a force acts, and, more specifically, is the material or technique with which an artist works. "To give work substance, we require a medium." [1] A medium can be a raw material, like clay, although generally *medium* refers to a raw material and the tools and instruments necessary to work the raw material. Ceramics is a medium, including the tools and raw materials it encompasses—kilns, molds, wheels, various hand tools, glazes, and clay. A medium can be an end in itself, as when a ceramicist creates a sculpture directly in clay. Or a medium can be used as part of a design process, as when a landscape architect creates a clay model of a proposed design. In this case, the "design" will ultimately be built or fabricated in other materials, at a much larger size.

A medium need not be static like clay. Music, dance, and theater are examples of time-based media. They must be experienced over a period of time and are often preserved as annotation or recordings. A raw material need not be visible, tactile, or aural. The digital medium has no sensory effect on us *except* what is designed into the interface. It cannot be experienced and worked in the same way that clay or wood can be without the intervening aid of technology. In such cases, it is difficult to distinguish between the raw material and the tools that work it. Is the raw material the electronic signal or the bits?

How do designers "get their hands on" bits? The computer interface can be thought of as the prosthetic hands, eyes, and ears for experiencing bits. Or, in the same way that an artist uses a chisel to work wood, the interface can be thought of as a tool to work bits. An interface, like a tool, deeply impacts how the artist works—a chain saw has a different effect on wood than does a finely honed chisel.

The need for an interface is common to all electronic media, including video and audio recording/editing. However, the capabilities of video and audio recording/editing are limited compared with the capability of a computer; each of the former has essentially one capability, or output, whereas the capability of a computer is multifaceted. An interface for video or audio production is prescribed by the clearly delineated framework of the technology itself. A computer interface is not prescribed. Although limited by current technology, the interface is a point of innovative experimentation.

CAD is often referred to as a tool. A tool increases efficiency. A medium allows an idea or feeling to be manifested. CAD clearly acts as a good tool, increasing the efficiency of analysis and drafting immensely. But CAD also can be considered a medium—a part of the digital medium—because it enables the manifestation of ideas.

What differentiates a good medium from a mediocre or bad one? One way to determine this is to evaluate how well the medium fulfills its primary role of providing scaffolding on which to build ideas and expression. How well does the scaffolding support and foster the developmental process as well as the final expressive result? A medium's strength lies in its ability to enable the making of representations. The fundamental properties of a medium determine what types of representations can be created with it.

3.1.1 Properties

The properties of a medium frame the designer's approach to a creative task and influence the efficiency and ultimate success of that task. Through the choice of a medium, the designer implicitly establishes a "world" populated with a particular shape vocabulary, or "tokens." Mitchell suggests:

> *A drawing board and traditional drafting instruments, for example, establish a Euclidean design world populated by two kinds of graphic tokens—straight lines and circular arcs—that can vary in size and position and be related to each other as parallels, perpendiculars, and so on. A designer toying with a cardboard working model enters a design world populated by plane polygons that can be shaped in different ways and translated and rotated in three-dimensional space. Designers shaping clay with their fingers, or cutting polystyrene blocks with hot wires, enter yet other kinds of design worlds [2].*

If tokens are the primitive elements out of which representations can be assembled, then operators are tools for manipulating elements. Tokens and operators fundamentally characterize a medium. For example, in a design world of paper with drawn straight lines and arcs, the basic operators might be a pencil, an eraser, a straightedge, and compasses. In a design world of cardboard polygons, the basic operators might be a matte knife for shaping polygons, hands for translating and rotating polygons, and a glue gun for joining polygons together. In a CAD system, the operators are algorithms that manipulate the data structure, which mathematically defines tokens [3].

Selection of a medium, which implies the primitives and operators for a design world, establishes a "domain of formal possibilities" for a designer to explore [4]. He or she should be concerned that the domain is appropriate to the task at hand. For example, if the intention is to explore different possibilities of a three-dimensional form that is curvilinear and free-form, it would be senseless to work with rectilinear wooden blocks.

The properties of a medium are only part of what defines it. Usability fundamentally affects what can be done with a medium.

3.1.2 Usability

Each medium has it own particular affordances (what it can do) and constraints (what it can't do). "Every physical material has tolerances within which it is workable and outside of which it breaks down." [5] Clay can be shaped only to a certain degree of thinness before it collapses under its own weight. An unconstrained medium would have little identity and would offer little resistance and challenge. It is often the constraints that inspire creative solutions. We may ask, "What can this medium do?" A medium has versatility and density, allowing us to shape it into multiple states. The multiplicity of states creates a continuum of process. A medium can immerse us in all its various states [6].

With the ephemeral digital medium, bits can be infinitely reconfigured, but the software and hardware define what one can actually do with the bits. A program encompasses only one slice of the many possibilities enabled by computation. For example, a word processor allows text editing but not the ability to make measured drawings. Therefore, although computation is a dense and versatile medium, the software and the interface both afford and constrain our access to it.

Resnick [7] asked, "Would you rather have your child play the piano or play the stereo?" This question concretely highlights how an instrument or interface influences access to a medium. The piano has versatility and density; one can create an unlimited number of compositions utilizing individual notes modified by nuances of speed, pressure, and duration. Within certain constraints, the piano has seemingly infinite possibilities. On the other hand, a stereo can play back prerecorded compositions with limited nuances of volume, timber, and equalization. Its sound-making possibilities and opportunities for creativity are very limited in comparison to a piano.

Learning to work with a physical medium is primarily a process of discovery, a process that is usually pleasurable. It is easy, even fun, to "mess with" a medium, especially if one has no particular goal. Most physical media don't require a manual for use. Instead, the experience of working the medium, watching someone else work it, and seeing previous results of working it tends to be a larger part of the learning process. In the case of electronic media, which may involve hardware or software with standard button or GUI interfaces, a manual is often required. The simple logic of cause and effect in the physical world is not obvious here.

It may not be just the satisfaction of gaining skill, solving a problem, or making artifacts that makes working with a medium satisfying. The repetition of an activity, the physical or mental exercise of it, and the losing of oneself in a process where the unconscious becomes the guide are all pleasurable. Pleasure and challenge go hand in hand:

> *Contrary to what we usually believe...the best moments in our lives are not the passive, receptive, relaxing times—although such experiences can also be enjoyable if we have worked hard to attain them. The best moments usually occur when a person's body or mind is stretched to its limits in a voluntary effort to accomplish something difficult and worthwhile [8].*

3.1.3 Appeal

Designers choose a particular medium of expression to work with not only based on what they can do with it, matching their particular needs with the properties of a medium, but also based on what a medium inspires by its sensory appeal. The senses play a large role in our relationship to a medium, at least in the case of a physical medium. We are initially attracted to a medium because it has a pleasurable effect on our senses. We are drawn by a certain texture, weight, temperature, odor, sound, or color.

Through our senses, a medium can stimulate our imagination. The potential thing we might create excites us, or we simply enjoy the process of handling it [9]. A physical medium invokes the pure pleasure of interacting with the physical world. Clay, for instance, has tremendous tactile appeal. Depending on its density and chemistry, it can feel like cool flesh or warm dough. But few physical media address just one sense. Clay makes a dull thud when you drop it or a detectable squish when you knead it.

Natural clay smells deliciously of damp earth and has a palette of subtle browns and grays. Sculpey and Play-Doh come in bright primary and neon colors.

Computer interfaces, which are our only experience of the digital medium, typically have low sensory appeal compared with most physical media. One sense, the visual, is emphasized. The vivid, glowing screen is highly seductive, with complex, hyper-real visualizations that can include movement and color. Digital sound, whether connected to visualizations or by itself, can be equally attractive. The digital medium can produce unique new sounds, in structural combinations not limited or delineated by physical instruments and players.

Although bits, which are the raw material of this new medium, are invisible, silent, odorless, tasteless, and intangible, the attractiveness of the digital medium is enormous. This is probably because beauty is a conceptual as well as a sensory experience. An electronic medium is attractive for its power, speed, and ability to transcend the limitations of the physical world [10].

3.2 Choosing a Medium

Because the properties of a medium frame, or affect, how a task is approached, and influence its efficiency and success, choosing an appropriate medium for a task is important. Designers must seek a medium that enables them to create the type of representations they desire. In the case of fine art, the medium may drive the task. But the qualities of the medium itself often attract and inspire the designer and draw him or her into a relationship. The designer must, in a sense, fall in love with a medium in order to be motivated to practice with it and gain the necessary skill or virtuosity to do deep creative work. A commitment, or at times even an obsession, may be formed with a medium, which sustains the need to practice, thereby developing increasing skill and technique, until a medium becomes “transparent” to the designer’s voice.

3.3 Becoming Skilled with a Medium

From practice, we draw satisfaction in finding that we acquire skill at manipulating a medium. Hand-eye coordination, muscle control, and timing are important factors in skill. “The meeting of tool and medium provides a locus for skills.” [11] Skill is the acquired ability to do something well. While we are gaining skill, we develop technique. Technique is the manner by which a person fulfills the technical requirements of his or her particular art or field of endeavor. When we become exceptionally good at working a medium, we are called a virtuoso. Over time, virtuosity propels the refinement of tools for working a medium, as can be seen in the design of musical instruments. “The development of technique for technique’s sake is also responsible for improvements in instrument-making, which steadily seeks increased sonority, suppleness, volubility, and color.” [12]

With physical media, manual dexterity plays a large role in the pursuit of skill and virtuosity. A better understanding of human manual skill acquisition may inspire greater appreciation of human adaptation to interacting with the physical world.

3.3.1 Manual Skill

We learn to manipulate the objects in our environment by understanding the relationship between our actions (in the form of efferent—motor—commands sent to the muscles and joints) and the perceived reaction of manipulated objects (in the form of afferent—sensory—feedback from our sense organs). A rich sensory environment that addresses all our sense organs simultaneously provides a broad spectrum of information for our sensorimotor systems to utilize.

When we first encounter a new tool, for example, we are very aware of its size, shape, weight, texture, and so forth. As we become proficient users of that tool, these aspects recede from our awareness, and the tool becomes an extension of our body. We have learned how the tool will behave and can predict its response for a given action. Loomis describes this learning process as “modeling the linkage” between efferent commands and afferent feedback from the tool [13]. He suggests that our ability to project our apparent interface with the environment beyond the bounds of our body to the end of a tool is most likely to occur when our sensory inputs (afference) are lawfully related to our motor outputs (efference).

It is our recognition of this lawful relationship, often contingent on similar past experience, that promotes the recognition of the object’s identity and external location, or our ability to regard the tool as an extension of our own body. This occurrence represents a robust internal representation of the relationship between *action on* and *reaction of* an object being manipulated. It can also be considered a measure of skill. This representation might not be cognitive or even accessible to conscious awareness, but the individual can eventually reach a point where the linkage and the extension are "transparent."

Common to many theories of manual skill acquisition is the concept first proposed by Bryan and Harter of progression through stages of learning to higher orders of skill [14]. Bryan and Harter observed the process that would later be called "chunking." Chunking was first observed as a way of extending the capacity of short-term memory by grouping "like" elements of information into meta-elements [15]. Chunking also operates on the output from the motor system, combining multiple component movements that together execute an action into one chunk, or "motor program." [16]

Motor programs serve two important functions. First, they allow for the execution of actions that occur too close together to be processed individually by our sensorimotor response system. Second, they allow for levels of supervisory control, freeing up our central processing system for other work. Hence, we are able to eat lunch and read the paper simultaneously.

These mechanisms, modeling the linkage and chunking, come into play as we learn to use computer interfaces. GUIs use direct manipulation in an attempt to capitalize on the human sensorimotor system. Contrast the clicking of a mouse with a barely detectable twitch of one or two fingers to the modeling of clay with hands, arms, and upper-body involvement. Stripping off the nuance of physical control that one has in the physical world greatly reduces the opportunity to develop manual skill and technique. And with complex software like three-dimensional modelers, users are still often left with cognitive overload, as they try to remember names and numbers.

3.4 Summary

To find reasonable solutions to the shortcomings of CAD, it is helpful to understand that computer technology does not simply afford new tools but that computers are also a new medium of expression—the digital medium.

Any medium can be defined by these three characteristics:

1. Properties: The tokens and operators that determine its appropriateness for a task, influencing efficiency and success.
2. Usability: The affordances and constraints that determine the its limits of workability.
3. Appeal: The pleasure of working it, which includes tactile, visual, aural, and olfactory feedback and contributes to level of engagement, motivation, and inspiration.

How can we develop interfaces that facilitate our connection to the computer as a digital medium of expression, thus enabling us to reach a new level of creative design by tapping simultaneously into our deeply rooted physical intuition, while being connected to the infinitely flexible computation power of the machine?

Chapter 4:

Qualities of Physical Media Compared with Digital Media

In Chapter 3, I defined a medium as a combination of properties, usability, and appeal. The properties of a medium establish a "world" populated with a particular shape vocabulary (or elements) and tools (or operators) to manipulate those elements. The usability of a medium is determined by its capabilities and limitations. The appeal of a medium influences the designer's level of engagement and contributes to pleasure, inspiration, and motivation. In sum, a medium is a combination of the following traits:

Properties (primitive elements and operators)
Usability (affordances and constraints)
Appeal (sensory and conceptual attractiveness)

However, when a designer works with a medium, he or she does not tend to analyze it into component parts, as in the definition above. Rather, the designer recognizes certain *qualities,* which stand out as particularly unique, appealing, or advantageous in the design process. It is this qualitative experience, gained over time from working with a medium, that helps the designer to ultimately choose how and when to best use a particular medium. This kind of perception identifies what might be a small capability such as "undo" in the digital realm, or an invisible capability such as tactile feedback in the physical realm, and recognizes or the tremendous impact it may have on a design process.

4.1 Qualities

4.1.1 Physical Media

Not many people today are discussing the qualities of physical media to the degree that computers and the digital medium are touted. As described in Chapter 1, the advent of computers has demoted the status of physical media for the past few decades to "old-fashioned" or "legacy." One must look several decades earlier, when the demise of handicraft to mechanized manufacturing inspired contemplative texts on the process of working with materials by hand. Focillon wrote in the 1930s:

> *The hand knows that an object has physical bulk, that it is smooth or rough.... The hand's action defines the cavity of space and the fullness of the objects which occupy it. Surface, volume, density, and weight are not optical phenomenon. Man first learned about them between his fingers and the hollow of his palm [1].*

This reference not only brings attention to the material aspects of physical media such as surface, volume, density, and weight, but also emphasizes the importance of the tactile sense in the process of physical form-making. In fact, the most-powerful qualities of physical media may be their direct correlation to our senses; correspondingly, our senses have evolved to allow us to thrive in the physical, material world.

With Focillon's help, below is my first take on the qualities of physical media, followed by my second take, where I regrouped elements to eliminate redundancies:

Physical media	**Regrouped**
tactile	tactile (texture, density, weight, surface, volume, temperature)
visual	visual (texture, surface, volume, color)
aural	aural (sound)
olfactory	olfactory (odor)
spatial	spatial
ambiguous	ambiguous
persistent	persistent
textured	
dense	
have weight	
have surface	
have volume	
have temperature	
have color	
make sound	
have odor	

This reorganization could have taken another approach, grouping the senses within the material properties such as "surface (tactile and visual)" or "color (visual)." However, these properties do not stand alone as clearly as the senses do. In other words, in the physical world touch can exist without vision, but a surface cannot exist without volume, and a color cannot exist without a surface? However, I kept "spatial" as a separate quality even though it could be considered part of "tactile" and "visual," because it is such a significant advantage of physical media over the digital.

4.1.2 Digital Media

Although I use the term *digital media*, which is a broad term, I am using it here in the context of architecture, so I am really thinking about current CAD systems instead of all things that could be considered digital media. A casual gathering of digital media qualities from some articulate proponents rendered this first list, which I then regrouped into the second list:

Digital media	**Regrouped**
(Sutherland)	
structured	intelligent (structured, procedural, multimedia)
precise	precise
scalable	transformable (scalable)
(Mitchell)	
copyable	copyable (nondegradable)
reworkable	reworkable, undoable (nondegradable)
undoable	
(Negroponte)	
compressible	portable (compressible)
nondegradable	
multimedia	
(Holtzman)	
real-time	fast, *real-time (moved to physical media)*
ephemeral	ephemeral
(Murray)	
procedural	
(others that I added)	
fast	
portable	
transformable	
visual	visual
aural	aural

Sorting out the redundancies from the first list of digital media qualities was more difficult than sorting the list of physical media qualities. The complexity of the technology, its rate of evolution, and the need for an interface all make it more difficult to catagorize. Below I explain some of my thinking.

Intelligent (structured, procedural, multimedia)

Of interest to architects is the ability to create three-dimensional drawings or digital models and then transform them in various ways. These models are dependent upon computers having the capacity to store numbers and perform procedures on those numbers. Sutherland [2] called drawings derived from data "structured." Murray [3] describes computer environments as inherently "procedural," meaning the computers can execute a series of rules, as when a digital model is scaled or otherwise transformed. Negroponte [4] defines *multimedia* a "commingling of bits," or different media—print, photography, video, animation—sharing a similar storage format. I struggled to find a term that encompasses these capabilities, which all have to do with the common issue of data storage and processing. "Intelligent" may seem to overstate what these capabilities encompass, but no other term is as accurate.

Transformable (scalable)

The term *scalable* does not encompass all the transformations possible with digital representations, which could include such operations as curving straight lines or extruding a two-dimensional shape to three-dimensions. So, I thought of "scalable" as one aspect of "transformable."

Copyable (nondegradable) and Reworkable (undoable, nondegradable)

Copy and Undo are advantageous functions of digital media compared to physical media. The ability to make perfect copies of digital files and the ability to undo a procedure on a file is achieved by the system progressively saving a copy of the previous version. The nondegradable quality of bits when they are copied makes these capabilities possible. Therefore, I considered "nondegradable" as an aspect of both "copyable" and "reworkable." I considered "undoable" as an aspect of "reworkable" because the infinite reworkability of the digital medium is achieved, not just by the Undo function in software, but by the metaphorical undo capability at any level of a digital process by retrieving previously saved files.

Portable (compressible)

Portable can be taken in a relative sense to describe current hardware, which is much smaller and thus more portable than previous generations of hardware. It can also refer to the data—bits—which are inherently small and are compressible by removing redundancies. So, I considered "compressible" as an aspect of "portable."

Fast and Real-time

Computers are faster than humans at numerical calculation. Computers are also faster at reshaping and rescaling digital models than humans are at reshaping and rescaling physical drawings or models. However, using a computer requires a great deal of waiting time to start up, open and process files, connect to networks, print, digitize, and so forth, making computers perceptually slower than physical media in many cases. When computers are described as "real-time," they are behaving at the speed of the real, physical world (which means they are actually processing data very fast). Physical media is inherently real-time, while digital media is perceptually real-time sometimes. They also sometimes seem faster than real-time, and at other times, slower than real-time. Thus, I placed "real-time" on the list of physical media qualities.

4.1.3 Comparisons

PHYSICAL MEDIA	DIGITAL MEDIA
tactile	nontactile
visual	2-D visual
aural	recorded, synthesized aural
olfactory	nonolfactory
spatial	representative of space
ambiguous	explicit
physically transformable	logically transformable
persistent	ephemeral
real-time	faster than real-time
not intelligent	intelligent
inexact	precise
moderately copyable	infinitely copyable
moderately reworkable	infinitely reworkable
physically portable	electronically transferable

Next, I attempted to correlate the lists of physical and digital qualities (shown above). Some qualities on the lists were the same. For example, both lists had "visual" and "aural." Three qualities of digital media were also true enough of physical media to be added to that list: copyable, reworkable, and portable. I added more-descriptive words to distinguish between, for example, the physical "moderately reworkable" and the digital "infinitely reworkable." Some qualities on the lists corresponded well, not necessarily as opposites but as related, such as "real-time" and "fast." Some had no correspondence, resulting in my adding new, negative qualities to each list to complete the correlation. For example, digital media is simply "nonolfactory" compared to physical media.

Because I was interested in determining the desirable qualities of each realm, having negative qualities served no purpose, so I eliminated them (shown below).

PHYSICAL MEDIA	DIGITAL MEDIA
tactile	
visual	2-D visual
aural	recorded, synthesized aural
olfactory	
spatial	representative of space
ambiguous	explicit
physically transformable	logically transformable
persistent	ephemeral
real-time	faster than real-time
	intelligent
	precise
moderately copyable	infinitely copyable
moderately reworkable	infinitely reworkable
physically portable	electronically transferable

I then created a table (Table 1) with one column of all the qualities, and two columns where I could rate each quality within the physical and digital realms as present (+) or not present (–). Because qualities can be present but in a lesser form, I also used an in-between rating (0).

Qualities	**Physical**	**Digital**
tactile	+	-
olfactory	+	-
spatial	+	-
ambiguous	+	-
persistent	+	-
real-time	+	0
physically transformable	+	-
logically transformable	-	+
ephemeral	-	+
explicit	0	+
representative of space	0	+
fast	0	+
intelligent	-	+
precise	0	+
visual	+	+
aural	+	+
reworkable	0	+
copyable	0	+
portable	0	+
(totals balance out)	6	6

Table 1: Qualities of physical and digital media, each rated as present (+), not present (-), or in between (0).

4.2 The Qualities Discussed

4.2.1 Tactile

Place a ball of clay in front of just about anyone, young or old, and they will soon begin to knead it. It is irresistible, as are many physical media. Clay, wood, paper, stone, paint—all are appealing, intriguing, and satisfying to touch. We get pleasure from touching things. Touch is the oldest sense and the most important one psychologically. As stated earlier, it is so crucial that if we didn't enjoy touching and being touched, we would probably never reproduce, and our species would die out. We have touch receptors all over our body, although in some parts they are more dense. Hands and fingertips, in particular, have some of the most sensitivity [5].

Manipulating a physical medium by hand enables us to determine its malleability, weight, temperature, and tolerances for stability. With practice, we can develop motor skills specific to that medium, which enables us to become more facile with it. The more facile we become with a medium, the more effortlessly we can work. Touch provides information to the brain so that we are able to manipulate objects in three-dimensional space [6]. The hand works in two ways: It can manipulate, and it can receive feedback. This two-way channel has direct bearing on our ability to develop motor control [7]. Adding vision and hearing to touch makes us efficient at understanding and manipulating objects in space.

Tactile input is said to be ten times more influential than verbal input is to the brain [8]. We can also feel things that we cannot see; a tiny sliver can often be felt with a fingertip even if it cannot be seen with the naked eye. Designers use the sensitivity of touch unconsciously. They often begin a drawing by quickly running their hands over the surface, smoothing but also determining the "tooth" and hardness or softness of the paper. Designers also use the sense of touch to manipulate and orient tools and materials, to better understand by tracing with their fingers, and to gesture at drawings and models or in space.

The digital medium has no inherent tactile qualities beyond what the interface provides. Most architects use CAD with a standard GUI with a keyboard and mouse. Adding virtual tactile properties to GUIs has proved to be complex and expensive. The hardware necessary to synthesize tactile feedback often utilizes tiny sensors and mechanical parts. So far, these prototype systems lack verisimilitude, feeling mechanical because they have limited feedback compared to real, physical feedback [9]. Although satisfactory solutions may eventually be developed, virtual tactility may be desirable only when size, as in computer-assisted surgery, or distance, as in space exploration, require it.

Efficiency for understanding and manipulating forms in three-dimensional space is diminished without the tactile component in a CAD environment. This can add cognitive overload, as the user attempts to process objects in space through a single sense-channel, the visual. Also lost is a sense of weight, material, and surface texture, although these may not be important to a digital model where the form itself is primary and the material or texture can be unspecified. But also missing is the pleasure that is normally derived from touching physical materials and textures.

Physical tools and materials enable two-handed interaction, compared with a GUI where much of the activity of drawing is strictly one-handed (and one task at a time). With the GUI, even though one hand is needed to activate function keys while the other is using the mouse, the kind of interaction where both hands perform continuous tasks in concert does not exist. Two hands working together can perform the same activity simultaneously, such as mold clay. Two hands can also work asynchronously, such as one holding a ruler and the other marking with a pencil. Buxton asserts that "GUIs can be greatly improved through incorporation of this class of input." [10]

4.2.2 Visual

Vision has been called the most important sense for modern humans, because vision is the sense most related to alphabetic culture and abstract thinking [11]. Print media has dominated Western culture for centuries. Developing and communicating ideas, particularly in science, requires text explanations supported by visualizations such as diagrams, charts, and graphs.

Vision can also illicit visceral responses. Certain kinds of visual stimulus related to color, symmetry, and light produce universally pleasurable responses in humans [12]. These responses are the basis for the visual appeal of natural landscapes, animals, and other humans. Physical media are visually appealing on many levels, not only because of color and texture but also because of other qualities such as transparency, opacity, and the ability of many materials to capture and transform light.

Vision also provides information that is basic to everyday functioning. Alone or in combination with hearing, vision allows us to detect things at a distance. Vision, touch, and hearing work hand in hand to enable us to excel at understanding and manipulating objects in three-dimensional space. Focus and peripheral vision are qualities of vision that are useful in survival but are also of value to the creative process of design. Seeing a proposed design with peripheral vision or out of focus reveals the basic form more acutely. Although these qualities of vision may be used with computer displays, they are more flexible and powerful in three-dimensional space.

Visual representation is where the digital medium excels for designers. McCullough confirms that: "...the computer has become a visual medium." [13] Interactive graphic simulations, digital movies, hyper-real renderings, and heads-up displays are a few of the extra-visual capabilities of computers. CAD environments provide simultaneous multiple views, wire-frame or rendered views, panning, and zooming. The discipline of information display has experienced enormous advancements with the high-resolution, dynamic, interactive graphic capability of digital media. However, even though computation affords these tremendous extra advantages in representation, they don't replace the sensitivity of human vision in a three-dimensional space.

4.2.3 Aural

Sounds can be pleasurable—the squish of wet clay being shaped on a potter's wheel—or painful—a table saw cutting through a chunk of wood—although both can be satisfying. This is because sound, like other sensory input, provides us with both information and pleasure. Music gives us pleasure. as do a number of natural sounds, such as bird songs, cricket chirps, and falling rain. Working with a physical medium may provide a more subtle aural pleasure. The scratching of a pencil or pen on paper, the rustling of paper, and an X-Acto blade cutting cardboard all reinforce the quiet rhythm and flow of work.

Like the tactile sense, sounds also provide clues as to the nature of tools and materials. If you heard absolutely nothing as you were cutting wood with an electric saw, you would have much less of a sense of whether the saw was straining and you were in for a potentially dangerous snag. The sound that a material makes can sometimes reveal its nature better than seeing or touching it can. A hard, clear material may look and feel like glass, but the sound made by tapping on it will reveal that it is plastic. Hearing is also spatial. Sound resonates off of walls and objects, revealing or reinforcing spatial arrangements. In combination with our tactile and visual sense, hearing assists in efficient understanding and manipulation of objects in three-dimensional space.

Virtual sounds may not be appropriate in a CAD environment, beyond interface cues such as beeps to inform that a requested procedure is complete. The rhythm of work is appropriately accompanied by the clicking of mouse and keyboard. What is the sound of mathematically defined forms in a void, anyway? Material-related sounds, such as those used in children's paint software or the spatial audio currently used in virtual reality systems, are difficult to achieve without seeming comical or annoying.

4.2.4 Olfactory

Smells are memorable. A smell can vividly bring back a past experience initiating an emotional response in us such as relaxation, excitement, or anxiety. For example, the aroma of freshly cut grass can give many adults a momentary carefree feeling of their childhood in a quiet suburb. Smells play an important role in our attraction to each other, making them significant to species survival. Women's hormonal cycles can change by olfactory stimulation. Most parents can recognize their own children just by smell. Smells can even stimulate learning and retention. It was found that children who were given olfactory stimulation along with a list of words were better at recalling the list than when given the list without olfactory clues [14].

Although smell has little or no direct bearing on the efficiency with which we physically manipulate objects, as does touch, vision, and hearing, smell plays an emotional role in the use of physical media. Physical materials have distinct smells, ranging from appealing (natural clay, wood, linseed oil) to toxic (some metals and plastics). An appealing smell likely increases the appeal of a medium. A smell may create a mood in the designer that promotes creativity. Isen [15] has found that even a small increase in the feeling of happiness can increase creativity.

The digital medium has no smell, which could be perceived as either positive (safe and nontoxic) or negative (sterile). Having no smell may diminish our emotional response to it.

4.2.5 Spatial and Representative of Space

The *somatosensory* system makes up most of our experience of three-dimensional physical space [16]. Touch is the most familiar of the somatic senses, which also include *proprioception,* the sense of the position of the limbs, and *kinesthesis,* the sense of the movement of the limbs. Our sense of space is supplemented by vision, hearing, and our sense of balance centered in the inner ear. It is a misconception that a two-dimensional visual representation of a three-dimensional space can be as easily comprehended, navigated, and remembered without the benefit of proprioception and kinesthesis.

There is a great efficiency in representing physical structures with physical media. Such models differ only in scale or material from the final outcome of a design. Physical models offer the user an intuitive understanding of complex geometries and physical relationships that are difficult or impossible to describe in any other way. After observing engineering students solving a design problem, Brereton and McGarry [17] concluded that design thinking is heavily dependent upon references to physical objects and that designers seek out physical props to help them think through design problems and communicate design ideas.

There is even much value in working with physical two-dimensional representations, such as drawings in a three-dimensional space. Easy rearrangements such as juxtaposition, sequencing, and overlapping support exploration necessary to the creative process. Trace paper, for example, allows progressive sketching upon a base drawing without disturbing the integrity of the base drawing. Trace layers can be stacked, reordered, or reoriented to new positions. Viewing from varied distances by pinning up on a wall provides a new perspective on a drawing or permits easy comparisons among a group of drawings.

Physical materials in three-dimensional space support communication by enabling pointing and gesturing in three-dimensional space. Harrison and Minneman [18] studied designers at work and report that objects are an integral part of design communications and form a body of representations that are drawn upon by other designers. In a three-dimensional space, designers can gather around drawings and models and feel an engagement with the other designers and the materials themselves. That same level of engagement does not occur when a group gathers around a computer screen because of the size and because all are focusing forward toward the screen.

The two-dimensional environment of a standard computer screen never feels large enough. Juggling multiple windows to juxtapose, sequence, pan, zoom, and shrink can be tedious. Cognitive overload can occur as the user mentally translates two-dimensional representations into three-dimensional forms.

However, there are advantages to these two-dimensional representations of space. They can contain a multitude of information linked to the representation, such as measurements and material specifications. They can be see-through to reveal internal structures by use of a wire-frame or they can specify a view at a particular slice of a digital model. They can be dynamic, running what-if scenarios that would be too costly to construct with real materials, such as trying out particular layouts, lighting, colors, and so forth. Virtual walk-throughs can be made from digital models to provide a limited sense of space and pathways. Although these simulations do not replace the use of physical mock-ups, they can be helpful in providing more varied representations as aids for solving a complex design problem. Clients and other consultants also can benefit by supplemental visualizations of proposed designs.

4.2.6 Ambiguous and Explicit

Ambiguity is nourishment for creativity. Minsky [19] defines creativity as a process of "re-representation." Ambiguous representations enable re-representations. Take the example of sketching with pencil on paper. In a sketch, a line that is drawn as the edge of a wall can be reinterpreted to be a column or wire. The designer or other designers opportunistically discover new ideas based on misinterpretations or reinterpretations of the sketch. In observations of designers sketching, Schon [20] found a process of negotiation between designer and sketch. The designer draws, then interprets his or her own sketch, then continues or redraws the sketch in a process that yields a progressively more refined design. In empirical studies of designers, Goel [21] and Bilda [22] found that sketching facilitates design idea generation while CAD does not. Goel's evidence suggests that sketching supports design thinking because it is a "dense and ambiguous symbol system."

The fluid process of sketching and the ambiguity of the sketched representation have analogies to physical prototyping. Physical "sketch models" can be interpreted in multiple ways; they too are ambiguous and, like sketches, facilitate re-representation.

Physical materials such as pencil on paper and clay, lend themselves to sketching. They record gestures easily whether they begin as blobs or blocks in a subtractive process (e.g., carving) or as strokes in an additive one (e.g., drawing). When a designer wants to transform a raw material into an explicit representation, it can be challenging. Compare the difference in effort between making a rough sketch with pencil on paper and making a realistic-looking rendering.

Explicit means “leaving no doubt as to the intended meaning.” It is possible to be explicit with a physical medium, but it requires skill and effort. The tools and techniques that are available, in combination with the material itself, influence the effort required. However, the skill of the designer may have the most influence here. A gesture can be ambiguous, but it can also be an explicit expression of an emotion, which brings to light an important point. An explicit representation can convey a specific emotion or it can convey an exact form. Physical media are good at recording gestures (expressing emotion) and somewhat good at mechanical, emotionless representations (conveying information).

CAD behaves in an opposite way to most physical media. It is not easy to record gestures with CAD, but it is easy to create mechanical, emotionless representations. Into a void, the designer enters forms by specifying their exact measurements. Even if the intent of the designer is to gesture an approximate form, the computer responds in a similar way, mechanically recording vertices. Free-form, curvy shapes simply require more vertices. Capturing other aspects of gesture, such as speed and pressure, is not possible at this time with standard systems.

4.2.7 Precise

Precision is required in any design process. Once a concept and preliminary design are set, based on rough measurements and analysis, the need for precision increases as the design process progresses, culminating in the construction drawings. The smaller the project, the more a contractor or fabricator could be depended on to compensate for vague specifications as part of the building process. Large, more complex projects have many more variables and details that must be specified, and building costs must be accurately estimated in advance to avoid expensive overruns.

Tools and materials determine how easy or difficult it is to achieve accuracy. For instance, if you needed to draw a plan of a building to scale, you would probably use a sharp pencil on smooth paper with a professional scale, as opposed to charcoal on rough paper with a child’s ruler. In other words, the granularity or fineness of materials, combined with the accuracy of measuring tools, affects the precision with which a drawing or model can be made.

Computers excel at precision. Bits have no granularity. Their precision is limited only by processing power and memory, which already far exceeds the precision that can be achieved with physical media. All forms are mathematically defined. The numbers produce the drawing. As a result, CAD has made construction drawings more accurate, which has made the construction process more manageable. Architecture plans act like a contract between the client and the builder. The more precise and explicit they are, the more accurate are the expectations of costs and the fulfillment of the final product.

Computers have also increased the analysis capabilities of designers. Architects have always needed to address impacts to their proposed projects, such as how wind might affect a tall building or if drainage patterns on a property will create erosion over time. Before computers, this task was done intuitively in combination with calculations by hand. Computer analysis programs can take into account many more variables in a much shorter time than a human can. Effects that can be easily quantified and require many calculations are well suited to computer analysis. However, the analysis is only as good as the algorithms in the software or the interpretation of the results.

4.2.8 Persistent and Ephemeral

Something that exists for a long time is persistent. Most physical media—stone, wood, paper, and so on—are persistent by our perception of time. The Great Sphinx at Giza in Egypt was carved from a solid outcropping of rock some 3,500 years ago. When it was excavated by archaeologists in the late 1800s, from the sand that buried most of its body, it was still recognizable as a sphinx, even after all that time and after having sustained cannon fire from various armies in recent history. A more malleable medium like paper doesn't last that long; four or five hundred years will reduce most to crumbles.

Unlike a drawing on paper, media such as dance or music is described as time-based, meaning it must be experienced over a length of time. They are dynamic rather than static like a drawing. Electricity introduces a new twist on time-based. An electronic medium is only active while it is plugged in to a power source, which is why it is described as transitory or ephemeral. Video must have electricity to "play," or to be worked (recorded and edited). Computers present another variation on ephemeral that is more akin to "alive" than the "playing" of a videotape. Electricity gives life to a computer allowing it to respond to input, or at least that is our experience of interactivity.

Digital media are not purely ephemeral. A soap bubble is ephemeral. Digital data that defines an image or a three-dimensional model is stored on a disk, even when the power is off. The visual representation is ephemeral but the data stays put, even if we can't sense it. Little doses of persistence have value in the digital realm. The state of your computer desktop luckily remains the same from your last session and doesn't revert back to some default state. Web pages are relatively persistent: servers are kept on all the time but pages are often updated.

Although persistence has its advantages—not tethered to a power source, stable, and bonded to sensory qualities—ephemeral media can be dynamic and alive-seeming.

4.2.9 Physically and Logically Transformable

What makes the digital medium such a powerful aid to design is the combination of being ephemeral *and* able to store models as data and run procedures on those models. Digital models are logically transformable by running mathematical procedures on the data that define the model. Transformations can include scaling, skewing, distorting, extruding, adding curvature, giving perspective, and so on.

Physical media can be physically transformed, by hand or with tools. One must contend with the properties of the raw material. Clay can be molded into freeform shapes, but it will not stand up if molded too thin. Wood is much harder to shape and has a grain. It requires much more effort to shape than pliable clay, but it has more strength and can hold its shape even if cut thin.

4.2.10 Fast and Real-time

Speed can be measured only in comparison to something—fast compared to what? Computers are defined as fast machines because they can perform certain types of procedures faster than humans. But on a practical level for a designer, this translates to advantages as well as disadvantages. To do some rough sketching, nothing exceeds the speed of pencil on paper. Consider the time it takes to start up a computer, start up the software, open a new document, name it, and save it compared with the time it takes to open a sketchbook and lift a pencil. If the end result must be hard copy, factor in the time to print a computer file.

To do a measured drawing, a CAD environment is likely to be more efficient. With a large set of construction documents, there will inevitably be numerous changes to them over the course of design finalization, approvals, and construction. Although the initial drawing set could take roughly the same amount of time whether done by hand or by CAD, changes done in a CAD environment are much faster. One correction to the digital model makes the correction on all subsequently printed drawings. By hand, this could involve correcting many individual drawings.

While a design is being worked on in the early phases by hand, performing rough assessments by eye, such as shade effects of a tall building, can happen seamlessly in a few minutes. Here, a human with a sketch can work quickly. When more detailed and accurate analyses are required, such as studies showing sun/shadow progression through the day or seasons, and the designer must do some numerical calculations, the process takes more time. When complex analysis is required on a project, it is more efficient to use analysis software, because computers can accomplish a large number of calculations faster than a human can. However, to do the analysis, the computer must have a digital model to work with.

Much of the slowness of using digital media is related to the input and output of data from analog to digital and back to analog. These tedious transfer steps are labor-intensive and prone to frustrating hardware and software complications.

When software is attempting to simulate a real event, like walking through a virtual building (using VR or GUI), it is described as real-time if system has no delays in its response time. The real world is always real-time, while computer systems achieve it some of the time.

4.2.11 Intelligent

Sutherland may have misrepresented physical drawing by calling it "just dirty marks on paper," but he was right about the value of CAD when he suggested that "CAD is useful because the model can be used for more than just producing a picture." [23] CAD drawings are structured; they contain information beyond just the pictures that can be derived from them. A CAD model is a database. Mathematical procedures can transform the digital model in scale, shape, and orientation. Much information can be derived from the database, including materials lists, floor-area calculations, and numerous analysis results such as energy use and structural viability.

A digital model can be used as a database that is fed to analysis and simulation software to get results of such assessments as heating and cooling efficiency or room acoustics. Knowledge-base applications go a step further in attempting to perform evaluations on digital models for such things as code adherence, facilities planning requirements, and even style consistency. So far, the robustness of these types of applications has not been high.

4.2.12 Reworkable

Physical media have different tolerances for reworking. Watercolor, for example, has low tolerance for reworking. Once paint is placed on paper, it cannot be removed completely. Any attempts at reworking a painted area can result in muddied colors and irreparable damage to the paper. You can't put pieces of wood or stone back together after they are cut, without the consequences of gluing or joints. Plasticine, which never dries out, can be reworked repeatedly. However, it will pick up debris and dirt from the work environment and look discolored.

Time-based media, such as music, dance and theater, is infinitely reworkable with no permanent consequences to the sound waves or the piece itself. The digital medium is also infinitely reworkable, subject only to the limitations of a software package or degradation by hardware glitches. Negroponte [24] describes bits as "nondegradable" which allows them to be copied infinitely with out any loss of quality. "Undo," a powerful capability of the digital medium, is enabled by this quality of bits.

4.2.13 Copyable

A work created by hand with a medium such as paint or pencil is one of a kind. Reproduction methods such as photography or photocopying produce a copy in a different medium. Copying in the original medium, by hand, can never produce an exact copy, although it may be difficult to distinguish the two. Goodman makes the distinction between autographic, a piece that is one of a kind, and allographic, a piece that can be performed or reproduced many times. He defines a work as autographic, "if and only if the distinction between the original and forgery of it is significant; or better, if and only if even the most exact duplication of it does not thereby count as genuine." [25]

Goodman asserts that perhaps initially all arts are autographic. "Where works are transitory, like music, or require the work of more than one person, like architecture, a notation may be devised in order to transcend the limitations of time and the individual." [26] The digital media may change this assertion. A digital file can be copied infinitely with no degradation to the original or the copy. Is a digital file ever autographic? It may be considered so if printed only once in a physical form, and if the only copy of the digital file is subsequently destroyed.

In the same way that bits can be reworked with no degradation, they can be copied exactly, in part or in whole, with no degradation to the bits, and the copy is indistinguishable from the original.

In the analog world of tape recording, a copy is always inferior to the original. With a video recording, for example, the copy is a *generation* away from the original. Each generation results in a loss of quality. In the case of one-of-a-kind, handmade work, a copy must be made by hand. Copies require as much, or more, work as the original and depend to a great extent on the skill of the copier. It is not humanly possible to make a handmade copy *exactly* like the original.

4.2.14 Portable

The raw material of the digital medium—data—is tiny and weightless. It can be sent electronically or carried on lightweight, hand-size disks. Data processors and associated hardware continue to shrink. A laptop is more portable than a physical desk with its associated tools, and the laptop offers a comparable drafting capability. The current generation of tablet computers attempt to be even more lightweight. A workstation or desktop PC compares quite equally to the physical desk, both being nonportable. Digital portability excels when a large set of construction documents can be saved on a few Zip disks or e-mailed in minutes around the globe.

Physical tools and materials have mass and weight, which renders many of them not very portable. But there are those few items, like a small sketchbook, with which the computer cannot yet compete. They are not only small but convenient and appropriate to the serendipitous act of sketching.

4.3 Summary

Qualities of a medium are defined by our experience of that medium and by how we might apply it to a task at hand. Physical media possess sensory richness in comparison to digital media, which excels at fluidly transformable, ephemeral representations.

Chapter 5:

The Experience of a Physical Medium

5.1 The Senses

The senses are our input devices. Scientists are only beginning to put together the complex relationship between our sense organs, brain, and behavior. “The latest findings in physiology suggest that the mind doesn’t really dwell in the brain but travels the whole body on caravans of hormone and enzyme, busily making sense of the compound wonders we catalogue as touch, taste, smell, hearing, vision.” [1] Both Ackerman [2] and Csikszentmihalyi [3] state that information gained from sensory input is crucial to survival and that our senses have evolved to provide such information. For example, the sense of taste has evolved so that we can distinguish nourishing substances from harmful ones.

Ackerman [4] and Csikszentmihalyi [5] also suggest that the experience of pleasure is inextricably intertwined with informative sensory input. We respond positively to certain stimuli, actively seeking it out and thereby increasing our chances of survival. For example, food that is good for us tastes good (in the natural world—not the processed world of chocolate and potato chips!), and things that are poisonous taste bad. Also many foods have appealing colors and shapes. Try taking some toddlers (who have few preconceptions about food) for a walk in the woods and they will want to pick every berry they encounter, examine it close up, feel it, squeeze it, and eventually taste it. If it tastes good, they will want more; if it tastes bitter (poisonous), they will spit it out. The interconnection between pleasure and survival is so crucial that if we didn’t enjoy looking at other humans, or touching and being touched, we would probably never reproduce, and our species would die out.

In Chapter 3, I discussed how sensory richness plays a large role in our experience of a physical medium. It defines its appeal and supports skill and technique development for the designer. Sensory richness also supports cognitive processes such as learning and memory.

5.1.1 Constructionist Learning

The experience of interacting with a physical medium combines sensory input with cognitive and motor processes. The result is a rich experience that enables creativity, learning, and problem-solving to occur. A parallel can be drawn between designing and the education model known as constructionist learning. Much of the research into constructionist learning substantiates a multisensory, creative, problem-solving approach that embodies knowledge and thus fosters deeper learning. Take, for instance, my nine-year-old daughter's recent social studies segment on Egypt. Besides hearing lectures and demonstrations at school, she was asked to write a report, construct a diorama, and make an Egyptian costume to wear to a banquet where she ate Egyptian food.

Constructionist learning is learning by making. It puts every student in the role of designer. As Papert [6] suggested, children are builders of their own intellectual structures. Builders need building materials. It is well accepted among educators that this type of multifaceted approach makes concepts more concrete, deepening their understanding and making them more memorable. Computers are not excluded from this model of learning. They contribute to this approach by making complex dynamic systems more concrete and comprehensible. Physical artifacts contribute by addressing multiple senses, which makes many other types of knowledge more comprehensible and memorable.

5.2 Interacting with Physical Media

The experience of exploring what a physical medium can do is cognitively, physically, and emotionally engaging and further clarifies the design experience. One such concept, a *state-space,* refers to the perimeter of possibilities within which a designer can explore the physical properties of a medium (discrete or continuous, elastic or plastic, soft or resistant), together with the hands or tools used to work a medium [7].

5.2.1 Discrete Physical Media

Consider the process of composing a design with Lego blocks or a similar construction toy. The designer instantiates vocabulary elements by moving them into a work space. These instances can be grouped by snapping them together. Instances or groups can be selected and moved (translated and rotated) into new positions. The vocabulary of elements, together with these operators, establish a state-space for exploration. A simple three-dimensional computer modeling system might provide exactly the same vocabulary and operators, and thereby establish a comparable state-space for exploration [8].

For construction toys like these, any path through the state-space generates a series of sensory experiences: You feel the hardness and weight of the elements and subassemblies with your hands, you experience translations and rotations both visually and kinesthetically, you hear and feel the elements click together, and you may even smell the materials. These pleasurable and engaging qualities of the sensory experience help to motivate exploration and, as constructionist theory suggests, they support effective learning about the domain that is being explored.

This sensory experience is generated not only by the application of operators but also by the testing of states. You can pick up configurations of elements to feel if they are heavy or light, you can explore their properties of balance, and you can gain insight into structural stability by witnessing structures wobble and collapse. The results of such probes have suggestive power; if you see that a structure is about to topple over, for example, you might add elements to balance it. You might feel challenged to push configurations to their limits of stability.

By contrast, the comparable experience of exploring such a state-space with three-dimensional modeling software is sensorily and affectively barren. States are presented on the display with two-dimensional graphics, and the tactile, auditory, and olfactory dimensions are missing. The application of operators typically offers no sensory experience at all beyond selecting and dragging with a mouse within a GUI. Constructionist theory suggests that opportunities for learning in this environment will be correspondingly diminished.

5.2.2 More-Complex State-Spaces

Building blocks, such as Froebel blocks, support more-advanced exploration through some subtle but crucial changes in physical properties. They provide a limited vocabulary of discrete elements, like Lego blocks, but they do not snap together. Instead, they allow translation and rotation increments to vary continuously. Therefore, they establish a state-space that is discrete in some aspects and continuous in others. Also, the ways that you probe the states are different. Rather than picking up large subassemblies of Froebel blocks, because they would fall apart, you build up assemblies on the floor and slide them around along the floor plane. You experience a world controlled by gravity instead of attachment, that is unless you use glue [9].

Another type of state-space results if you replace chunky, rigid elements with thin, elastic ones. These may consist of wooden or elastic strips that function as splines, the springy tape preferred by automobile designers, or thin sheets of paper, metal, or plastic. The resulting state-space includes not only instantiation, grouping, translation, and rotation operators, but also elastic deformation operators. The sensory experience has enlarged to include the feeling of springiness and resistance. If you deform elements beyond their elastic limits, you introduce another complexity into the state-space. You get compositions of bent metal rods or folded cardboard.

If you utilize operations of cutting and material removal, another dimension of design variation results. If you apply tools to sheet cardboard, such as scissors or knives, a state-space results that is appropriate for architects who want to explore compositions of planes for walls, floors, and roofs. If you apply saws or chisels to solid blocks of wood or stone, you have a carver's state-space. The comparable operation is the subtraction operator of a solid modeling system. The experience of the carver's realm can vary considerably, depending upon the hardness, softness, or granularity of the material.

Modeling clay has a state-space in which shapes and initial vocabulary elements are not preserved. The units of construction are freeform blobs. These blobs are not elastic but deform plastically and retain their shape. Material may be removed from a solid mass, but it may also be added to a mass, so that shapes are constructed by accrual. The designer's experience is an intensely tactile one, with the feel and resistance of the clay on the fingertips playing a crucial role.

5.3 Summary

Physical design media establish state-spaces in the same way that digital media do, but the experience of exploring these state-spaces is generally a much richer, more multisensory one. Because of this rich sensory feedback, physical media possess cognitive, motor, and emotional advantages over disembodied digital media. Through sensory appeal, they attract and inspire exploration. Through spatial qualities, they facilitate understanding of complex geometric forms and enable easy juxtaposition, pointing, and gesturing. This richness and complexity is often highly engaging and emotionally satisfying, thereby establishing conditions for creativity and learning. These are all convincing reasons why designers have not abandoned physical media, even with the availability of the digital medium.

Chapter 6:
Superimposing

In Chapter 5, I argued that physical tools and materials possess cognitive, motor, and emotional advantages over the digital medium because they provide rich sensory feedback to the designer. However, the digital medium possesses new qualities, such as mathematically defined forms, transformability, and infinite reworkability, which may enhance effectiveness and efficiency in a design process. I believe that the limitations of current CAD systems at this time are primarily at the interface level, in the transfers between physical and digital representations and in the interaction between humans and the digital medium.

6.1 My Hypothesis

6.1.1 The Problem Restated

Computer tools have proved to be invaluable to the practice of architecture—but so have pencils, pens, paper, and clay. As a result, an uneasy coupling has occurred between physical media and the digital medium. They are used, side-by-side, each one where it is most appropriate. Inherent in this side-by-side environment is the need to continually digitize and print in order to switch back and forth between physical and digital representations. More fundamentally, the GUI is limiting when it is the only interface to computation for design purposes. The root of these shortcomings is the hard division between the physical and digital realms.

6.1.2 Possible Solutions

Possible remedies to these shortcomings include the following:

1. Improve digitizing and printing capabilities.
2. Add virtual tactile feedback capabilities to the GUI.
3. Superimpose computation and physical media.

6.1.3 Superimposing Physical Media and Computation

My hypothesis is that superimposing computation and physical media will combine some of the advantages of both realms. It can bring the cognitive, motor, and emotional qualities of physical media into a computation-rich setting. It also has the practical value of reducing the need to switch between physical and digital representations. In short, superimposing computation and physical media will provide these benefits:

1. Reduce the use of command-based interfaces and cognitive overload.
2. Reduce the need for suspending workflow to print or scan.
3. Increase the cognitive, motor, and emotional qualities of interfaces by bringing these advantages from the physical realm to computer interfaces.
4. Potentially create tools that are more enabling to designers than those that currently exist.

6.1.4 Superimposing Explained

By superimposing, I mean creating smart physical media and augmented reality interfaces. This can be achieved by embedding computation using small processors, and tag and sensor systems, or by utilizing scanners and projectors on the surface of materials. A good medium combines a relevant and interesting state-space with sensory feedback that is both useful and emotionally satisfying for the designer. Digital media typically provide interesting state-spaces to explore, good visual feedback, and the capability to perform useful computations upon states. But the sensory feedback that they provide is impoverished, resulting in an experience that, over time, becomes tedious and emotionally tiresome. Superimposing physical and digital media can combine the best of both worlds by combining rich, multimodal sensory feedback with the ability to perform useful computations.

The new technology that will support this approach includes smaller, cheaper scanners, flat-screen displays, and wireless tag and sensor systems. These superimposed physical/digital tools, materials, and environments could take several forms. For instance, a studio could have scanners embedded in the wall that scan continuously to input two-dimensional and three-dimensional data of physical drawings and models. Walls and tabletops could have large displays as output. The second approach is to focus on portability and augment existing physical tools and materials with input devices such as tiny sensors, cameras, and scanners. Output could take the form of projections directly unto materials, such as paper or physical models. Most likely, both large expensive systems and small portable systems will have a place in the design studio of the future.

Although a multiplicity of interface types is useful in a design environment, I am proposing that the most benefit can be gained by adding computation to physical media, as opposed to expanding the sensory bandwidth of the GUI by adding such things as virtual tactile abilities. These types of virtual feedback lack the verisimilitude of real senses, gaining back only a small amount of lost sensory feedback. I believe they are most appropriate to situations where real physical feedback is not possible, as when size or distance is a mediating factor.

Following is an expanded version of the table comparing qualities of physical media with those of the digital medium (Table 2). Added to it are “Digital with Tactile” (qualities of systems that have virtual tactile capabilities added to existing GUIs) and “Physical with Digital” (my proposed solution—superimposed physical media and computation). By adding up the scores it is evident that “Physical with Digital” retains the most number of qualities from both realms.

Qualities	Physical	Digital	Digital with Tactile	Physical with Digital
tactile	+	-	0	+
olfactory	+	-	-	+
spatial	+	-	-	+
ambiguous	+	-	-	+
persistent	+	-	-	+
real-time	+	0	0	+
physically transformable	+	-	-	+
logically transformable	-	+	+	-
ephemeral	-	+	+	-
explicit	0	+	+	0
representative of space	0	+	+	+
fast	0	+	+	0
intelligent	-	+	+	+
precise	0	+	+	0
visual	+	+	+	+
aural	+	+	+	+
reworkable	0	+	+	0
copyable	0	+	+	0
portable	0	+	+	0
(totals balance out)	6	6	7	9

Table 2: The ratings suggests that a quality is present (+), not present (-), or in between (0).

6.1.5 Foundations of Superimposing

Ubiquitous

Superimposing computation and physical tools and materials is consistent with the notion of "ubiquitous" computing, a new interface paradigm that turned the all-virtual paradigm inside out. In 1991, Mark Weiser, head of the Computer Science Lab of Xerox PARC, presented a new vision of specialized hardware and software connected by wires, radio waves, and infrared that would blend into the fabric of the man-made environment. In this way, Weiser suggested, computing technology would be enabling without being intrusive and overwhelming [1].

As a testament to the power of the "ubiquitous" paradigm, many researchers are now working within it. In 1994 the notion of **Graspable User Interfaces** was introduced by Fitzmaurice, Ishii, and Buxton [2]. This early example of a tangible user interface or TUI (an acronym coined by Ishii) allowed direct control of electronic objects through physical handles for control.

TUIs

Ullmer and Ishii [3] give some insight into the complexity of issues that emerge with that mixing of physical and virtual worlds. They suggest that the abacus is a compelling prototypical example of a tangible interface. However, the abacus is not an input device. It makes no distinction between input and output; instead, the beads, rods, and frame serve as manipulatable *physical representations* for abstract numerical values and operations. Simultaneously, the components also act as *physical controls* for manipulating their underlying associations.

A GUI makes a distinction between input devices, such as a mouse, as *controls,* and output devices, such as monitors, as portals for *representations.* In contrast, tangible interfaces seamlessly integrate representations and controls, as in the tradition of the abacus.

As an example, Ullmer and Ishii discuss Urp, a tangible interface for urban planning. The interface combines a group of physical architectural models with an integrated projector/camera/computer that projects graphics onto the surface of a table where the models rest. The building models cast graphical shadows under the control of a physical clock face whose hands can be manipulated. A physical material wand binds alternate material properties to individual buildings. When a building is bound with a glass material property, it casts solar reflections as well as shadows.

In the Urp interface, physical models of buildings are representations of actual buildings. Their form, as well as their position on the Urp surface, serve both as controls and as representations of the state of the user interface. Indeed, if the projector/camera/computer were turned off, the physical representation would say something about the state of the entire system. In a GUI, a mouse holds no representational value. It acts simply like an extension of pointing, while the icons on the desktop are the representative elements. (See section 7.3 "Tangible User Interfaces" for more about Urp.)

According to Ullmer and Ishii, tangible interfaces are typically built using systems of physical artifacts. Taken together, the ensembles possess several properties. The physical artifacts are persistent—they cannot be eliminated or spontaneously created. They also carry physical state—they cannot be altered and they are tightly coupled to the digital state of the system. Tangible interfaces combine physical artifacts together in several different ways. In Urp, for example, the spatial configuration of elements is the defining parameter for the underlying system. Relational configurations are defined by sequencing and adjacencies.

More concisely, Ullmer and Ishii go on to present key characteristics of tangible interfaces [4]:

1. Physical representations are computationally coupled to underlying digital information.
2. Physical representations embody mechanisms for interactive control.
3. Physical representations are perceptually coupled to actively mediate digital representations.
4. Physical state of tangibles embodies key aspects of the digital state of a system.

What happens when the physical artifacts are not just controls but have significance whether tethered to the computation or not? This would be the case in the realm of design. Urp in fact is a rearrangeable model of downtown Boston buildings even when the computation is turned off, even though it was created custom for the Urp interface. Illuminating Clay, a recent prototype of Ishii's Tangible Media Group (and the subject of the experiments conducted for this thesis), grew out of Urp, but is not tied to any particular physical artifact the way that Urp is. (See section 8.1 "Description of Illuminating Clay" for a more thorough explanation.)

Adding tangible controls to computation, and adding computation to physical artifacts are two ways to think about TUIs. Both have validity, although in the world of three-dimensional design, adding computation to physical artifacts would have the most application. Superimposing is primarily an augmented-reality approach. However, the most important question at this point is: What type of interface works best for the designer and the particular design problem at hand?

6.1.6 Instances of Bootstrapping Physical and Digital Media

Insight and inspiration can be gained about strategies for new interfaces by witnessing instances of bootstrapping done by designers. Bootstrapping, in the context of new technology, means adapting a system to address a different problem than it was originally designed for, or getting a faulty system to work. Of interest are instances where designers found ways to spontaneously superimpose digital and physical media to address their particular needs. Below are a few examples.

Trace paper over the computer screen

This is a fairly common technique. I have used it myself as much as 15 years ago. It is useful to trace a piece of a larger drawing to further develop that section. Once the designer "grabs" the relevant shape on paper, he or she can move the tracing to a tabletop to work. This is usually much faster and more convenient than attempting to print a section of a larger computer drawing. Similarly, I have seen designers compare a shape from one software package to another with trace paper on the screen.

Juxtaposing/collaging physical images to computer screen images

I have seen designers tape physical images or pieces of physical images to their computer screens to see if they "work" in a composition, before committing to the task of scanning the physical image.

Projecting a computer image on a wall

Within the context of a presentation, I have seen several designers gather around a projection from a computer image, tape a piece of paper within the projection, and draw and gesture on the superimposed projection/paper.

Projecting a computer image on a table

This happened in the class where the prototype Illuminating Clay was used (see section 9.5.2 "Class Log"). They had the unique advantage of having a computer connected to a video projector mounted on the ceiling and pointing down at a large table. During one class session, the members of the class bootstrapped the Illuminating Clay projector to project Illustrator drawings onto two site models. Some students had worked out several proposed housing layouts for the site and printed them out. They attempted to lay the printouts on top of the chipboard model in correct alignment. Someone got the idea (obviously from experiences with Illuminating Clay) to project them onto the tabletop where the model was sitting. It required only a small amount of rearranging of a couple of cables from the Illuminating Clay PC to a second PC in the same room. The display from the second PC was now connected to one of the ceiling-mounted projectors. The display filled the tabletop. The chipboard model was rotated and moved to see how the housing plan might fit on the site. Some modifications were made to the drawing in Illustrator in response to seeing how the plan worked with the terrain. At times, the model was removed and trace was laid down under the projection; students explained ideas and then proposed changes to the Illustrator drawings. This bootstrapped system worked very well. The whole class could see and contribute much more easily than by looking at a small screen or even a wall projection. Everyone could easily point, gesture, and sketch. The session was intense, and it appeared that much progress was made on the housing layout.

6.2 A Vision of the Future Design Studio

I propose that the studio of the future will be the complete opposite of the 1970's vision and might instead look quite similar to the traditional studio of the past but with some seemingly magical capabilities, such as those described in my fantasy (see Preface). Clutter resulting from projects in progress will abound. This work will be evident primarily in the form of old-fashioned physical media, or at least it will look that way. The greatest evidence of the digital media will be the large displays integrated into the walls and desktops. A thin, portable notebook computer and various small handheld digitizers will also be evident. Other computer technology will be so small and embedded in physical tools and materials that it will not be noticeable.

In any future scenario, the process of converting from physical to digital representations will play a large part. Current trends in developing input devices focus on "high-level" sampling, which then requires new techniques to intelligently interpret the new forms of data. Increasingly powerful processors will enable real-time systems that capture data continuously. This will eliminate the current interruption of the design process that's necessary to sample physical models and unlock the restriction of being in only one domain at a time, either physical or digital.

In one future vision, scanning would be ubiquitous, adaptive, iterative, and nonuniform. Imagine a studio or office with a built-in 360-degree scanner. It continuously scans the room, building up an accurate model over time. Objects that are partly or even completely hidden may be revealed temporarily. Instead of generating a complete sample and then synthesizing it, scanning and synthesizing become an ongoing process.

One might assume that high-level samplers would make the practice of computer modeling obsolete. So far, this does not seem to be the case. A possible answer, offered by Fitzmaurice, et. al. [5], is that sampled data is not always in the best form for further development by the designer. The designer's mental model of the curves and surfaces that make up the object may not correspond to the scanned object as they would have if the designer had modeled the object directly in the digital environment.

This problem may be remedied by creating smart sculptural modeling materials. If modeling materials had wireless tags embedded in them to define points, the synthesizing software could use information about the physical properties of the material to establish geometric primitives to construct three-dimensional geometric models. Tags might be located at the ends of inflexible rods (such as Tinkertoy construction sets, for example), so that they define vectors in three-dimensional wire-frame models. Similarly, tags on flexible rods could be captured as splines. If located at the vertices of a wire mesh, they could capture the surface geometry defined by that mesh. And, if distributed throughout a material like clay, they could be captured as a cloud of points. The designer might then choose a modeling material that reflects his or her own formal design vocabulary, with a new awareness of how different materials become represented in digital models [6].

Smart modeling materials could be real-time, and, as such, the most obvious way to display a digital model captured from a physical model would be on a standard monitor. This approach has the disadvantage that the designer must choose between watching the physical model or watching the screen display. With the techniques of augmented reality and the use of head-mounted stereo displays, it is possible to superimpose computer graphics directly onto physical models. Accurate registration can be a problem, and although the hardware continues to improve, it requires users to wear awkward, expensive apparatus. At some point in the future, the physical model itself may be able to double as a display by painting tiny addressable particles onto the surfaces of the physical model.

6.2.1 Hybrid Operations

By utilizing augmented reality techniques, it would become possible to perform operations that take both physical and digital shapes as operands. For example, a solid modeler might compute the intersection of two solid shapes—one being held in the user's hand, the other existing virtually in the digital model. A screen display might show the result when the physical and virtual shapes are "pushed together," and the line of intersection might be projected onto the surface of the physical shape. In this way, physical objects could be used as tools to sculpt virtual shapes [7].

It could also be possible to develop shapes from physically designed starting points. For example, two physical blocks might establish a spatial relationship, and the system might automatically repeat that relationship to generate a more complex form, which would then be projected back as a virtual model. Physical objects might also be arranged to specify the starting shapes and rules of a shape grammar, with the system deriving and displaying designs in the language specified by the grammar.

The results of hybrid operations could then be instantiated physically by actuators embedded in the physical model. Alternatively, output devices such as laser cutters or deposition printers could be used to produce new physical shapes to be reintroduced into the work environment. In this way, as a design develops, the designer could work with an increasingly complete and detailed physical model.

6.2.2 Linking and Unlinking

I am not suggesting that designers always need or want environments where physical and digital models are tightly coupled in real time with a consistent interface using augmented reality techniques. The freedom to vary representations as a design develops and new issues are explored should not be undervalued or ignored. Designers usually move back and forth between different representations—whether for brainstorming, design development, communicating with others, checking earlier assumptions, or more-subtle emotional reasons—at various stages of a project [8].

Providing a setting in which designers can easily move back and forth among virtual, physical, and hybrid environments, with varying sizes, scales, and resolutions is a better solution. Also, designers should be able to introduce different types of physical models and couple or uncouple them to digital models as desired. For example, an architect might begin work with Styrofoam blocks to establish basic functional relationships among building volumes, then move to clay to begin sculpting the shapes of those volumes, then use materials like wood, cardboard, paper, or plastic to elaborate on details and explore changes in materiality.

The manner of the physical/digital coupling may also vary from stage to stage in a design process. Sometimes, it may be highly desirable to provide real-time coupling, as in Illuminating Clay. At other times, it may make more sense to keep digital and physical models uncoupled and employ three-dimensional scanning and rapid prototyping to translate between them as required, as in Gehry's process.

6.3 Summary

An ideal creative design environment should provide a multiplicity of physical modeling media, powerful digital media capabilities for capture and development of digital models, a setting in which physical and digital models can be linked, and convenient tools for quickly linking and unlinking as desired. Paramount should be the creative process itself, with the technology transparently supporting the thoughts and gestures of the designer—where the switching between physical and digital design modes creates the least amount of drag on creative momentum and design flow, and the least amount of confusion to bodily orientation or position.

Chapter 7:

Related Prototypes

Starting in the 1970s, a few researchers experimented with physical interfaces to CAD in the form of rigid blocks. Recent related projects have embedded computing technology into blocks, flexible plastic, flexible tape, and fabric, all of which provide a basis for further work in smart sculptural materials. New technology research points to a more fluid coupling and uncoupling of media types. Tangible and augmented reality interfaces depend a great deal on sensors, which are rapidly becoming smaller, cheaper, and more capable.

Below is a survey of prototypes that relate directly to the field of three-dimensional creative design. Many other recent interface prototypes mix computation and physical artifacts but do not relate directly to the topic of three-dimensional design, so they are not included here.

7.1 Construction Kits

Several research efforts have produced construction kits that have computational capability embedded in the components. In each case, the blocks communicate with each other to identify proximity. Using that information, with given shapes and sizes, some derive position. The first three prototypes described below (Universal Constructor, Physical Construction Kit, and ActiveCube) can be considered input devices. The last two prototypes (Programmable Brick and Triangles) can be categorized as output devices.

Starting in the late 1970s, Aish and Noakes [1] implemented a "building block system," and Frazer [2] produced a series of intelligent modeling kits for interactively representing the structural and thermal properties of buildings. Frazer's **Universal Constructor** consisted of sensor-augmented smart blocks. The sizes and shapes of these blocks were known, the sensors embedded in the blocks reported back positional information, and a real-time digital model of evolving configurations of blocks was maintained. It was used to represent abstract systems such as cellular automata.

Along a similar track, **Physical Construction Kit** [3], developed by the Mitsubishi Electronic Research Lab in 2000, is a sophisticated building block method allowing LEGO-sized blocks to be assembled into arbitrary forms. The position of the blocks in an assembly, which can be as large as 560 blocks, is sensed by the computer and displayed as a three-dimensional CAD model.

ActiveCube [4], developed at Osaba University (Japan) in 2001, is another construction kit of identical cubes, each equipped with a processor for autonomous communication between cubes. A sensor and a display/actuator output channel communicate to a desktop computer, and a virtual model of the cubes' configuration is displayed in real time. ActiveCube was designed to be a children's toy. All three of the above projects provide a physical interface to virtual model, but are significantly limited by the fixed nature of the blocks.

The Lifelong Kindergarten Group at the MIT Media Lab has developed learning construction kits that they call "digital manipulatives." [5] **Programmable Bricks,** begun in early 90s, are Lego blocks that have input ports for receiving information from light, touch, and temperature sensors, and output ports for controlling motors and lights. A computer program written in Logo can be downloaded to a "programmable brick" from a desktop computer. A newer version of Programmable Bricks, called **Crickets,** was developed in 2000. Each "cricket" contains a Microchip PIC processor capable of two-way infrared communication. Children can use Crickets to create communities of robotic creatures that interact with each other.

In a similar vein, **Triangles** [6] is a physical/digital construction kit, prototyped by the Tangible Media Group at the MIT Media Lab from 1998 to 1999. It consists of a set of identical, flat plastic triangles, each with a microprocessor inside and magnetic edge connectors. The connectors physically attach the triangles to each other, which allows data to pass from triangle to triangle. A wire connects the triangles to a desktop computer. Triangles can be programmed from the desktop computer and has been used for nonlinear storytelling games, as a configuration interface for media events, and by artists for personal expression. Triangles and Programmable Bricks are examples of embedded computation in rearrangable blocks.

7.2 Smart Sculptural Materials

Taking computer-enhanced physical materials beyond discrete, modular forms, Orth [7], in the Opera of the Future Group at the MIT Media Lab, has attempted to develop what she calls "**smart sculptural computing materials,**" which are plastic, soft, and malleable. From 1997 to 2001, she experimented extensively with fabrics to discover ways to embed them with computation. In the process of developing a number of soft fabric interfaces for musical instruments, she has developed a fabric keypad, a new conductive yarn capable of tying an electro/mechanical knot, and an advanced process for machine embroidery to create highly conductive and visually diverse electrodes.

7.3 Tangible User Interfaces

Neurosurgical Interface [8], created in 1994 by Hinckly, uses a position-tracked doll's head and knife to allow users to dissect a graphical representation of the brain. The complex three-dimensional structure of the brain can be intuitively explored by physical manipulation of the knife and the doll's head. Experiments initially used a sphere to represent the head, but a doll's head gave better tactile and visual cues about the orientation of the head.

The concept called **Graspable User Interfaces** was introduced by Fitzmaurice et al., [9] in 1995. These interfaces use physical artifacts, which they call "bricks," to directly control virtual objects. The bricks are new input devices that are tightly coupled to the virtual objects. They operate on top of a large horizontal display surface known as **ActiveDesk.**

Sinclair's **Haptic Lens** [10], developed in 1997, is a half-inch-thick elastic surface that maps deformations by pressure. For sensing, it uses a low-resolution three-dimensional surface digitizer that consists of an easily compressible elastometer bounded on one side by an opaque white deformable membrane and on the other by a clear rigid faceplate. It can be used to scan the surface of small physical objects by pressing them against the input membrane. One can also manually manipulate the membrane to directly edit virtual surfaces.

Underkoffler's **Urp** [11], ongoing since 1997, is a tangible workbench for urban planning. Part of his **Luminous Room** project at the MIT Tangible Media Group, it captures two-dimensional locations of buildings in a real-time city planning simulation. Interaction is by direct manipulation of three-dimensional architectural models that sit on a two-dimensional surface and act as representations/controls for the underlying simulation. The architectural models cast accurate shadows and reflections or divert simulated airflow in the form of two-dimensional computer graphics projected directly onto the physical model. The buildings are marked by unique colored dot patterns discernible by simple image-recognition algorithms. A video camera continuously tracks the dot-pattern positions so that the computer graphics can be accurately registered to the buildings.

Limitations of Urp include parts of the model being blocked from the viewpoint of the projector; these appear to be in shadow, and no information is projected upon them. Also, the user's hands can cast shadows onto the model. It should be possible to essentially overcome these difficulties in future versions, by using multiple cameras and projectors.

In 1999, Balakrishnan, et el., [12] introduced a **bendable strip** for inputting curves to three-dimensional modeling software.

HandSCAPE [13] is a tangible interface prototype developed in 1999 by Lee of the Tangible Media Group at the MIT Media Lab. It is an orientation-aware, digitally augmented measuring tape that can serve as a simple input device for generating digital models from straightedged physical objects. Like a traditional measuring tape, it measures length. In addition, an orientation sensor allows vector measurement.

Illuminating Clay [14] was developed by Ishii, Piper, and Ratti at the MIT Tangible Media Group from 2001 to 2002. (See section 8.1 "Description of Illuminating Clay.")

SandScape [15], developed by Wang, et al. at the MIT Tangible Media Group in 2002, builds upon URP and Illuminating Clay. The user alters a landscape model consisting of sand in a shallow box, while seeing the resulting computational analysis projected on to the surface of the sand in real time. The system works by capturing the surface geometry of the sand model, which is lit from underneath with a powerful source of infrared light. A monochrome infrared camera mounted above the model records the intensity of light passing through the sand.

7.4 Displays on Physical Materials

Shader Lamps [16], developed by Raskar et al., in 2001, provides a three-dimensional physical display by projecting non-distorted and evenly colored computer graphics directly onto the surface of an irregular physical object using multiple projectors. Some level of interactivity is provided by changing the rendered highlights on the surfaces of the physical form according the head position of the user.

CADcast [17], developed by Piper at the MIT Tangible Media Group in 2001, provides a three-dimensional template for the physical construction of building models. A sequence of perspective images created from a CAD model, and indicating the order and position of each component of a building model, is projected into the workspace and used to guide the user to construct a physical model. Although CADcast is a demonstration of how physical and digital representations can be merged in a design environment, the interface is limited to one-way interaction with the user following projected instructions from the computer. This and the above project, however, confirm that using three-dimensional physical models as display surfaces can work convincingly.

7.5 New Musical Instruments

Many new musical "instruments" have been developed with the addition of technology to a nonmusical artifact. Here I mention only two, an instrumented shoe and Musical Trinkets, because of their use of sensors. In a third project, sensors are added to a cello-like instrument.

Paradiso [18] created an **instrumented shoe** in the Responsive Environments Group at the MIT Media Lab from 1997 to 1999. Using dense wireless sensing, the shoe measures 16 different parameters at the foot, detecting essentially anything the foot does. The data is telemetered back to a remote host, leaving the shoe untethered. The data is then mapped to audio, essentially making the shoe into a musical instrument. A dancer wearing a pair of these shoes creates his or her own music.

In the Responsive Environments Group at the MIT Media Lab during 2000, Hsaio [19] used a two-dimensional sensing field to read the position and angle of wireless tags. This infrastructure supported an interface for music control called **Musical Trinkets**. Wearing finger rings with embedded tags and moving the hands within the sensing area, a user can elicit musical riffs from the system. Hsaio also developed a cubical frame incorporating Helmholtz coils to read the position and angle of wireless tags within a three-dimensional space. Although this cube was not fully operational, it is easy to imagine, with refinements to the technology, how this could be applied to traditional spatial tasks such as physical modeling.

Machover and the Opera of the Future Group at the MIT Media Lab created **Hypercello** [20][21], which began with the question: How can digital technology build on an old craft of musical instrument making without sacrificing what is valuable about traditional instruments? Hypercello uses the same physical interface of a traditional cello; you play it by stroking a bow against strings that you hold down with your fingers to form musical tones. Its shape and material, however, are different—a metal frame with many sensors attached to it, and wires going to a bank of computers. The diverse combination of sensors, custom invented and designed by Gershenfeld of the Physics and Media Group at the MIT Media Lab, gather data as the musician plays. Bow position, pressure, angle, and speed, as well as finger position, all are recorded at a data rate comparable to what is audible from a traditional instrument.

Yo-Yo Ma took part in the project and was an essential bridge between the technology and the art. He not only performed with Hypercello, he also offered advice as to what parts of his technique were relevant to measure and what parts were irrelevant. He helped Machover, who wrote the piece "Begin Again Again" especially for Hypercello, to create musical mappings that used the sensor data in ways that were artistically meaningful and that built on Yo-Yo Ma's technique.

7.6 Computer-Generated Tactile Feedback

Phantom [22][23], developed by Massie at MIT in 1994 and now at SensAble Technologies, is a haptic interface that uses a thimble, stylus, or grip handle for interaction. It was originally developed for use with computer graphics, simulating feedback from clay and other familiar materials. Subsequently, a noncommercial plug-in to use Phantom with Alias/Wavefront's Power Animator software was developed. It has since been adapted for numerous research applications including remote-controlled surgery.

Much of the research into computer-generated tactile feedback is occurring in the field of remote-controlled surgery. These minimally invasive procedures have the advantage of inflicting only tiny incisions that limit damage to the body and help speed recovery. However surgeons struggle with receiving only visual feedback to find anomalies so that they do not exert excess pressure on delicate tissue. **Remote Palpitation Instruments** [24], being developed by Howe at Harvard's BioRobotics Laboratory, convey tactile information from inside the patient's body to the surgeon's fingertips. The "tactile display' consist of a line of ten individually activated pins that are raised against the finger-pad.

Tissue mechanics is a related research field to remote-controlled surgery that seeks to describe the non-linear behavior of body tissues. Harvard's BioRobotics Laboratory, in association with Massachusetts General Hospital's CIMIT simulation group is developing a **"tissue atlas of material properties"** [25] for use in medical simulation technology.

Chapter 8:

Experiments with a New Prototype: Illuminating Clay

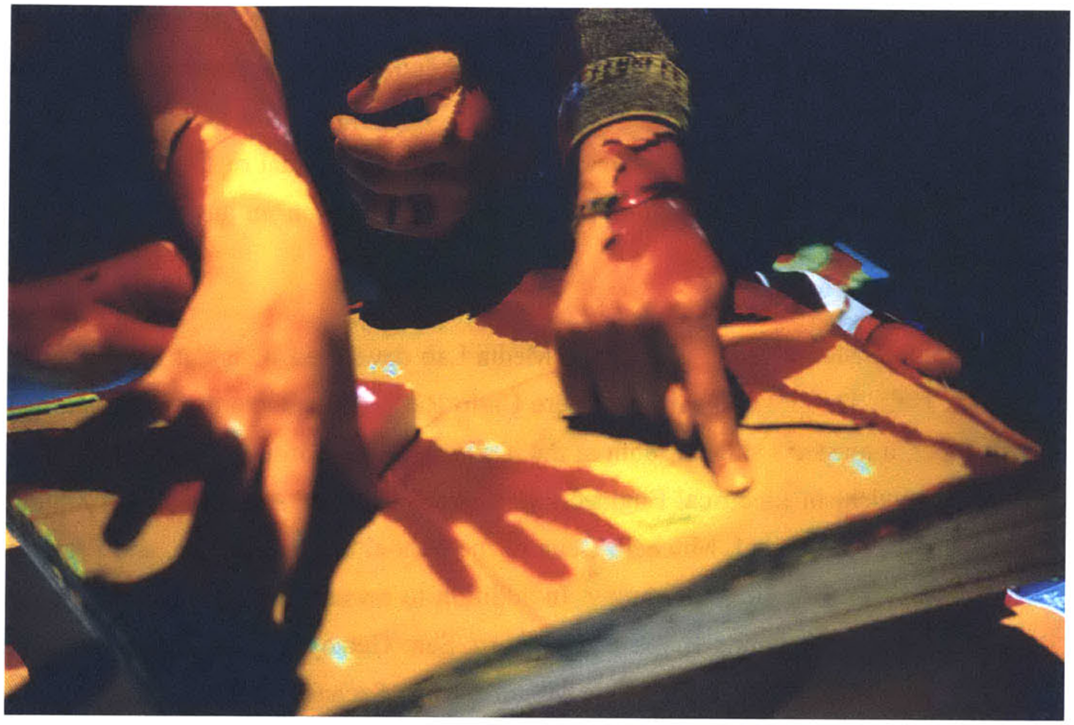


Figure 6. Students using Illuminating Clay.

8.1 Description of Illuminating Clay

Illuminating Clay (IC) [1][2] captures the advantages of both the physical and digital realms. It is a novel system for the real-time computational analysis of physical landscape models. A user of the system alters the topography of a landscape model made from clay or any other suitable material. The changing geometry is captured in real time by a ceiling-mounted laser scanner and converted to a depth image of the model. The depth image serves as an input to a library of landscape analysis functions. The results of this analysis are projected by means of a ceiling-mounted projector back into the workspace and registered with the surfaces of the model.

IC combines physical materials with computer graphics. The projections on the surface of the model are color computer graphics with a resolution of 240 x 240 pixels. The scanning area where the physical model sits is 18 x 18 inches. The laser is in a fixed position, so it recognizes two and a half dimensions, i.e., variations of height from a surface, but cavities not visible from above are undetected. A menu containing icons of the analysis algorithms borders two sides of the scanning area. The other two sides show section cuts of the model. Next to the scanning area, a menu is projected onto the tabletop from a second ceiling-mounted projector. Here the user chooses the algorithms from a text menu and also sets parameters for algorithms. On a nearby wall, a three-dimensional digital model of the physical model is projected by a third ceiling-mounted projector. Interaction in any of the projected windows is done with a mouse.

The Tangible Media Group at the MIT Media Lab developed IC under the direction of Hiroshi Ishii. The project managers were Carlo Ratti, a postdoctoral researcher, and Ben Piper, a master's student, both at the Tangible Media Group. Yao Wang, a master's student in Electrical Engineering, was the software architect. Contributions were made by William J. Mitchell, Dean of the School of Architecture, and Eran Ben-Joseph, Professor of Urban Planning. In addition to myself, numerous others assisted with the project, including Bryan Blumenkopf, Saro Getzoyan, Ken Goulding, Kartik Lamba, Alexander Mekelburg, Aaron Mihalik, Ishan Sachdev, and Bo Zhu.

IC was designed for use by landscape architects and planners. By softening the hard barrier between the physical and the digital, I believe it has significant implications to current design practice;

1. It allows one to design with a clay topographic model and have simultaneous real-time computational feedback. That feedback can take several forms: a number of surface analysis algorithms, a section of the model, and a three-dimensional digital model. The designer shapes the clay surface, and within two seconds—perceptually real time—a computational response occurs. The designer has a fast, flexible, and varied representation of a physical form, extending and informing the process of sketching with clay.

2. It provides real-time topographic analysis of a physical model. Typically, in current practice, as a designer works, every change he or she makes in a physical

representation requires mental assessments—is the size right? is this footprint level? is this slope too steep? and so forth. Further into the process, when a CAD model is created and subjected to software analysis, technical flaws can be discovered in the design, such as slopes that are too steep or drainage that is inadequate. Because IC works in real time, it can act as an aid to those ongoing mental assessments in the creative process. It enables a designer to try out various possibilities and immediately see the impact on a design of, say, slope or drainage. The feedback is low resolution, in keeping with the sketch quality of clay.

3. It creates a platform for communication that is flexible and rich in information. Landscape architecture and planning projects often deal with very large tracts of land and require the input of many specialists. These might include earth engineers, water management specialists, horticulturists, real estate economists, lawyers, and transportation engineers. Furthermore, landscape interventions inevitably affect large numbers of people living on or near a particular site. It is often necessary for the designers of a landscape project to communicate their vision to the local inhabitants and adequately address their questions and concerns. IC enables landscape architects and planners to quickly illustrate the impact of a scenario in concrete terms, thereby allowing various specialists and lay members to understand proposed solutions better.

8.2 The Experiments

8.2.1 Goal of the Experiments

The goal of the developers of IC was to create a more informed and enabling environment for design to occur. Thus, my goal became:

> ***Seek out evidence of how IC affects a design process as compared with current practice.***

I developed three hypotheses about how IC affects the design process, and these helped shape the form of my experiments:

1. IC could offer a designer with an appropriate "sketch" environment, like a clay model does, because of the low resolution of its graphics and its speed, or real-time capability (providing physical media advantages).

2. IC could better inform the creative process by providing computational feedback to manipulations of a clay model, thereby bringing some analysis to the early phases of design (providing computation advantages).
3. IC could, like physical drawings and models, facilitate communication among designers but with the added dimension of much richer, dynamic information.

8.2.2 Method

A creative design process is not mechanical or rote, so counting repetitious results of a task has little significance. The final product—the design itself—also has little significance, because it would be impossible to take into consideration all the personality variables of a designer that might influence a creative product. My goal required that I look for evidence in the *process* of design. I chose to use protocol analysis of a design task supported by observations and interviews.

Protocol analysis is a method by which one records and then analyzes the minute events of a process. Videotaping provides an efficient means to achieve this. Subjects are often asked to "think out loud," so that the researcher can better understand their thoughts and actions. In these experiments, I not only videotaped the task but also interviewed the subjects after they had performed the task, giving them the opportunity to recall and reflect on their experience. I transcribed the tapes so that I had two sources to draw from. The videotapes provided a visual record and the transcripts a verbal one. The videotapes also provided a record of timing and the tone of voice that the subjects expressed.

8.2.3 Establishing the Task

Duration and complexity of the design problem were a consideration in devising a task for subjects to perform. Most real-life design problems that employ the skills of a landscape architect or planner require work to occur over days and often many months. Usually, a team of designers is involved. It was, however, conceivable to compose an exercise that would last roughly 30 minutes, with only a few constraints on a one-acre site. A short exercise would provide control but lack reality. A long-term project would provide more reality but little control. In the end, I was fortunate to have the opportunity to test some of both.

Long-Term Project

An opportunity presented itself for a long-term project. IC was going to be used by a site planning course at MIT, Illuminating Sites, in the spring of 2002. A graduate-level class in the Urban Planning Department in the School of Architecture, it would be taught by Eran Ben-Joseph, Professor of Urban Planning, with Hiroshi Ishii, Professor of Media Arts and Sciences, and Director of the Tangible Media Group at the Media Lab. IC would be used during the second half of the semester. During that six weeks, students would develop a design for a 200-acre site that included a "green" golf course and 60 units of housing. IC would be available to the students for use on this project, along with the typical suite of tools and materials, i.e., paper and pencil, chipboard, clay, CAD, image processing, and so forth. The students would not be required to use IC but were expected to attempt to incorporate it in their design process where they found it to be helpful. There would be no parallel control project (i.e., a similar one that did not use IC) to compare with this one. But I planned to observe how it was used by the students in the class and also conduct interviews with them at the end of the semester.

Short-Term Task

To devise a short-term task, I referred to sample problems from the landscape architecture licensing exam. I took a grading exercise, changed the original parameters, and added a few more variables. I developed one set of directions and found three one-acre sites that were similar in nature but varied in their actual terrain. Below are the directions for the short-term task:

For the given site:

1. Parcel site and place two buildings, each 40 x 60 feet.
2. Connect buildings with driveways to existing street.
3. Establish finished floor elevations and modify all contours as necessary to accommodate new construction.
4. Minimize cut and fill.
5. Maximum slope:
    a. Driveway - 10%
    b. Walks - 5%
    c. Cut and filled earth - 2:1
6. Drain all surface water around structures and driveways using swales.

Initially, I chose to use trace over a contour map as a control task. I then realized that the physical clay model required for IC was in itself an advantage, so I established a second control task using trace, a contour map, and a clay model. I chose to not include IC by itself (i.e., without a contour map) because it was designed to supplement rather than replace the use of physical maps. I also chose to not include a CAD environment because it is not commonly used in the beginning stages of a design problem, and it presents another set of variables such as what software, system, and so forth. Here is the final set of the test and control tasks for the short-term task:

Test – IC Tool Set: trace paper, pencils, architect's scale, contour map of site, clay model of site, a couple of modeling tools, IC

Control A – Clay Tool Set: trace paper, pencils, architect's scale, contour map of site, clay model of site, a couple of modeling tools

Control B – Paper Tool Set: trace paper, pencils, architect's scale, contour map of site

8.2.4 Structure of the Experiments

Given the resources available to me, and the variables I was working with, I constructed this test grid:

		Test Tool Set	**Control Tool Sets**	
	Subjects	**Illuminating Clay**	**Clay**	**Paper**
Short-term	Professional individual	2nd (site 2)		1st (site 1)
	Professional pair	1st (site 2)	2nd (site 3)	
	Student group 1	X (site 1)		
	Student group 2		X (site 2)	
	Student group 3			X (site 3)
Long-term	Class	X (project)		

Table 3. Each professional subject performed the short-term task twice, each time with a different tool set. I alternated the order in which the tool sets were used and which of the three sites was assigned to each tool set. When the student subjects did the short-term task, they were divided into groups, and each group used a different tool set and site to do the task once. The class did the class project.

8.2.5 Recruiting Subjects

The experience level of the designer was the first issue I considered in recruiting subjects. Skilled designers are able to previsualize and take shortcuts to design solutions, based on years of practice. This might make IC more helpful to a novice designer. On the other hand, skilled designers are dealing with the demands of real-world problems and have a need for effective tools. They might find IC to be an asset to them.

Individual vs. group design processes was the second issue I considered. With the exception of very small projects, most landscape architects and planners work in teams with other designers and also engage clients, specialists, and concerned citizens in larger group encounters when appropriate. How a tool or environment lends itself to working with varied numbers of people is significant to the design process. I wanted to gather data on individual and group use of the prototype.

Professional Subjects

Professional landscape architects were recruited by e-mail to take part in the short-term task. Their participation was voluntary, and they were offered a modest gift certificate in appreciation for their participation. I chose three subjects whose experience ranged from 2 to 30 years. One subject worked individually; two subjects worked collaboratively.

Student Subjects

Eleven students were enrolled in Illuminating Sites. Eight were majors in the Planning Department; three were from other majors, i.e., Architecture, Engineering, and the Media Lab. Students in the class were invited to take part in the short-term task. Ten students volunteered.

8.2.6 Physical Setting

My choice for the location of the experiments was already determined, because IC was installed in a classroom/conference room in the Urban Planning Department at MIT and could not be moved. The room has doors that can be closed to block out most outside noise and light. It has no windows. The lights are on dimmers, so the light level could be adjusted. A large conference table occupies the center of the room. Some large, blank white walls are available for projected images. When running, IC fills almost the entire conference table and one wall with computer graphic projections. When IC is off and the model stand removed, the room is like any other conference room. The projectors and scanner installed on the ceiling are unobtrusive. All the tests took place in this room with the exception of two. When the students performed the short-term task, they were divided into three groups and worked simultaneously. One group used IC in the room where it was installed. The two control groups worked in two adjoining rooms.

8.2.7 Consent

Each subject was asked to sign a "Consent" form and an "Agreement To Be Videotaped" form in compliance with MIT's Committee on the Use of Humans as Experimental Subjects (COUHES).

8.2.8 Demonstrations and Directions

Each subject had a demonstration of IC before performing the task. The professional landscape architects received a 15- to 20-minute demo directly prior to performing the task. The students in the class received a 45-minute demo a month before performing the task and also had three opportunities for hands-on practice during class in the intervening weeks.

Prior to performing the task, I gave each subject these directions verbally:

This is not a test of you, your talent, or your abilities. Instead, it is a test of the prototype Illuminating Clay. I am trying to determine if Illuminating Clay is a useful and effective tool for landscape and site design. Please attempt to perform the task that you are given using whatever knowledge and experience you have as a designer. All of your reactions to, opinions of, and techniques used with Illuminating Clay are valid and of interest to me. If at any time you wish to stop and not take part in this experiment, you may do so. Please remember to "think out loud" as much as possible, even if it feels awkward, because that will help me to better understand your experience.

8.2.9 Known Shortcomings of the Experiments

Even before they were begun, I was cognizant of some significant shortcomings to the experiments:

Size of the Study

I was doing most of the work myself on a limited budget so, by necessity, this was a small study.

Not All the Variables Were Consistent

1. The students in the class were familiar with the developers and were privy to the goals and shortcomings of Illuminating Clay.
2. Operation of IC switched between Ben Piper and Yao Wang. Each had a different style of interacting with the subjects.

The Learning Curve of the User

The commands necessary to operate the prototype were easy to learn, but Illuminating Clay was not necessarily easy to integrate into a personal design process. Becoming facile with a tool and using it comfortably and effectively is a progressive process, involving a learning period or experimentation and practive. The subjects had only one training session with Illuminating Clay and then used it once in the short-term task and only a few times in the long-term project—not really enough time to "own it."

Choosing an Appropriate Problem

Most real-world landscape design projects are long and complex, taking place over weeks, months, or even years with involvement from multiple designers. With a project such as this, it would be possible to observe the use of Illuminating Clay but not to run a tightly controlled experiment. The simplicity of a short-term problem in some ways limited the necessity for Illuminating Clay. Thus, any choice of a test project would involve compromises.

Requirements for Creativity

The short-term task and the long-term project both required problem-solving within given constraints but did not require a great deal of creativity. This gave a clear focus and goal to the tasks. If they were more freeform, allowing for more creative solutions, it may have been more difficult to compare one protocol to the next. IC may support the creative process very well, but these experiments do not substantially test for that.

Chapter 9:

Protocol Analysis: The Findings

9.1 Format of the Analysis Presentation

I present analysis of the protocols that I collected in the following format:

1. ***Subject overview***
2. ***Stages of events in the protocols***
3. ***Summary of events and observations***

While evaluating the research results, I was able to describe stages based on patterns and consistencies in the protocols. Each stage is defined as a series of steps on a single aspect of the task, such as placing the building footprints. The steps roughly consist of analysis, decision, reflection, and implementation. I present the analysis of the protocols in the following order:

1. ***Professional subjects performing the short-term task (Individual, Pair)***
2. ***Student subjects performing the short-term task (Group 1, Group 2, Group 3)***
3. ***Student subjects doing the long-term project (Class)***

(Note: The names of the subjects have been changed.)

Simon

9.2 Analysis of Individual (Short-Term Task)

9.2.1 Overview, Individual

Simon is a male in his early 30s. He has a master's degree in Landscape Design and works at a landscape design firm. He has approximately four years of professional experience. First, Simon was given the task to do using the Paper tool set. Second, he performed the task using the IC tool set. Yao Wang, the chief programmer of IC, was operating the prototype for Simon.

9.2.2 Individual, Part 1: Paper Tool Set

Stages

Step 1: Preparation

Simon is given task directions and a contour map. He places the contour map on the table in front of him, smoothing it with his hands while he observes the contour lines, and tapes it to the table. Then he lays a piece of trace over it and lightly tapes that down.

Step 2: Building Footprints

Using a physical scale to measure and as a straightedge, Simon sketches the footprint of one building to scale, roughly in the location that he has chosen. He is concerned with placing the longer side of the footprint along the direction of the contours. He then readjusts the location of the trace slightly, trying a few different positions, to get a more optimal location. Once he is satisfied with the location of the first footprint, he retapes the trace to the table. Simon then sketches the footprint for the second building.

Step 3: Driveways

Simon positions the physical scale on the contour map to determine the placement for the driveways to maintain a 10 percent slope or less without having to excavate extensively. He sketches in the two driveways.

Step 4: Readjustment

Now that the driveways are sketched in, Simon readjusts the building footprints slightly to conform to them and then hardens up all the elements sketched to this point.

Step 5: Floor Level of Buildings

Simon determines the best floor level of the buildings by looking at the contours that each footprint intersects.

Step 6: New Contours for Driveways

Working down from the building footprints, Simon marks new locations for the contours that intersect the driveways. After he marks reference points, he redraws the lines to establish a 10 percent or less slope. So far, this is the most time-consuming activity.

Step 7: Drainage

Simon redraws contours for swales. He mumbles numbers. It appears to be more difficult to figure out than the driveway contours. The solution that he chooses appears to be more guesswork than calculation.

Summary, Individual, Part 1: Paper Tool Set

Simon did the control task first, using just the contour map. He worked diligently, proceeding in methodical fashion and making efficient progress. He was clearly experienced and knowledgeable about solving the kind of problem presented in the task. After a quick assessment of the site, which he appeared to do as he taped the map to the table and placed the trace over it, he began by sketching in locations for the building footprints. Second, he sketched locations for the driveways, taking the given slope into consideration. At that point, he went back and readjusted the building footprints slightly, ensuring that all parts were working together, and then hardened up his drawing. He then redrew the contours for the driveway grading, beginning by determining the level of the building footprints and working downslope from them. Last, he assessed the need for swales around the buildings and redrew the contours for the swales.

Simon spent, by far, more time redrawing the contours for the driveways than on any other part of the task. Placement of the buildings and driveways appeared to be almost effortless and took little time, while redrawing the contours required some mental calculations and then was tedious to complete. As time-consuming as it was, redrawing the driveway contours appeared to be straightforward. However, figuring out the need for and placement of swales appeared to be difficult and involve random guesswork. Simon completed this part of the task rather quickly, as it appeared to be impossible to accurately access the need or success of a swale with the tools that he had.

Because Simon did not talk much during his session, I asked him to present his design to me and to recap his design process. His report simply confirmed my observations, with no new insights except that he saw the task not as a design problem but primarily as a grading problem (i.e., a technical rather than aesthetic problem), which likely influenced his focus on redrawing contours rather than uniquely placing buildings and driveways.

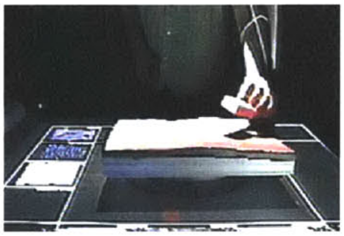
What was striking about Simon's execution of the task was how process-based it was. He spent very little time contemplating, or *not* engaged in drawing. It was as though the process of drawing was the scaffolding to this thinking. Both were seamlessly connected. He was thinking by doing. As stated earlier, after only a brief glance or two at the map and directions, Simon began taping his map and trace to the table and drawing the building footprints. As he was doing those steps, his focus indicated that his assessment of the site and his decisions about placement continued hand in hand with the drawing process itself.

9.2.3 Individual, Part 2: Illuminating Clay Tool Set

Stages

Step 1: Preparation

Simon is given task directions, a clay model, and a contour map. IC is turned on. He glances only briefly at the contour map. He focuses on the clay model, touching it lightly. He then asks if IC can project contours on the model. Yao explains that the Contour algorithm is very inaccurate and suggests Slope as an alternative. The Slope algorithm is projected.



Step 2: Building Footprints

Simon casually places the building models at different locations on the clay model. He is still trying to fully understand the feedback from the Slope algorithm. Yao has adjusted the parameters of Slope to show any slope greater than 10 percent as red. After a few questions about how to interpret the colors in the feedback, Simon settles on a location and carves out some clay to create a level footprint.

Step 3: Driveways

Simon suggests that if there were a grid that could be overlayed on the model, it would give an indication of relative scale and be helpful. Because this site is similar in scale to the last, he can estimate the width of the road based on his previous task. He draws the driveways on the model. Feedback from the Slope algorithm indicates that the driveway slopes are less than 10 percent, as specified in the directions.

Step 4: Drainage

Simon requests the Drainage algorithm. He is pleased that the feedback from Drainage shows that the water runoff on the site is behaving as he expected. He sees a couple of problem spots that he corrects by creating swales on the clay model. The Drainage algorithm confirms that the swales redirect the site drainage effectively. He is pleased at how the Drainage algorithm makes it easy to understand what is happening with the water flow on the site. "This is very cool," he states twice. He feels confident with the level of accuracy of the feedback, concluding, "...at this scale, it is good enough."

Step 5: Readjustment

Yao has gone back to the Slope algorithm and has readjusted the parameters to show slopes steeper than 22 percent as red. There is still some red showing. Simon had determined previously that all slopes were 10 percent or less. It appears to be more difficult to read the feedback than he thought, or IC is not behaving consistently. He readjusts some of the slopes based on this new feedback.

Summary, Individual, Part 2: Illuminating Clay Tool Set

Simon used IC for his second task, after first doing the task with just a contour map. Upon beginning this task, he quickly decided that both tasks involved sites that were fairly similar. His first request was to have IC project contours onto the clay model. When told that the Contour algorithm was not very informative because of its resolution, he adapted to using the Slope algorithm instead. It was a little unclear to him as to what Slope was indicating. Simon proceeded with the feedback he had and worked swiftly to solve the task in a sequence of steps similar to those he used with just the map in the previous task.

Yao Wang was operating IC. He and I made a few suggestions about using the capabilities of IC, but mostly Simon was left to drive the process by his own requests, based on what he remembered about IC from the demo at the beginning of his session. Thus, the task and how to most effectively solve it took the forefront of Simon's process. His requests and questions were few, indicating that he needed only a small amount of feedback from IC to make him feel confident to solve the task.

Simon's process of solving the task with IC was similar to his previous process when he used just a map. After completing the building and driveway placement using Slope, Simon requested the Drainage algorithm. The feedback from that appeared to please him. He twice stated, "This is very cool," and spent some time contemplating the feedback. He then created swales around his buildings on the model. It appeared that Drainage made the effectiveness of swales very clear.

After making swales and seeing the Drainage feedback, Simon thought he was finished with this task. Yao went back to the Slope algorithm on IC, possibly because he had been thinking about how to use it more effectively. He changed the color parameters so that everything with a slope greater than 22 percent became red. Some areas were still showing up red, so Simon readjusted those areas to eliminate it.

Malcolm & Nick

9.3 Analysis of Pair (Short-Term Task)

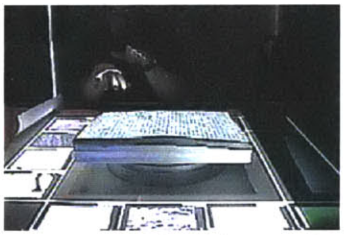
9.3.1 Overview, Pair

Malcolm and Nick worked as the pair. Malcolm is a male in his 50s, who is a landscape design professional with approximately 25 years of experience. Currently, he is a principle in a landscape design firm. Nick is a male in his late 20s. He has a master's degree in Landscape Design and works at the same landscape design firm. He has approximately two years of professional experience.

Malcolm and Nick first used IC, a clay model, and a contour map to do the task. They performed their second task with a only a clay model and contour map. Ben Piper, one of the project managers of the IC prototype, was operating the software for Malcolm and Nick.

9.3.2 Pair, Part 1: Illuminating Clay Tool Set

Stages

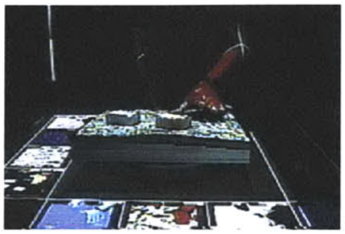


Step 1: Preparation

Malcolm and Nick are given a task description, clay model, and contour map. IC is started. Focus goes from the task at hand as Ben Piper, who is operating IC, begins explaining some of the details of operating the mouse for IC. He appears to want Malcolm to operate the mouse himself. Malcolm is interested in the information but is not inclined to take control of the mouse. After several minutes of explaining, Ben selects the Slope algorithm. Malcolm and Nick attempt to read the slope in different parts of the site, touching the model here and there to better understand the site and to ensure that they are understanding the feedback from IC accurately. There is much adjusting of the parameters of Slope to set the color parameters so that the feedback is easier to understand.

Step 2: Building Footprints

Nick asks Malcolm if he is ready for Nick to begin; Malcolm says yes. Nick places the building models on the clay model, pressing them into the clay in an attempt to create a flat footprint. Both Malcolm and Nick observe the feedback from the Slope algorithm.

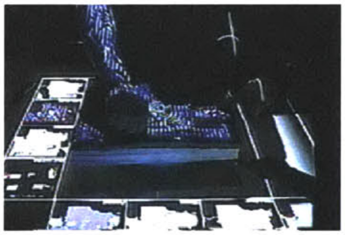


Step 3: Driveways

Malcolm and Nick observe and discuss the feedback from the Slope algorithm to determine the best location for the driveways. Nick begins to sculpt the driveways. Malcolm and Ben adjust the parameters of Slope to try to make the information easier to interpret. Malcolm asks if they can use the cross-section tool to create a cross-section image of their proposed driveway location. By rotating the model on its stand, they can achieve the correct location for the section (as the section tool stays in a fixed Cartesian position). Malcolm copies the angle of the slope from the projection on the tabletop to a piece of paper. He then calculates the slope using a physical scale. He determines it is "bang on" 10 percent.

Step 4: Readjustment

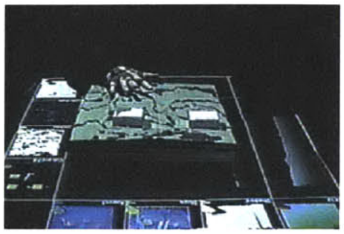
Malcolm and Nick request the Drainage algorithm. They spend a little time attempting to understand the feedback accurately. Once they feel comfortable with their understanding, Nick does some readjustment of the building placement. He then attempts to create flat footprints by pressing and carving.



Step 5: Drainage

Malcolm and Nick contemplate and discuss drainage patterns for the entire site. Nick adds a couple of landforms with the excavated clay from the building footprints.

They request to go back to Slope, and they see that they must adjust some areas that are too steep. Then, back to Drainage. They continue to make adjustments to the surface of the clay, including adding some swales. Malcolm and Nick theorize and discuss how the drainage patterns of the site would effect it over time, including erosion and pooling.


Step 6: Continue to Experiment with IC

Ben encourages Malcolm and Nick to try using the Aspect and Shadow algorithms. Malcolm suggests that Aspect would be most useful if one is concerned with vegetation. He is more interested in Shadow. Ben and Malcolm spend some time adjusting the parameters of Shadow in an attempt to get it to show the shadows at a certain time of year. It works, but the shadows are so tiny that it is not of much interest. Malcolm and Nick both comment on how important contour lines are to their process and particularly so for the contractors. They try the Contour algorithm, then Ben suggests trying Cut and Fill. Malcolm states that they already know that cut and fill are equal because they didn't take any clay away from or add any to the model. I suggest doing a high-resolution scan that Malcolm and Nick had requested earlier. All agree.

Summary, Pair, Part 1: Illuminating Clay Tool Set

It was apparent that Malcolm and Nick had compatibility and experience working together. They communicated constantly by talking and gesturing. They had a common understanding about how to approach the task they were given, and they appeared to have specific complementary roles in the process of solving the task. Malcolm was the mastermind and primary measurer. Nick worked the clay and took care of the details.

Ben Piper, who was operating IC, talked a fair amount during the task, often bringing the attention to the capabilities of IC, so the session became almost half test, half demo. Malcolm, in particular, responded well to this and was very interested in finding ways to adapt IC to his process of design.

Malcolm and Nick did not use the contour map except for a quick glance. They immediately focused on what IC offered. When asked later why they did not use the map, Malcolm replied, "Because the information was there, in IC." They worked in a way that was relaxed and exploratory. Malcolm was clearly confident in his own abilities and did not feel the need to perform the task at a particular speed or proficiency.

Both subjects spent some time at the beginning just contemplating and discussing the feedback from IC, becoming familiar with the site but also getting a feel for this new tool. However, they soon came to a point of feeling comfortable with their understanding and quickly proceeded to place the buildings, carve out building footprints, and place and carve driveways. For that portion of their work, they used the Slope algorithm. Malcolm suggested using the Section capability to check the slope of a proposed driveway location. This required using hand calculations to figure out the slope from the computer graphics. It was a clever adaptation to using IC. After completing the building footprints and driveways, they requested the Drainage algorithm.

Drainage gave them a new view of the site, and they again stopped progress on the task to contemplate and discuss the feedback. Once they felt comfortable with their understanding of the feedback, they readjusted the buildings and driveways and moved on to create swales and a couple of landforms with the excess clay. As Nick was touching up the model, he involved Malcolm in a discussion about the effect of drainage over time on the site, mentioning erosion and pooling. The algorithm itself does not indicate this information. Malcolm and Nick were theorizing this based simply on drainage direction and velocity indicated in the Drainage algorithm.

Both subjects expressed the desire for a better Contour algorithm, stating that "...contours are very important in our process, particularly during implementation." They also tried Shadow but found it ineffective for this particular site. They thought that Cut and Fill and Aspect were not necessary for this task.

9.3.3 Pair, Part 2: Clay Tool Set

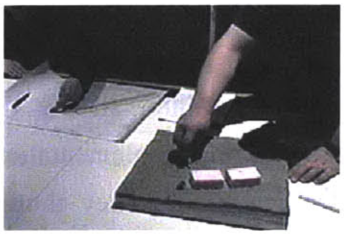
Stages

Step 1: Preparation

Malcolm and Nick are given a task description, clay model, and contour map. Both examine the contour map, touching and pointing to contours and using the physical scale to calculate the slope. They determine that this site is quite similar to the one in the previous task. They discuss actual contour numbers related to possible building sites. They use the physical scale on the map in an attempt to find where the slopes are already 10 percent.

Step 2: Building Footprints

Nick places the building models on the clay model, quickly establishing a good location for them. He then removes them and carves into the clay to create a flat footprint for each.



Step 3: Driveways

Using a physical scale, Malcolm shows Nick where the driveways can "curve around" without having to do much excavation. Nick carves the driveways into the clay model. He uses the physical scale on the model to confirm that the slope is 1:10 or less. He then uses the excess clay to create a couple of new landforms on the model.

Step 4: Drainage

Nick creates some swales while Malcolm chats with Ben on other topics.

Summary, Pair, Part 2: Clay Tool Set

Because so much discussion was happening, by the time Malcolm and Nick got to this task, time was getting short and everyone was fatigued. I believe that this influenced the speed at which they performed the task. Malcolm and Nick began this task by examining the contour map and using the physical scale to determine slopes. They assessed the site quickly, noting that it was quite similar to the site in their previous task. Nick proceeded to swiftly place the buildings, carve footprints, and place and carve driveways. Malcolm used the physical scale on the clay model to ensure that the driveways were at or less than a 10 percent slope. Drainage was not discussed. Nick carved some swales with no input from Malcolm.

Group 1 (Lulu, Holly, Chip, & Will)
Group 2 (Penny, Ruby, & Tim)
Group 3 (Anna, Mike & Joe)

9.4 Student Subjects (Short-Term Task)

Ten students who were enrolled in the Illuminating Sites class participated in the test. I divided the students into three groups of four, three, and three. Because of the number of students and the male-to-female ratio, they did not divide evenly. I set up the groups so that each group had at least one male and one female, and so that the three students who were not Planning majors were each in a separate group. No effort was made to put together friends or students who might have had more experience working with each other. The group of four was assigned to IC; the other two groups were given the control tool sets.

The groups were set up to work in three adjoining rooms but where they could not hear or see each other. Each group was given the necessary materials. Ben Piper was operating IC for Group 1. Eran Ben-Joseph and I roamed between groups to answer any questions. After completing the task, the groups met and briefly shared their experiences and results.

9.4.1 Overview, Group 1

Group 1 consists of two females, Lulu and Holly, and two males, Chip and Will. All are graduate students in City Planning and are in their mid 20s to early 30s.

9.4.2 Group 1: Illuminating Clay Tool Set

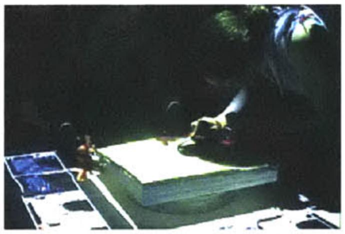
Stages


Step 1: Preparation

Chip places the contour map over the clay model, which is under the scanner of IC. All are examining the map, running their hands over it and attempting to become familiar with the site. Occasionally, someone lifts the map to peek underneath at the clay model. They casually move the building models around on the surface of the map, trying out locations. Lulu wonders if they should mark the contours shown on the map, onto the surface of the model. The consensus from the group is no. Using the map as reference, she marks only the road more prominently on the clay model. Holly attempts to operate IC. She discovers that the mouse is not working. Ben restarts IC. When it comes back on, the group realizes IC is scanning the map and not the model, creating some confusion. They remove the map from the model. They are using the Slope algorithm. All are discussing what they should do first. Finally, Lulu suggests that they should site the buildings, and she puts them on the model.

Step 2: Building Footprints

All are discussing the buildings. Are they houses? Should they be close together? Should there be one driveway or two? They examine the slopes, mostly looking at the map, which is to the side of IC. They are using the scale on the map and gesturing and pointing. They are talking through various alternatives, considering amount of cut and fill, placement of property lines, and driveway placement. Occasionally, they switch to looking at the clay model, using the scale on it. They wish they could have contour lines on the model. Ben tells them the algorithm is not very accurate. They try selecting a section where they want the building to go to determine if it is a viable location. They use the physical scale on the model to determine slope as well. After several tries, they find what they believe is the flattest spot for the building. Then they work to align the angle of the building with the contours, by looking back and forth between the model and the contour map. They attempt to move the model over to the table projection so they can work there, but the scale is not the same as under the laser. (I'm not sure why they want to do this.) Finally, they agree to start cutting the footprint. Holly selects the Cut and Fill algorithm after some discussion with Ben about how it works. Then Lulu begins carving the building footprints, with ongoing input from the others.



Step 3: Drainage

After completing the building footprints, Lulu is joined by Chip and Will in carving some swales. Then, briefly, all four work at carving the clay. Will stops carving, and the other three continue for a while. As they work, there are moments of silence in between banter about the drainage, the building footprints, and the techniques and tools of carving.

Step 4: Driveways

The group moves haphazardly into making the driveways. Chip requests that IC be put back on Slope. Holly is not sure how to end the Cut and Fill session. Something gets confused, and Cut and Fill does not reflect all the changes that have occurred since they started carving the building footprints. All are disappointed. Chip requests Drainage. Discussion about placement of driveways ensues, including evaluating slopes on the model. Section is selected again, and the physical scale is used on the model. Lulu, Chip, and Will all manipulate the clay on the model. The group attempts to use the Cut and Fill algorithm again for the driveways. This time, they get it right, but the cutting and filling was apparently insignificant for IC, and someone's head was also included in the calculation. Time is up.

Summary, Group 1: Illuminating Clay Tool Set

Group 1 began by placing the contour map on top of the clay model, which was under the scanner of IC. All observed the contours and also felt the shape of the model under the map with their hands. They spent some time discussing how to begin and figuring out how to use IC for this task. IC had to be restarted a few minutes after the group started work on the task, so they demanded an extra five minutes to make up for lost time. This was a logical request at the time, although in retrospect, it was obvious that they spent the downtime of IC fruitfully, by continuing to become familiar with the site. Meanwhile, making adjustments to IC while it was up and running probably took time away from solving the task.

After more discussion about how best to approach the task, the group focused on placing the buildings, mostly because Lulu forcefully asserted, "Shouldn't we site these [buildings]?" The group then proceeded to discuss and then decide on building locations, and then carved the footprints. Next, they discussed and carved the swales around the buildings. Last, they discussed and carved the driveways.

Although the implementation of the elements was orderly, the discussion that took place during the entire process of solving the task tended to be circular, as they reconsidered all the elements at every step. This appeared to reflect confusion from lack of experience. Also, having too many variables—four people and the most tool options—may have added to the confusion.

Group 1 struggled to utilize Illuminating Clay effectively. They appeared to gain the most familiarity of the site from the contour map, although the Slope algorithm helped them somewhat. They spent a great deal of time using the Cut and Fill algorithm, but it was not clear what it would have offered them, even if they had gotten it to work correctly. The Drainage algorithm appeared to clarify how the drainage would behave on the site. Also, the ability to grab a section helped them to estimate the slope angle, particularly for driveway placement.

9.4.3 Overview, Group 2

Group 2 consists of two females, Penny and Ruby, and one male, Tim. The two females are graduate students in City Planning. The male is a graduate student at the MIT Media Lab. He has an engineering background. They are in their late 20s to early 30s.

9.4.4 Group 2: Clay Tool Set

Stages

Step 1: Preparation

Penny places the contour map on top of the clay model. All observe the contour lines on the map and run their hands over the surface of it, feeling the shape of the clay model underneath. Ruby places the building models casually on the surface, then all move them around to try different locations. Tim uses the physical scale on the surface of the map, which is on the model, to check slopes. All peek underneath the map occasionally to see the relationship between the contours and the model. Penny asks if they should mark the map contours on the model. It is agreed that marking only the road is necessary. Penny marks the road by poking through the paper map in a few spots. Tim removes the map from the model, and Ruby begins to sketch some placement ideas on the map. All are looking back and forth between the map and the model but mostly at the map. After some time, they go back to working mostly on the model, using the physical scale to measure slope and placing the building models on the clay.

Step 2: Building Footprints

After checking out the slopes and finding the flattest areas of the site, they agree on tentative locations for the buildings. They consider the driveway locations, discussing several scenarios. Finally, time is getting short, so Penny begins to carve the footprints for the buildings. Tim continues to determine the driveway locations. They discuss where swales might be necessary.

Step 3: Driveways

Time is now up, but the group continues to work, all carving the driveways and the building footprints. They comment, "This is fun." They continue to work, adding some quick swales, until they are asked to join the discussion of all the groups.

Summary, Group 2: Clay Tool Set

Group 2 began by placing the map onto the surface of the clay model. They became familiar with the site both by observing the contours and by feeling the shape of the clay model underneath. Decision-making was mostly accomplished by having the map and the model side by side. They sketched on the map, tried out scenarios on the model, and measured on both with the physical scale.

They spent a long time making decisions as to the placement of elements, probably reflecting a lack of experience. They placed the buildings first and the driveways second, then quickly carved some swales.

9.4.5 Overview, Group 3

Group 3 consists one female, Anna, and two males, Mike and Joe. Anna and Joe are City Planning majors. Mike is an Architecture major. All are graduate students in their late 20s to early 30s.

9.4.6 Group 3: Paper Tool Set

Stages

Step 1: Preparation

Mike tapes the map to the tabletop, then tapes a piece of trace over it. At the same time, Joe draws the building footprints on a separate piece of paper using a physical scale to get the correct size. Once drawn, he cuts them out. When the trace is taped down, all three run their hands over the map while observing the contours as if to attempt to understand it better. Mike asks, "Do we know what we're doing yet?" As if to answer his own question, Mike reads the task directions out loud. Anna asks Eran how wide a driveway should be. Mike asks what setback is required for the buildings. Although everyone is busy, the subjects appear to be finding their way in unfamiliar territory.

Step 2: Building Footprints

Joe places the paper building footprints on the map. A discussion follows as to where to best place the buildings. They argue about how to properly read the physical scale to determine the slope. While figuring it out, all point and gesture a great deal at the map, move the building representations around, and use the physical scale on the map. They agree where not to put the houses and begin checking out slopes for the driveways. A few minutes later, they agree on locations for the buildings, stating, "Let's just do this and see what happens."

Step 3: Driveways

Mike and Joe, with scale and pencil in hand, are each working on one of the driveways. All are discussing the slope, drainage, and cut and fill of various locations for the driveways. They are counting contours to establish how they might redraw them in various scenarios. Joe does a section sketch on a separate piece of paper in an attempt to better understand the slopes. For a long while, they continue to discuss how to redraw the contours. Finally, Mike asks, "Why can't we figure this out?" Then joking, he adds, "I wish we had a 3-D model!" All laugh because they know that the other groups do. This appears to relieve the tension that has been building. Soon afterward, they think that they have figured it out. Then, no. A little more figuring, and they agree on a solution.


Step 4: Readjustment

They all work with pencil on the map to harden up the building footprints and driveways and to redraw the contours. At first, there is continued discussion about contour placement. Then there is quiet while all work diligently, with occasional chitchat off-topic. They want to add stairs, but time runs out.

Summary, Group 3: Paper Tool Set

Group 3 spent a great deal of up-front time figuring out where to place the elements. They began by carefully reading the directions, making two-dimensional building footprint models, examining the slopes on the map, and asking Eran questions about issues that they could not determine from the task directions, such as how wide the driveways should be. They moved forward, solving the task effectively but with a great deal of doubt as to whether their assessments and decisions were good.

Once they committed to placement of the elements, they proceeded with hardening up their sketch and redrawing contours. They struggled for a while with how best to redraw the contours to accurately reflect the necessary grading. They mentioned the need for stairs between the driveways and buildings but ran out of time to draw them. During the course of working, no mention was made of swales, although redrawing contours may have achieved the proper drainage. No mention was made about calculating equal cut and fill.

The Class

9.5 The Class (Long-Term Project)

9.5.1 Overview, the Class

All the students enrolled in the class took part in the project. They worked very collaboratively. Individual students or groups of students would assume specific jobs to contribute to the project as a whole. Most all the sessions utilizing IC involved the whole class. The students who prepared the physical models may have spent, at most, two extra sessions with IC outside of class time. IC was used intermittently in the class. Below, I describe only the events that included IC or had a direct bearing on it.

9.5.2 Class Log

04.03.02: Demo of IC

An approximately 45-minute demo of IC is given by Ben Piper in the classroom/conference room in which it will be used. (Two months prior to this, students had a demo at the Tangible Media Group lab.) Several visitors are attending, making it a somewhat formal unveiling of the prototype, and class members have the opportunity to try only a small amount of hands-on experimentation.

04.08.02: No use of IC.

4.10.02: Experimenting with Models

This is the first time that students get to play with IC freely and begin to apply it to the project. Eran Ben-Joseph is directing and Yao Wang is helping to run IC. Students have been experimenting with physical model-making and report that the specially formulated Model Magic still dries too fast for their purposes. They have another approach in progress. Taking a large contour map of approximately half the site, they glued many standing pegs that were cut to the correct height of the topography. The plan is to place a sheet of latex over the pegs, or a thin layer of Plasticine (heretofore referred to as clay), sandwiched to a flexible wire screen. The scale of the model is 1:60, and it is approximately 3 x 5 feet in area.

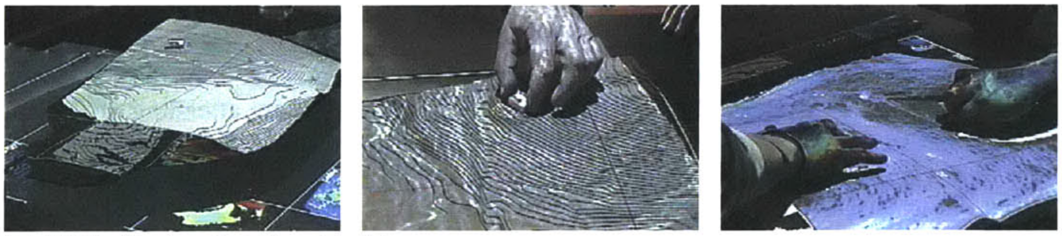
Eran places the peg model under the laser of IC. A student places the latex on the pegs. IC is scanning only intermittently. Everyone is stumped as to what the problem is. They think it might be the height. They experiment by lifting the model up and down. First, it seems to help, but then not. They try the 18- x 18-inch generic demo model made of white Plasticine—it works fine. Now they wonder if the surface of the latex sheet will not scan. (It is somewhat transparent.) They try doubling it up, then replacing the latex with the light-colored sweatshirt from a student. It appears to work better, but still the scanning is intermittent. They try the latex over the sweatshirt. Same result.

The focus moves away from IC to other issues on the project. At the end of class, the clay/screen sheet is finished, and that is placed over the pegs and under the scanner of IC. It doesn't work either. Rotating seems to affect whether it works or not. Yao makes some adjustments on the computer screen to make sure it is set up correctly. Finally, he thinks maybe the metal screen that is showing around the outside of the clay is confusing the laser.

04.15.02: Models for Class
No use of IC, but there is a discussion of what models are needed for the project. They decide to make one design model and one presentation model.

04.17.02: No use of IC.

04.24.02: No use of IC.



04.29.02: Trying Out New Models
Before class: Students have created a 1:60 scale chipboard model of just the area of the site that will contain the housing. It is roughly 15 x 30 inches. Eran places it under the scanner of IC and checks out various algorithms like Shadow and Slope. He then places a layer of white clay backed by wire mesh over the chipboard and pounds it down to conform to the chipboard model. The clay layer is larger than the chipboard model. Eran makes a small dent in the clay and places a building model on the site. The building model is approximately 1 x $^{3}/_{8}$ x $^{1}/_{4}$ inches. It is obvious that the scale of the site pushes the limits of the resolution of IC. 1:20 would be a more appropriate scale for the current prototype. That would mean that the scanning area of 18 x 18 inches could accommodate approximately a one-acre site. Eran points out that at 1:60 scale, a tiny divot in the clay equals five feet.

Carlo Ratti is visiting, and Eran suggests to him that the projections are out of alignment with the model. Yao uses the remote to align the projector. IC is not working consistently. Carlo explains that the scanner needs to "see" some part of the table on the right and left sides of the 18- x 18-inch base that holds the clay model in order to calibrate itself. This is the solution to the problem of scanning the large model from a few classes ago. The model can work as long as it is angled in such a way that it does not block out the table completely.

Class begins: Discussion occurs about possible ways to make a model that will suit the purposes of the project and work with IC. No one is particularly enthusiastic about making models. Eran asks, "How are we going to use [IC] in the class and in the final presentation?"

Eran and the students explore some of the algorithms in IC. They try the clay on the wire mesh over the peg model and then back over the chipboard model. All are trying to understand how to read and understand the feedback. When Drainage is put up, the discussion changes from IC to the water runoff on the site. For a short time, the class is immersed in the site and the project rather than in the prototype.

Slope is selected. Eran puts a piece of trace with a house plan over the surface of the clay. Some students manipulate the clay underneath the trace to modify the terrain to accommodate the proposed housing. This doesn't appear to work well. The students spend some time just observing Slope, then discuss where to place housing units and roads. They switch back to Drainage. They wonder if a building model placed on the clay model will cause the drainage arrow to turn. They can't tell definitively with the tiny house models at the 1:60 scale, but by placing a large block on the site, it is obvious—yes, the arrows are redirected. Students check out the Aspect algorithm.

Eran asks, "Is there anything we can learn from [IC] about the site?" Several students say yes. A discussion about the drainage on the site follows.

05.01.02 Brief Discussion of IC

Eran and Hiroshi lead a discussion about the advantages and disadvantages of IC. Hiroshi poses the question, "Does IC help novices design better, or nondesigners understand the project better?" A student replies, "At a presentation, if there is a model, everyone flocks to it." Another student replies, "It is harder to change a model, so drawing is still great at the beginning stages." Hiroshi questions, "What advantages does CAD offer?" Eran replies, "The biggest advantage of CAD is the ability to make changes. It saves so much redrawing time." A student replies, "If you want to do any analysis with software, you must have a CAD model to run the analysis on." Another student adds, "You can also collage and scale." Eran states, "Accuracy is not necessarily better with CAD, but it probably can do faster calculations." I ask, "Is IC comparable to GIS (geographic information system) because it does some of the same type of analysis? A student replies, "In GIS, you can change the analysis, but you cannot change the site. Most offices create several alternatives to a design proposal and run simulations on each." I ask, "What else is IC adding to the early phase of the design process besides rough analysis?" No one is really sure yet. A student replies, "The scale issue is major..." Another student replies, "One of the disadvantages of IC is that we can't capture the before and after and compare them at this point."

05.06.02: Projection on Table

Some students have worked out several proposed housing layouts for the site. The drawings they made are printouts from Illustrator. They attempt to lay them on top of the chipboard model in correct alignment. Someone gets the idea (obviously from experiences with IC) to project them onto the tabletop where the model is sitting. It requires only a small amount of adjustment and rearranging of a couple of cables from the IC PC to a second PC in the same room. The display from the second PC is now connected to one of the ceiling-mounted projectors. The display fills the tabletop. The chipboard model is rotated and moved to see how the housing plan might fit on the site. Some modifications are made in the drawing in Illustrator in response to seeing how the plan works with the terrain. At times, the model is removed and trace is laid down under the projection; students explain ideas and then propose changes to the Illustrator drawings. This bootstrapped system works very well. The whole class can see and contribute much more easily than when looking at a small screen or even a wall projection. Everyone can easily point, gesture, and sketch. The session is intense, and it appears that much progress is made on the housing layout.

05.08.02: Short-Term Task

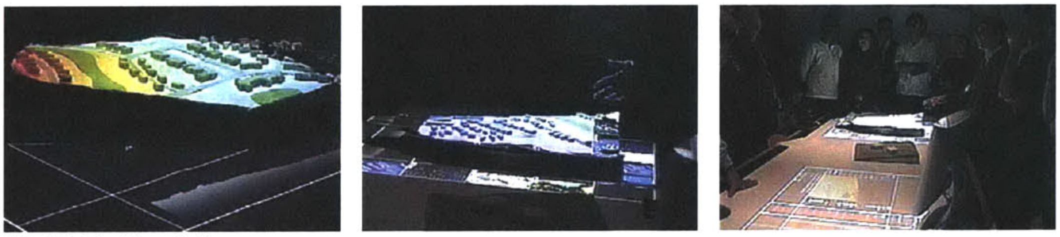
The experiments with IC are done.

05.013.02: Preparation for Final Presentation

IC is not used.

05.15.02: Plan for Final Presentation

A plan for the final presentation is created. IC is not used.



05.17.02: Final Presentation

IC is used toward the end of the presentation. The plan is to show drainage, but it then segues into a full-fledged demo of IC for the visitors.

Summary, the Class

The class material included many issues that were not related to or enabled by IC. This included such things as making a site visit, researching environmental laws, checking into local zoning ordinances, and reviewing related development projects. Thus, it made sense that IC would be used in class less than one-third of the time. According to Eran Ben-Joseph, "It's not the perfect solution. The class we're using this technology in, I don't think there's a perfect match there. But...maybe it's a place to try it."

In class, it was first incorporated while building physical models of the site. The models needed to be appropriate to the project and also work with IC. Second, IC was used with those models to analyze the site and try out some design scenarios. Third, it was used in the final presentation. Students reported only two instances outside of class time that they used IC. One was to test the models while making them. The second was during preparation of the model for the final presentation.

Students struggled to find a size and material to build a model to work with IC. A latex sheet over pegs, cut to the height of the topography, was their first solution. The scanner had trouble reading the latex, and the pegs were too spread out to be effective. In the end, the students found that a chipboard model, which they were comfortable making, worked surprisingly well with the analysis functions of IC. The feedback was easy to read despite the dark color and layered shape of the chipboard. Placing a $^1/_4$-inch-thick sheet of Plasticine over the chipboard provided a smooth white surface for feedback, and small modifications to the surface could be tried out as well.

Through exploring the algorithms of IC, the students became familiar with the project site. It was a unique platform for discussion, as students learned the tool as well as the site, moving fluidly from focusing on how the tool worked to the shape and nature of the site. What was most startling as an observer was to witness when the tool became transparent, and excitement about what the tool revealed was paramount. This happened approximately one-quarter of the time that students were using IC in class, mostly with the Drainage algorithm. The class also bootstrapped part of the system, adapting it for their own use. They connected one of the ceiling-mounted projectors to another computer where the layout sketches for the housing were saved. All could easily gather around the projection on the tabletop. They placed their models under the projection to see how the layouts fit on the topography. The sketches, done in Illustrator, could be sized to the approximate scale of the model. They also placed trace under the projection, so that they could sketch modifications to the designs.

The class used IC as the finale to their final presentation. Whether it was effective in getting their program across or in convincing anyone of its value was not apparent. The presentation, which was complete at that point, moved on into a demo of IC, because it was of interest to the professionals who were invited to critique the presentation.

9.6 Summary of Findings

9.6.1 General

Fundamental

Importance of Touch Was Universal

Touch was universally significant among all the subjects in getting familiar with the site and in making decisions for the placement of elements. Almost every subject ran his or her hands over the site as the first step, whether working on a two-dimensional contour map or a three-dimensional model. With the map, running hands over the representation of contours appeared to aid in understanding the site.

IC Fills a Need in Certain Areas

It appeared to be easier for the subjects to intuit certain kinds of information from the site than other kinds of information. This depended on the type of representation they were working with. Slope was fairly easy to visualize from a contour map; Sun/shade was easy to visualize from a clay model. Drainage, on the other hand, was difficult to visualize from any of the physical representations (see next paragraph). IC appears to be able to fill the gap when a designer cannot intuit information from a physical representation of a site.

Drainage #1

Drainage appeared to be the most useful, and fascinating, algorithm. It clearly provided insight into this natural force on the site, which was difficult to intuit. When subjects were not using IC, drainage issues were considered more briefly. All subjects used the Drainage algorithm. In interviews, all the students mentioned Drainage as the most helpful function of IC. For example, one student said, "It was also interesting to see how the drainage pattern changed to make sure that our swale actually worked the way it should have worked. That's something that I wouldn't have normally done or had the ability to do."

All Subjects Requested a Contour Algorithm, Settled for Slope

All subjects wanted contours projected onto the clay model. Several subjects mentioned it as a *very* necessary function. Most used Slope as an alternative to contour information to understand the percentages of the slopes. However, it was difficult to always understand the feedback from the Slope algorithm. Simon suggested that a grid at a known scale projected on the model would be very helpful.

Section Was the Runner-up

The Section capability was helpful in figuring out the slope at a particular spot on the model. It always was used in concert with a physical scale to calculate slope with pencil and paper.

Landscape Architects vs. Planners

Landscape architects found IC to be useful as an early design-phase tool; planners found it less so. Landscape architects frequently build clay models and use them in the initial design phase of a site. For them, it is a familiar vocabulary. Planners sketch with pencil and paper and not frequently with models. However, planners found IC useful as a presentation tool.

Believing in the Accuracy of Technology

Because IC is a prototype, there are some anomalies in the accuracy of the feedback. However, it was apparent that everyone assumed the computer feedback was accurate to begin with. The more experience that a subject had, the more likely he or she was to recognize these anomalies as they used IC.

Amazing to Witness When a Tool Becomes Transparent to the Work

When a tool becomes transparent, the focus of the user shifts from the tool—getting it to work, attempting to decipher the feedback, adjusting controls, and so forth—to the task itself. There were several strikingly clear instances of this, usually occurring while using the Drainage algorithm.

Trivial

Getting Used to the Feedback Took Time

Everyone needed time to get used to the graphics in order to understand the feedback. Not all the feedback was easy to understand.

Who Was Operating Made a Difference

It was not possible to always have the same software operator for all the experiments. Ben Piper and Yao Wang shared the job, and they both had distinctly different approaches. Ben tended to encourage the subjects to try out many options in IC. He often commented on how they were using it. Yao let the subjects drive the choices of which options to try.

9.6.2 Short-Term Tasks

The Methodology of the Professionals Was Clear and Organized

For the professionals, each stage (i.e., Preparation, Building Footprints, Driveways, and Drainage) was composed of a clear set of steps: analysis, decision, and reflection. A fourth step, implementation, appeared to happen, overlaid on the first three steps, and carried on to completion. In other words, they spent little or no time with idle hands. They worked seamlessly from one step to the next, and then from one stage to the next, using measuring, drawing, or carving in order to think by doing.

The Methodology of the Novices Was Disorganized

The novices spent a great deal of time at the first stage (Preparation) analyzing and deciding placements for all the elements. They measured and drew, but they were not productive much of the time. Before implementing each subsequent stage (i.e., Building Footprints, Driveways, and Drainage), they would quickly revisit the decisions they made at the Preparation stage. But more so than the professionals, while implementing a decision, their focus would stray to other topics. Some of this behavior could be attributed to working in a larger group and feeling the need to come to a consensus before moving forward.

Order of Approach Was Consistent; Decisiveness Was Varied

All solved the problems with the same order of stages: Preparation, Building Footprints, Driveways, Drainage. One student group switched the order of Drainage and Driveways.

IC Helped Novices Understand the Site Better

A question that had been present in the developers' minds was: Would IC be a better tool for novices than for professionals? Based on my observations, I believe that IC helped novices understand the site better because it offered multiple representations of the site. However, the novices were less equipped than the professionals to know what to do with that information.

Professionals Utilized IC More Effectively

Professionals knew what information they needed about the site for each step and actively sought that from IC. They remembered specific functions from the demo that they then requested during the task at the appropriate time.

Two Tasks Equaled Less Vigilance on the Second

When subjects performed two tasks, they performed the first one with more diligence.

Implicit Assumptions About What Was a Finished Task

All subjects worked to the level of accuracy that the medium with which they were working afforded them. For instance, those subjects working just with contour maps redrew the contours for the new elements, requiring a great deal of mental math. Those working with the clay models simply manipulated the clay, requiring a sense of three-dimensional form but no math. Those working with the contour maps, where it is very difficult to visualize the flow of water in swales and to draw the contours for them, tended to slur over the effectiveness of their swales. Those working with the clay models, where it is easy to create swales and intuitively make guesses at the water flow, took swales more seriously. Those working with IC, where the Drainage algorithm clearly illustrated the flow of water, worked hardest to make their swales effective.

IC Influenced the Amount of Time Spent on Tasks

This could simply be due to the fact that one medium can work better for certain tasks than another. For example, IC was good at showing drainage patterns compared to the clay model or contour map (which left it up to the intuitions of the designer). Could this kind of influence, that a tool or medium has, have broader implications in a design process?

9.6.3 Long-Term Project

Fundamental Mismatches

Making Clay Models

Planners don't usually make clay models to use for design purposes. Specifically, they don't create clay models, like landscape architects do, to "sketch" new topographic forms by aggressively manipulating the models. Instead, they commonly make models to better understand the site, try out layout schemes, and make presentations. These are usually chipboard and sometimes have a thin layer of clay on top. Attempting to make a model, or models, that suited the capability of IC was an unwanted burden to most of the students.

Working with Scale

The scale of the long-term project was much larger than was appropriate for the parameters of IC. The project site was 200 acres, and even a model of half the site at 1:60 was large: 3 x 5 feet. At that scale, the housing models were in the half-inch range and any little divot in the clay represented five to ten feet of depth. Not only was it a problem to get such a large model under the scanning laser of IC, but it was also impossible to make reasonable manipulations to the clay at 1:60 scale.

Trivial Factors

Ease of Use of the Prototype

Compared with typical CAD systems that architects and planners use, IC has only a handful of commands to learn. However, it did not lend itself to an immediate comfort level in the subjects for the following reasons:

> IC was difficult to start up. For instance, three projectors and one scanner had to be turned on. They required two remotes, which were kept locked up in the department

office. The cables from the computer to the projectors had to be hooked up correctly; they were often rearranged by other classes during the course of a day. One monitor served two computers and often had to be reconnected to the computer with the IC software. A password was required for the computer. A text command was required to start up the software.

Because of the three software windows that were projected with IC, it was easy to lose the mouse cursor and difficult to recover it, once lost.

The amount of development effort put into the user-friendliness of the IC interface was limited due to time and budget constraints. For instance, to enter a time of year for the Shadow algorithm, one would type 63 (for the 63rd day of the year) rather than March 3.

IC was, at times, flaky and had some known bugs that confused the users.

IC was installed in a classroom/conference room that was highly utilized, so at any given time during the day, chances were that another event was occupying the room.

IC Is a Better Presentation Tool Than a Physical Model Is

IC was used only in one formal presentation—at the end of the class. However, it appears quite clear that it can enhance a presentation model with more information than a physical model alone provides. In the student interviews, five out of five were of the opinion that IC was a good presentation tool. Two reasons were mentioned: It made invisible forces more understandable; and when someone made a suggestion, it could be more easily and accurately portrayed. One student put it this way:

> *...we could all truly understand what one person was describing and try it out. Typically, I remember that in the community meetings I've had with my job, I would have to explain to someone, "Well, it* might *look like this, and I* might *be able to draw it out." But to have had a model there to show people* exactly *what I mean would have been really helpful. And having a model that you can move things around in and manipulate the land would have been helpful as well.*

Negative Effects

In the interviews, four out of five students stated that time is so short for the amount of information they need to learn for their major that time spent with IC might be better spent learning more about site planning. (The one student who did not feel this way was not a Planning major.)

Students Benefited Indirectly

Students probably learned more about the project site and site analysis than they might have otherwise. Simply spending the extra time observing the feedback from the analysis algorithms of IC brought extra attention to issues such as the shape of the land and the drainage. Also, the emphasis on models probably not only added to a greater familiarity with the project site but increased students' awareness of model-making. In interviews, many stated that they enjoyed using IC and felt that it was a valuable experience.

> *Leaving this class and reflecting back on the class, I am a little bit disappointed that we weren't able to finish everything we had to learn about site planning, like traffic and road issues. It's a shame. A lot of that time was devoted to the technology. However, I think the technology is good. In a way, if we had gotten a lot of the technology and were able to really integrate it and use it, then the time would have definitely been worth it. This is not a final-product tool. It's something that you need at each step to check on what you're doing, to see if you're on the right track. I felt that this technology either has to be more integrated to what we did in the beginning or completely left out. It's not fair to the technology and it's not fair to the class to stick it on as a side note. It didn't do justice to either aspect. But I think it's a really neat technology, and I hope it's continued to be worked on and that it's not laid to rest, because it's fascinating.*

Chapter 10:

Conclusions

I have argued that superimposing physical media and the digital medium to create new design tools and materials would have cognitive, motor, and emotional advantages for designers over the current desktop GUI. It would also remedy the frequent need to print and digitize that exists in the current side-by-side work environment. At the conclusion of this work, I am confident that superimposing physical media and computation would create more human-centered interfaces.

Combining tactile and spatial qualities with the CAD interface would include these advantages to the designer:

> **Cognitive:** The necessity to process understanding of three-dimensional forms from a reduced version of one sensory input, i.e., only vision in a two-dimensional plane, would be eliminated.
>
> **Motor:** Efficient and skilled motor control would be easier with increased sensory feedback, particularly touch.
>
> **Emotional:** Pleasurable feedback to the senses, which can motivate and inspire, may increase creativity, skill, and technique.
>
> **Practical:** The need to constantly digitize and print may be reduced.

As one example of superimposing, the Illuminating Clay prototype successfully combines advantages of physical and advantages of digital representations. The physical clay model enables the designer to quickly understand complex three-dimensional forms, because he or she can create and manipulate them by hand, while moving about and seeing (and feeling) the results of his or her actions in a physical three-dimensional space. The projected graphics from the analysis algorithms provide the designer with feedback as to how making formal changes in the landscape geometry such as slope or aspect, might influence complex dynamic effects, such as shadow-casting or drainage. By inserting Illuminating Clay into my taxonomy of physical and digital media qualities (Table 4, below) suggests that Illuminating Clay retains more useful qualities than either realm separately.

Qualities	Physical	Digital	Illuminating Clay
tactile	+	-	+
olfactory	+	-	+
spatial	+	-	+
ambiguous	+	-	+
persistent	+	-	+
real-time	+	0	+
physically transformable	+	-	+
logically transformable	-	+	-
ephemeral	-	+	0
explicit	0	+	0
representative of space	0	+	0
fast	0	+	0
intelligent	-	+	+
precise	0	+	0
visual	+	+	+
aural	+	+	+
reworkable	0	+	0
copyable	0	+	0
portable	0	+	-
(totals balance out)	6	6	8

Table 4: The ratings suggest that a quality is present (+), not present (-), or in between (0).

10.1 Experiments with Illuminating Clay

The evidence from the user experiments with Illuminating Clay substantiates that, compared to current practice with existing CAD systems, IC brings some of the advantages of computation to the beginning phases of design without losing the tactile, spatial advantages of a physical medium. It does this by enabling the designer to easily rough out a design concept, while making the process more informed by supplementing the designer's eyeball analysis with objective analysis. Illuminating Clay also facilitates communication among designers by allowing them to utilize a physical model—which is easy to gather around, comprehend, and point to—but have the added fluid ability to try out various what-if scenarios and get immediate rough analysis of those options. Below is a more detailed summation of the findings of the experiments.

10.1.1 Findings

Fundamental Advantages and Disadvantages

Five fundamental advantages to Illuminating Clay were evident from the research:

1. **Illuminating Clay allows a designer to easily rough out a concept.** Although initially, a small amount of confusion existed over how to interpret the graphics, subjects found the low-resolution feedback useful for understanding the given site and roughing out a solution.

2. **Illuminating Clay makes the process more informed.** The designers' intuitions about the forms they were creating with the clay were confirmed by the feedback, and they could come to decisions easier and with more confidence. Subjects felt more certain that they were falling within the constraints of the design problem.

3. **Illuminating Clay facilitates communication among designers.** It did this beyond what a physical model does by supplementing human-to-human interaction with immediate visualizations that were more accurate than could have been sketched by hand. Subjects felt empowered with a better capability to express ideas on the fly to other designers and nondesigners.

4. **Illuminating Clay creates a real-time digital model of a physical model.** Although the digital model may not be of high quality (it is a "cloud of points" typical of three-dimensional scanners), the time and cost of digitizing and/or printing in the early design phase could be reduced.

5. **Illuminating Clay can impact learning.** By providing more varied representations of static landscape forms and dynamic effects, student subjects became more familiar with the site of the class project.

One fundamental disadvantage was evident from the research:

1. **Illuminating Clay presents the risk of "over-engineering."** It tended to keep the designer more focused on the physical constraints, taking him or her away from focusing on aesthetic concerns. Designers tended to explore the various algorithms of Illuminating Clay, which resulted in considering more of the practical problems that might arise with their solution. Just the presence of Illuminating Clay implicitly shifts focus from aesthetic to practical concerns. One student suggested:

   I think a lot of time could be saved if the two [design and analysis] were combined. Quite possibly, better decisions could be made. At the same time, perhaps it would be introducing the over-engineering of site planning, which could be a problem. In much the same way that engineers have controlled road systems with the over-engineering requiring such wide roadways and such, being overly conservative could occur.

Short-Term Limitations

Numerous short-term limitations were highlighted by the research. These will likely be altered with anticipated advancements to the technology or by putting more resources into a subsequent prototype.

1. **Unclear feedback:** The design of the graphical feedback needs more refinement. It is too dense, complicated, and confusing at times. (See *Type and Amount of Feedback* in section 10.2 "Lessons Learned About Tangible Interfaces.")
2. **Choice of algorithms:** The selection of landscape analysis algorithms in Illuminating Clay needs to be modified, eliminating some and adding others that are more standard to landscape architecture and planning.
3. **Small scanning area:** The size of the scanning area, which is limited to an 18- x 18-inch square, is much too small for most landscape models, although it is appropriate for very small sites or quick sketches.
4. **Confusing mouse interaction:** It is awkward to interact with a mouse to activate specific algorithms and set parameters for those algorithms. For these experiments, a standard mouse was used (although a wireless mouse was intended but arrived late). Even so, the awkwardness arose not from being tethered by a mouse cord but from losing the curser that needed to travel between all three display windows. Ironically, although working with the clay model is so direct and hands-on, inputting commands to the software is more difficult than working in a standard GUI due to the various locations of the projected GUI windows.
5. **Little or no natural light:** Like most computer displays, Illuminating Clay works best in a dark or dim room. Indeed, the projection is invisible in a well-lit room. Balancing the light needed to see the physical model and the darkness needed to see the computer projections is tricky.
6. **Difficulty of making clay models:** Illuminating Clay requires physical models of some kind, preferably with a malleable material like clay. Not all landscape designers or site designers have the skill to build clay models, and having to do so by hand is substantial work.
7. **Immobility:** The prototype is completely immobile. This is inconvenient in that the designer must always be transporting potentially heavy or delicate models to the "Illuminating Clay room" from his or her own workspace.

10.1.2 Limitations of the Research

Evaluating Illuminating Clay proved challenging for several reasons, and as a result, I acknowledge some limitations to my methods.

1. **Size of the study:** This was a small study.
2. **Consistency of variables:** The students in the class were familiar with the goals and shortcomings of Illuminating Clay, and the two operators of IC each had a very different style of interacting with the subjects.
3. **Learning curve of the user:** The commands to operate the prototype were easy to learn, but Illuminating Clay was not necessarily easy to integrate into a personal design process.
4. **Choice of an appropriate task:** Real-life projects are long and have no control project. Short tasks lack reality but can be tightly controlled. Including both types of tasks appeared to be the best solution, but it involved compromises as well.

10.2 Lessons Learned About Tangible and Augmented-Reality User Interfaces

Regardless of the limitations of the research and in addition to the specific findings of the experiments, several fundamental issues were highlighted by this research that have implications for a broader scope of superimposed, tangible and augmented reality interfaces for CAD systems These issues include the ability to accommodate appropriate scale, the right type and amount of computational feedback, and the necessity or not of real-time feedback. Each is discussed in more detail below.

10.2.1 Appropriate Scale

Architects design using representations of buildings or tracts of land. To work, they need to scale these large projects to a reasonable size. What is reasonable? Not so small that the necessary elements are imperceptible and not so large that they cannot fit on a tabletop is what usually defines the limits, although there are exceptions. Large, complex projects sometimes require much larger models to be built. A variety of scale becomes important as the design process progresses from overall concepts to more-specific details. The original massing of forms for an idea might have been drawn on a dinner napkin, while toward the end of design development, a detail of a hinge could take up an entire piece of paper. Tolerances in scale vary between architects and landscape architects. Hasbrouck suggests that "...as landscape architects, our tolerances are much different. Whereas in architecture, you might be working up to 1/32 of an inch, depending on what material you are using, we might deal with six-inch tolerances in some instances. We also operate at a range of scales, from backyards to regions."

In the Illuminating Clay experiments, the tract of land used for the long-term project presented some scale challenges. Because the site was 200 acres, it needed to be scaled to 1:60 (1 inch = 60 feet) to create a model of it that was approximately $2^1/_2$ x 4 feet. This was a reasonable size for the class to build, store, and move around the studio as needed. However, at that scale, the proposed buildings were less than $^1/_2$ inch each—not a size to effectively work with the design of the housing development. Although the class needed that 1:60 model of the entire site to design the golf course, they would have benefited from another model at a larger scale for just the housing development footprint (which took up only about one-sixth of the land). But given the time constraints of the class, the second model was not made. As it was, the 1:60 footprint of the housing development did not fit under the scanner of Illuminating Clay all at once, anyway.

The scanning area of Illuminating Clay is restricted to 18 x 18 inches, a decision based on hardware and software constraints and tradeoffs. Students attempted to work with the model by moving it to various positions under the scanner. This worked only part of the time, because the scanner depends on detecting at least one corner of the table to calibrate itself. Obscuring the corner seemed to set off a series of confusing responses from the system, which then took several minutes to return to a normal state.

10.2.2 Type and Amount of Feedback

What is the right type and amount of computational feedback in a tangible interface? Feedback occupies our attention. How much feedback helps in the creative process and how much hinders, or brings the focus of the designer away from formal issues to the specifics of, say, slope or drainage? Should solutions to this question focus on type of graphics in the feedback, the intensity of the graphics, resolution of graphics, or all three? Should numbers, even approximate numbers, be provided in the feedback, or should it consist of only abstract, graphical representations?

In the experiments with Illuminating Clay, two qualities of the feedback were evident. First, it was somewhat confusing to understand. This may have been due to the density of the projected graphics or to the nonstandard style and color of some of the representations. Second, it was bright, busy, and attractive. This made for an attractive demo, or first impression, but may not be the best solution for productive work.

The question really becomes: What should occupy the designer's attention? In the experiments, the subjects' attention and time spent on a task were altered by the presence of Illuminating Clay. This could be a positive result, bringing attention to a neglected aspect of a task (such as drainage of a site) that is difficult to predict in detail without the aid of the computer. Or it could be a negative result, causing the designer to get distracted by the desire to make the physical constraints work, and not focus on his or her aesthetic concept.

10.2.3 Real-Time or Not

Real-time interaction is when the response or feedback from the computer is not noticeably delayed, i.e., it feels instantaneous. Gestures and movement, in particular, require real-time computer response in order to feel natural. For example, in a VR (virtual reality) system, when you step forward, you expect the graphics to respond instantly to your movement to reflect your forward movement. If, instead, they take several seconds to "catch up" with you, the system is disorienting and, in the end, ineffectual.

During the development of Illuminating Clay, it was a priority to get real-time response from manipulations of the clay model. We on the development team believed that otherwise, the system would be disorienting and ineffectual, like in the VR example above. Tradeoffs with the resolution of scans and graphical projections were made in order to keep the response time to just under two seconds, which we decided felt close enough to a real-time response.

As it turned out, the experiments showed that users didn't use the feedback in real time. Instead, they tended to manipulate the clay and then stop and look. The amount of time in between concentrated "lookings" changed with the particular task, but it begs the question: What is the frequency of looking, when considering specific tasks or specific kinds of feedback? One looks in real time while shaping clay in order to orient the hand and tools, and to see how the clay is changing. That looking likely varies (I'm guessing from my own experience) between being focused and defocused. So the looking is not just defined by frequency but also by type.

Information such as the analysis feedback that was coming from Illuminating Clay appeared to require a different type and frequency of looking from the kind that occurs when manipulating a clay form. It did not require the defocused, continuous looking that manual control or form-making does. Instead, the type of feedback that Illuminating Clay provides required periodic, focused check-ins. The designers used the computer feedback to confirm or adjust their own eyeball analysis, then would work without the benefit of the computer feedback until they wanted to confirm their intuitions again. I estimate that the frequency of looking ranged from a couple of seconds to at least ten minutes. And rather than being evenly consistent, the pattern of looking could be described as a declining curve, frequent at first then progressively less over time for a specific task such as determining and carving the driveways. Usually at the beginning of the task, there would be a few minutes of prolonged looking as the designer contemplated the analysis feedback for the first time.

The fact that having hands on the clay altered the feedback may have influenced the pattern described above. With the current configuration of Illuminating Clay, it is almost impossible to manipulate the clay and get accurate computational feedback simultaneously. A discrete update switch, that is either automatic when no hands are detected, or manual may be a good solution.

10.3 Next Steps

Although this research was not an evaluation of the Illuminating Clay prototype, the use of it in my experiments revealed its advantages as well as some limitations. It is evident that Illuminating Clay is successful in its broad concepts but requires numerous small modifications should it be taken to another level of refinement. Some of the limitations have obvious solutions, such as adding desired analysis algorithms. Other solutions are not so obvious and may require several iterations of implemention and testing to get them right. Rather than comprehensively rebuilding the prototype and then doing a large evaluation, I believe it would be more informative to conduct discrete user tests on specific issues. In Section 10.3.1, "Discrete Tests Specific to Illuminating Clay," I make some suggestions for those tests.

It's tempting to want to leap into building other prototypes. However, in developing new prototypes, there is often not enough time or resources available to thoroughly investigate what makes sense for users. Prototype evaluations are often driven by the need to publish or to secure funding and approval to push that particular prototype to another level. In order to further the general development of tangible and augmented reality interfaces for CAD systems, I believe it would be valuable to conduct some small discrete tests that are designer-centric rather than prototype-centric. These could be tightly controlled and thorough. In Section 10.3.2, "Discrete Tests General to Tangible and Augmented-Reality User Interfaces," I make some suggestions for those tests.

10.3.1 Discrete Tests Specific to Illuminating Clay

Clarifying feedback

Design different styles, colors, and intensities of computer graphics projections for several of the most-used analysis algorithms and see if they influence comprehension of the feedback.

Influencing focus

(1) Investigate if the feedback can become more peripheral and still have value, rather than demanding so much of the designer's attention. (2) Try some algorithms that have aesthetic influence, rather than just analysis of practical features.

Investigating the need for real time

(1) Try different rates of refresh of the computational feedback. (2) See what designers would choose if could they set refresh rates themselves. (3) Try having refresh stop if hands are detected by the scanner.

10.3.2 Discrete Tests General to Tangible and Augmented-Reality User Interfaces

Comprehending three-dimensional forms

Present a three-dimensional form represented in various media: a CAD wire-frame model, a CAD rendered model, a physical drawing, and a physical model. Determine which medium is easiest to comprehend and recall the shape of.

Manipulating three-dimensional forms

Have subjects build a three-dimensional shape to specification with various media (as noted above). See how each medium influences the speed, accuracy, process, and results. Try the same test, but have subjects modify an existing shape.

Comparing vision and touch

Have subjects solve a design problem with one sense eliminated, either vision or touch. Look for subjects' efficiency and ways of compensating for the missing sense in the design process.

Influencing emotional state

Test to see if the emotional state of a designer is influenced by his or her use of different media. (Emotional states influence creativity, confidence, and memory.)

10.4 Summary

The sense of touch and space is fundamental to most three-dimensional designers such as architects. In our highly visual culture, we seem to have forgotten how important touch is in the design process. Design is often characterized as a highly conceptual activity. Early CAD researchers believed it could reside completely within the untouchable, ephemeral space of the computer, much like visualizing ideas in your thoughts. Who can design like that? Frank Gehry, one of the most notable architects working today, does the opposite: His design process is heavily dependent on touch and physical materials.

This is not to suggest that vision is not important. It is, in fact, the combination of vision and touch in a three-dimensional space that allows humans to excel at comprehending and manipulating tools and materials. It is these three elements—vision, touch, and three-dimensional space—that are crucial to design. To eliminate two of these elements—touch and three-dimensional space—and have only vision, as in the GUI, handicaps the designer. A GUI is appropriate under certain circumstances, such as text editing or, in some cases, creating measured drawings, but as the only interface to CAD, it severely limits how and when computation can be used in the design process.

To think that humans could or would want to design exclusively in a disembodied environment was a profound misunderstanding of human nature. Our educational system provides an informative parallel. Much of the last 200 years of education consisted of rote memorization from written or spoken words. During the past 30 years, influenced by the work of many, including Piaget and Papert, education has become multisensory. This includes doing field research, looking at artifacts, conducting experiments, building projects, singing songs, writing poems, writing stories, wearing costumes, and eating food, along with the traditional activities of reading books and writing reports. Substantial research suggests that this kind of educational environment is more effective because it *embodies* ideas rather than presenting them as abstract, disembodied events or facts.

I believe that it is time to engage the body with computer interfaces for CAD systems. This has particular relevance to the human-computer interface community, with the increasing interest in and popularity of ubiquitous computing, augmented reality, and tangible interfaces. All humans depend on their sensorimotor systems to interact with the physical world. Although it is possible that creative designers have a greater tactile and visual sensitivity that has drawn them to their profession, it is certain that some of what has been learned in this thesis can be generalized beyond the design community to all humans.

NOTES

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11. Ibid., 293
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13. Cooper, A., *The Inmates Are Running the Asylum: Why High-Tech Products Drive Us Crazy and How to Restore the Sanity,* 19–20
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15. Ibid.
16. Ibid.

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6. Ibid., 229-235
7. McCullough, M., *Abstracting Craft: The Practiced Digital Hand,* 13
8. Ackerman, D., *A Natural History of the Senses,* 229-235
9. Pawluk, D.T.V. and R. D. Howe, "Dynamic lumped element response of the human fingerpad"
10. Buxton, W., "Touch, Gesture & Marking"
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16 Goldstein, E. B., *Sensation and Perception,* 459
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18. Harrison, S. and S. Minneman, "A Bike in Hand: A study of 3-D objects on design"
19. Conversations with Marvin Minsky, 2000.
20. Schon, D. A., *The Reflective Practitioner: How professionals think in action*
21. Goel, V., "Cognitive Role of Ill-Structured Representations in Preliminary Design"

22. Bilda, Z. and H. Demirkan, "An insight on designers' sketching activities in traditional versus digital media," 49
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25. Goodman, N., *Languages of Art: An Approach to a Theory of Symbols,* 113
26. Ibid. 113

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1. Ackerman, D., *A Natural History of the Senses*
2. Ibid.
3. Csikszentmihalyi, M. and R. E. Robinson, *The Art of Seeing: An Interpretation of the Aesthetic Encounter,* 12-13
4. Ackerman, D., *A Natural History of the Senses*
5. Csikszentmihalyi, M. and R. E. Robinson, *The Art of Seeing: An Interpretation of the Aesthetic Encounter,* 12-13
6. Papert, S., *Mindstorms: Children, Computers, and Powerful Ideas*
7. Conversations with William J. Mitchell, 2002
8. Ibid.
9. Ibid.

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1. Weiser, M., "The computer for the 21st century"
2. Fitzmaurice, G., H. Ishii, and W. Buxton, "Bricks: Laying the foundations for graspable user interfaces"
3. Ullmer, B. and H. Ishii, "Emerging Frameworks for Tangible User Interfaces"
4. Ibid.
5. Fitzmaurice, G. W., R. Balakrishnan, and G. Kurtenbach, "Sampling, Synthesis, and Input Devices"
6. Conversations with William J. Mitchell, 2002
7. Ibid.
8. Ibid.

Chapter 7: Related Prototypes

1. Aish, A. and P. Noakes, "Architecture Without Numbers: CAAD Based on a 3-D Modeling System"
2. Frazer, J. "Three-Dimensional Data Input Devices"
3 Ryall et al., "Physical Constructions Kit"
4. Kitamura, Y., "ActiveCube"
5. Resnick, M., F. Martin, R. Berg, R. Borovoy, V. Colella, K. Kramer, and B. Silverman, "Digital Manipulatives: New Toys to Think With"
6. Gorbet, M. G., M. Orth, and H. Ishii, "Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography"
7. Orth, M. A., *Sculpted Computational Objects with Smart and Active Computing Materials*

8. Hinckley, K., R. Pausch, J. Goble, N. Kassell, "Passive Real-World Interface Props for Neurosurgical Visualization"
9. Fitzmaurice, G., H. Ishii, and W. Buxton, "Bricks: Laying the foundations for graspable user interfaces"
10. Sinclair, M., "The Haptic Lens"
11. Underkoffler, J., B. Ullmer, and H. Ishii, "Emancipated Pixels: Real-World Graphics in the Luminous Room"
12. Balakrishnan, R., G. W. Fitzmaurice, G. Kurtenbach, and K. Singh, "Exploring Interactive Curve and Surface Manipulation Using a Bend and Twist Sensitive Input Strip"
13. Lee, J., "HandSCAPE," 168
14. Piper, B., C. Ratti, and H. Ishii, "Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis"
15. Wang, Y. et al., http://tangible.media.mit.edu/projects/SandScape/SandScape.htm
16. Raskar et al., "*Shader Lamps: Animating Real Objects with Imaged-Based Illuminations*"
17. Piper, B.T.F., *The Illuminated Design Environment: A 3-D Tangible Interface for Landscape Analysis*
18. Paradiso, J. A., K. Hsiao, Y. Benbasat, and Z. Teegarden, "Design and Implementation of Expressive Footwear"
19. Hsiao, K., *Fast Multi-Axis Tracking of Magnetically Resonant Passive Tags: Methods and Applications*
20. Gershenfeld, N., *When Things Start to Think,* 27-44
21. Joseph A. Paradiso and Neil Gershenfeld, "Musical Applications of Electric Field Sensing"
22. Massie, T., and J. K. Salisbury, "The Phantom Haptic Interface: A Device for Probing Virtual Objects"
23. Massie, T., "A Tangible Goal for 3D Modeling"
24. Peine, W. J. and R. D. Howe, "Do humans sense finger shape or distributed pressure when detecting a lump in soft tissue?"
25. http://biorobotics.harvard.edu/research.html

Chapter 8: Experiments

1. Piper, B.T.F., *The Illuminated Design Environment: A 3-D Tangible Interface for Landscape Analysis*
2. Piper, B., C. Ratti, and H. Ishii, "Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis"

BIBLIOGRAPHY

Ackerman, D., *A Natural History of the Senses* (New York: Random House, 1990)

Aish, A. and P. Noakes, "Architecture Without Numbers: CAAD Based on a 3-D Modeling System," *Computer-Aided Design 16:6* (Nov. 1984): 321–328

Arias, E., Eden, H. and Fischer, G., "Enhancing Communication, Facilitating Shared Understanding, and Creating Better Artifacts by Integrating Physical and Computational Media for Design." in *Proceedings of Designing Interactive Systems: Processes, Practices, Methods, and Techniques, Amsterdam*, August 1997, ACM, 1-12

Arnheim, R., *Art & Visual Perception: A psychology of the creative eye* (Berkeley: University of California Press, 1963)

Arnheim, R., *Toward a Psychology of Art* (Berkeley: University of California Press, 1966)

Balakrishnan, R., T. Baudel, G. Kurtenbach, and G. W. Fitzmaurice, "The Rockin' Mouse: Integral 3-D Manipulation on a Plane," *Proceedings of SIGCHI '97* (New York: ACM Press, 1997): 311–318

Balakrishnan, R., G. W. Fitzmaurice, G. Kurtenbach, and K. Singh, "Exploring Interactive Curve and Surface Manipulation Using a Bend and Twist Sensitive Input Strip," *Proceedings of ACM Symposium on Interactive 3D Graphics '99* (New York: ACM Press, 1999): 311–318

Bazjanac, V., "The Promises and the Disappointments of Computer-Aided Design," in *Reflections on Computer Aids to Design and Architecture,* Negroponte, ed. (New York: Mason/Charter, 1975): 17–26

Ben-Joseph, E., H. Ishii, J. Underkoffler, B. Piper, and L. Yeung, "Urban Simulation and the Luminous Planning Table: Bridging the Gap between the Digital and the Tangible," *Journal of Planning in Education and Research 21*, 195–202

Bilda, Z. and H. Demirkan, "An insight on designers' sketching activities in traditional versus digital media," *Design Studies 24:1* (Great Britain: Elsevier Science Ltd., Jan. 2003): 27–49

Brereton, M. and B. McGarry, "An Observational Study of How Objects Support Engineering Design Thinking and Communication: Implications for the design of tangible media," *Proceedings of SIGCHI '00* (New York: ACM Press, 2000): 217–224

Bryan, W. L. and N. Harter, "Studies on the telegraphic language," *Psychological Review 6* (1899): 345–375

Burdea, G. C., *Force and Touch Feedback for Virtual Reality* (New York: Wiley, 1996)

Buxton, W., *Directory of Sources for Input Technology, 2001* (www.billbuxton.com/InputSources.html)

Buxton, W. and B. Myers, "A study in two-handed input," *Proceedings of SIGCHI '86* (New York: ACM Press, 1986): 321–326

Buxton, W., R. Hill,. and P. Rowley, P., "Issues and techniques in touch-sensitive tablet input," *Proceedings of SIGGRAPH '85* (New York: ACM Press, 1985): 215–223

Buxton, W., "There's More to Interaction than Meets the Eye: Some Issues in Manual Input," in *User Centered System Design: New Perspectives on Human-Computer Interaction,* Norman, D. A. and Draper, S. W., eds. (New Jersey: Lawrence Erlbaum Associates, 1986): 319–337

Buxton, W., "Touch, Gesture & Marking," Chapter 7 in *Readings in Human Computer Interaction: Toward the Year 2000,* R. M. Baecker, J. Grudin, W. Buxton, and S. Greenberg, eds. (San Francisco: Morgan Kaufmann Publishers, 1995)

Chaiklin, S. and J. Lave, *Understanding Practice: Perspectives on Activity and Context* (London: Cambridge University Press, 1993)

Coons, S., "Reflections Beyond Sketchpad," in *Reflections on Computer Aids to Design and Architecture,* Negroponte, ed. (New York: Mason/Charter, 1975): 27–29

Cooper, A., *The Inmates Are Running the Asylum: Why High-Tech Products Drive Us Crazy and How to Restore the Sanity* (Indianapolis: Sams Publishing, 1999)

Csikszentmihalyi, M., *Flow: The Psychology of Optimal Experience* (New York: HarperCollins, 1990)

Csikszentmihalyi, M. and R. E. Robinson, *The Art of Seeing: An Interpretation of the Aesthetic Encounter* (Los Angeles: J. Paul Getty Museum, 1990)

Debevec, P., C. Taylor, and J. Malik, "Modeling and rendering architecture from photographs: A hybrid geometry and image-based approach," *Proceedings of SIGGRAPH '97* (New York: ACM Press, 1997): 11–20

Fitzmaurice, G. W., R. Balakrishnan, and G. Kurtenbach, "Sampling, Synthesis, and Input Devices," *Communications of the ACM 42:8* (Aug. 1999): 55–63

Fitzmaurice, G., H. Ishii, and W. Buxton, "Bricks: Laying the foundations for graspable user interfaces," *Proceedings of SIGCHI '95* (New York: ACM Press, 1995): 432–449

Fradon, J., *Handbook of Modern Sensors: Physics, Designs, and Applications* (New York: Springer-Verlag, 1996)

Focillon, H., *The Life of Forms in Art* (New York: Zone Books, 1992 ed.)

Frazer, J. "Three-Dimensional Data Input Devices," *Computer/Graphics in the Building Process* (Washington, 1982)

Gelernter, D., *Machine Beauty: Elegance and the Heart of Technology* (New York: Basic Books, 1998)

Gershenfeld, N., *When Things Start to Think* (New York: Henry Holt, 1999)

Gerstner, K., *The Forms of Color: The interaction of visual elements* (Cambridge: MIT Press, 1986)

Goel, V., "Cognitive Role of Ill-Structured Representations in Preliminary Design," *Proceedings of Visual and Spatial Reasoning in Design* (University of Sidney, 1999): 131–145

Goldstein, E. B., *Sensation and Perception, 4th ed.* (Pacific Grove: Brooks/Cole, 1996)

Goodman, N., *Languages of Art: An Approach to a Theory of Symbols* (Indianapolis: Hackett Publishing, 1976)

Gorbet, M. G., M. Orth, and H. Ishii, "Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography," *Proceedings of SIGCHI '98* (New York: ACM Press, 1998): 49–56

Grossman, T., R. Balakrishnan, G. Kurtenbach, G. Fitzmaurice, A. Khan, and W. Buxton, "Creating Principal 3D Curves with Digital Tape Drawing," *Proceedings of SIGCHI '02* (New York: ACM Press, 2002): 121–128

Grossman, T., R. Balakrishnan, G. Kurtenbach, G. Fitzmaurice, A. Khan, and W. Buxton, "Interaction techniques for 3D modeling on large displays," *Proceedings of the ACM Symposium on Interactive 3D Graphics '01* (New York: ACM Press, 2001): 17–23

Harrison, S. and S. Minneman, "A Bike in Hand: A study of 3-D objects on design," in *Analyzing Design Activity,* N. Cross, H. Christiaans, and K. Dorst, eds. (New York: Wiley, 1996)

Hinckley, K., R. Pausch, J. Goble, N. Kassell, "Passive Real-World Interface Props for Neurosurgical Visualization," *Proceedings of SIGCHI '94* (New York: ACM Press, 1994): 452–458

Holtzman, S. R., *Digital Mantras: The Languages of Abstract and Virtual Worlds* (Cambridge: MIT Press, 1994)

Holtzman, S. R., *Digital Mosaics: The Aesthetics of Cyberspace* (New York: Simon & Schuster, 1998)

Howe, R.D., (http://biorobotics.harvard.edu/research.html)

Hsiao, K., *Fast Multi-Axis Tracking of Magnetically Resonant Passive Tags: Methods and Applications* (MIT: Master's Thesis, 2001)

Isen, A. M., "Positive affect," In T. Dalgleish & M. Power (Eds.), *The Handbook of Cognition and Emotion* (London: Wiley, 1999) 521–539

Ishii, H. and B. Ullmer, "Tangible Bits: Towards Seamless Interfaces between People, Bits, and Atoms," *Proceedings of SIGCHI '97* (New York: ACM Press, 1997): 234–241

Ishii, H., Underkoffler, J., Chak, D., Piper, B., Ben-Joseph, E., Yeung, L., Kanji, Z. "Augmented Urban Planning Workbench: Overlaying Drawings, Physical Models and Digital Simulation," in *Proceedings of Conference on IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR '02),* (Darmstadt, Germany, Sept. 30 - October 1, 2002)

Kabbash, P., W. Buxton, and A. Sellen, "Two-Handed Input in a Compound Task," *Proceedings of SIGCHI '94* (New York: ACM Press, 1994): 417–423

Kabbash, P., I. S. MacKenzie, and W. Buxton, "Human performance using computer input devices in the preferred and non-preferred hands," *Proceedings of InterCHI '93* (New York: ACM Press, 1993): 474–481

Kitamura, Y., "ActiveCube," *Abstracts and Applications of SIGGRAPH '00* (New York: ACM Press, 2000): 76

Kurtenbach, G., G. Fitzmaurice, T. Baudel, and W. Buxton, "The design and evaluation of a GUI paradigm based on tablets, two-hands, and transparency," *Proceedings of SIGCHI '97* (New York: ACM Press, 1997): 35–42

Lee, J., "HandSCAPE," *Abstracts and Applications of SIGGRAPH '99* (New York: ACM Press, 1999): 168

Lee, S., W. Buxton, and K. C. Smith, "A Multi-Touch Three Dimensional Touch-Sensitive Tablet," *Proceedings of SIGCHI '85* (New York: ACM Press, 1985): 21–26

Loomis, J. M., "Distal attribution and presence," *Presence 1:1,* 113–119

Machover, T., "Hyperinstruments: A Composer's Approach to the Evolution of Intelligent Musical Instruments," *Cyberarts,* 67–76

Massie, T., and J. K. Salisbury, "The Phantom Haptic Interface: A Device for Probing Virtual Objects," *Proceedings of ASME International Mech. Eng.,* International Society of Mechanical Engineers (New York, 1994)

Massie, T., "A Tangible Goal for 3D Modeling," IEEE Computer Graphics and Applications, 18, 3, (1998): 62–65

McCullough, M., *Abstracting Craft: The Practiced Digital Hand* (Cambridge: MIT Press, 1998)

Milne, M., "Whatever Became of Design Methodology?" in *Reflections on Computer Aids to Design and Architecture,* Negroponte, ed. (New York: Mason/Charter, 1975): 30–36

Mitchell, W. J., *The Logic of Architecture: Design, Computation, Cognition* (Cambridge: MIT Press, 1990)

Mitchell, W. J. and M. McCullough, *Digital Design Media: A Handbook for Architects and Design Professionals* (New York: Van Nostrand Reinhold, 1991)

Murray, J.H., *Hamlet on the Holodeck: The Future of Narrative in Cyberspace* (Cambridge: MIT Press, 1997)

Negroponte, N., *Being Digital* (New York: Random House, 1995)

Negroponte, N., ed., *Reflections on Computer Aids to Design and Architecture* (New York: Mason/Charter, 1975)

Norman, D. A., *The Design of Everyday Things* (New York: Doubleday, 1988)

Norman, D. A., *The Invisible Computer: Why Good Products Can Fail, The Personal Computer Is So Complex, and Information Appliances Are the Answer* (Cambridge: MIT Press, 1999)

Orth, M. A., *Sculpted Computational Objects with Smart and Active Computing Materials* (MIT: Ph.D. Thesis, 2001)

Papert, S., *Mindstorms: Children, Computers, and Powerful Ideas* (New York: Basic Books 1993)

Joseph A. Paradiso and Neil Gershenfeld, "Musical Applications of Electric Field Sensing," *Computer Music Journal* 21(2), Summer 1997, pp. 69-89.

Paradiso, J. A., K. Hsiao, Y. Benbasat, and Z. Teegarden, "Design and Implementation of Expressive Footwear," *IBM Systems Journal 39:3&4* (2000): 511–529

Patten, J., Ishii, H., Hines, J., Pangaro, G., "Sensetable: A Wireless Object Tracking Platform for Tangible User Interfaces," *Proceedings SIGCHI 01*, (New York: ACM Press, 2001): 253-260

Pawluk, D.T.V. and R. D. Howe, "Dynamic lumped element response of the human fingerpad," *ASME Journal of Biomechanical Engineering* 121(6): 605–611, 1999

Peine, W. J., P. S. Wellman, and R. D. Howe, "Temporal Bandwidth Requirements for Tactile Shape Displays," *Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition* (Dallas, 1997): 107–113

Peine, W. J. and R. D. Howe, "Do humans sense finger shape or distributed pressure when detecting a lump in soft tissue?" submitted to the *Seventh Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition* (Anaheim, 1998)

Pentland, A., "Perceptual Intelligence," *Communications of the ACM 43:3* (March 2000): 35–44

Peterson, S., *The Craft and Art of Clay* (Woodstock, N.Y.: The Overlook Press, 1996)

Pincherle, M., *The World of the Virtuoso,* trans. by Lucile H. Brockway (New York: Norton, 1963)

Piper, B.T.F., *The Illuminated Design Environment: A 3-D Tangible Interface for Landscape Analysis* (MIT: Masters Thesis, 2002)

Piper, B., Ratti, C., Ishii, H. "Illuminating Clay: A Tangible Interface with Potential GRASS Applications," *Proceedings of the Open Source GIS - GRASS User's Conference 2002* (Trento, Italy, September 2002)

Piper, B., C. Ratti, and H. Ishii, "Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis," *Proceedings of SIGCHI '02* (New York: ACM Press, 2002)

Polanyi, M., *The Tacit Dimension* (New York: Doubleday and Co., 1967)

Raskar, R., G. Welch, M. Cutts, A. Lake, L. Stein, and H. Fuchs, "The office of the future: A unified approach to image-based modeling," *Proceedings of SIGGRAPH '98* (New York: ACM Press, 1998): 179–188

Raskar et al., "Shader Lamps: Animating Real Objects with Imaged-Based Illuminations," *Proceedings of the 12th Eurographics Workshop on Rendering* (2001)

Resnick, M., R. Berg, M. Eisenberg, and S. Turkle, *Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Instruments* (Project Proposal, 1997)

Resnick, M., A. Bruckman, and F. Martin, "Pianos, Not Stereos," *Interactions, 111:5* (Sept.–Oct. 1996): 41–50

Resnick, M., F. Martin, R. Berg, R. Borovoy, V. Colella, K. Kramer, and B. Silverman, "Digital Manipulatives: New Toys to Think With," *Proceedings of SIGCHI '98* (New York: ACM Press, 1998): 281–287

Ryall et al., "Physical Constructions Kit," *Proceedings of SIGGRAPH* '00 (Los Angeles: ACM Press, 2000)

Rybczynski, W., *One Good Turn: A Natural History of the Screwdriver and the Screw* (New York: Scribner, 2000)

Schmidt, R., "Control Process in Motor Skills," *Exercise and Sports Sciences Review* (1976): 229–261

Schkolne et al., "Surface Drawing," *Proceedings of SIGCHI '01* (New York: ACM Press, 2001)

Schon, D. A., "Designing as a Reflective Conversation with the Materials of a Design Situation," *Research in Engineering Design 3* (New York: Springer-Verlag, 1994): 131–147

Schon, D. A., *The Design Studio: An Exploration of its Traditions and Potentials* (London: RIBA Publications Limited, 1985)

Schon, D. A., *The Reflective Practitioner: How professionals think in action* (New York: Basic Books, 1983)

Simon, H. A., *The Sciences of the Artificial* (Cambridge: MIT Press, 1969)

Sinclair, M., "The Haptic Lens," *Visual Proceedings of SIGGRAPH '97* (New York: ACM Press, 1997): 179

Spillers, W., "Some Thoughts on Automated Design," in *Reflections on Computer Aids to Design and Architecture,* Negroponte, ed. (New York: Mason/Charter, 1975): 61–72

Sutherland, I., "Structure in Drawings and The Hidden-Surface Problem," in *Reflections on Computer Aids to Design and Architecture,* Negroponte, ed. (New York: Mason/Charter, 1975): 73–85

Tsang, M, G. Fitzmaurice, G. Kurtenbach, A. Khan, and W. Buxton, "Boom Chameleon: Simultaneous capture of 3D viewpoint, voice and gesture annotations on a spatially-aware display," Alias|Wavefront, submitted for publication (2002)

Ullmer, B. and H. Ishii, "Emerging Frameworks for Tangible User Interfaces," *IBM Systems Journal 39:3&4* (2000): 915–931

Underkoffler, J., B. Ullmer, and H. Ishii, "Emancipated Pixels: Real-World Graphics in the Luminous Room," *Proceedings of SIGGRAPH '99* (New York: ACM Press, 1999): 385–392

Wang, Y., A. Biderman, B. Piper, C. Ratti, and H. Ishii (http://tangible.media.mit.edu/projects/SandScape/SandScape.htm)

Weiser, M., "The computer for the 21st century," *Scientific American* (Sept. 1991): 933–940

Wellner, P., Mackay, W., and Gold, R., "Computer Augmented Environments: Back to the Real World," *CACM 36:7*, July 1993