**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.