Sketch-based Interaction for Designing Precise Laser Cut Items

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For Uncle Jim

Abstract

Designers typically sketch during concept development, and use computer modeling software to finalize their ideas. Both tools—pencil and computer—are well-suited for their task. Sketching is fast, fluid, and lets people explore ideas efficiently; computation lets users make structured, detailed digital models. But in practice, design does not progress directly from idea to final product. Instead, designers use paper, then software, return to sketching to develop or change concepts, turn back to the computer to implement changes, and so on. The transition between between pencils and pixels is time-consuming.

Rapid fabrication and prototyping is a design area of increasing importance. Machines like laser cutters and 3D printers are becoming more common, and ordinary people are increasingly interested in these machines to design and make things. Current design software is made for professionals, not hobbyists. For avocational rapid prototyping machine users, software is the bottleneck.

This thesis presents *Sketch It, Make It* (*SIMI*), a sketch-based modeling tool that lets non-experts design precise items for laser cutting by sketching. This removes the need to transition between sketches and formal CAD models. SIMI users make line work, issue commands, create geometric constraints, and produce "cut files" for production on a laser cutter—entirely with a stylus. There are no modes (like line mode, erase mode) in SIMI: the meaning of user input is recognized by analyzing pen strokes and context.

Researchers have long sought to infer user intention by looking at sketches. The work presented in this thesis treats sketch recognition largely as an interaction design problem, rather than an artificial intelligence problem. Sketch-based techniques were developed to provide efficient user experience in specific contexts, including the laser cutter domain and the other sketch-based interaction techniques found in SIMI.

Two evaluations were used to measure SIMI's performance. First, a workshop involving sixty undergraduate architecture students was carried out. The students used SIMI and provided feedback on its technical performance and their own attitude about the software. Next, a task/tool analysis of SIMI and another common tool compares the steps needed to perform a simple design task.

Acknowledgments

When I was ten years old, I liked to play `trek` on my dad's CP/M computer. The goal was to control the Enterprise to blow up Klingons. To shoot, type an angle: 90 for up, 270 for down. But it was tricky when the bad guy was at a weird angle. One morning my dad stepped in to show me a thing or two.

He showed me how to think about spatial relationships with circles and triangles. He explained the calculator's weirder buttons (e.g. `arc tan`). If I knew he was subversively teaching math, I wouldn't have been interested. But his trick worked. Math was no longer just a chore foisted on me at school. It had a use—*math can be used to blow up Klingons*.

When I was twelve, I decided to write a book. My mom patiently read my (terrible) drafts, but she encouraged me to stick with it to completion. I kept on with it, and finished after two years. She keeps a copy of the final version for potential blackmail purposes.

I first want to thank my parents. Dennis Johnson taught me how to be a nerd. Pat Goehring showed me that encouragement and tenacity were vital ingredients to finishing epic projects (even if that project is horrible). Throughout graduate school my parents have been absolutely amazing. My sister Kelly and I are lucky to have them.

My high school teachers Tom Lippert, Al Naylor, and Loren Flater were the first to challenge me as an adult. Steve Shanley and Justin Beahm were my bandmates: we taught one another collaboration while producing an amazing noise. Jeff Rusnak suavely convinced me to move to Colorado after one year at the University of Northern Iowa.

At the University of Colorado, Clayton Lewis was the first to direct me into research. He introduced me to Gerhard Fischer, who brought me into his group, the Center for LifeLong Learning and Design (L3D). My first mentor there was Jonathan Ostwald, who taught me the value of characterizing and recording failure. Tammy Sumner and Leysia Palen were always available to talk about my projects and long-term goals. Without Tammy and Leysia's encouragement I wouldn't have considered grad school. Leysia introduced me to Mark and Ellen. Eric Scharff and Rogerio dePaula were L3D graduate students who gave me their perspectives on research and life in grad school (they could not scare me off).

Casey Jones was an unending supply of encouragement as I applied for grad school. Her "Mr. Smarty Pants" routine convinced me that maybe I really did have business going back to school.

At Carnegie Mellon, I was fortunate to be in the same cohort as Eric "Tiller" Schweikardt, Tony Tang, Sora Key, Yeonjoo Oh, and Shaun Moon. Susan Finger, Jason Hong, Sara Kiesler and Carolyn Rosé gave much-needed guidance during these early years. Martin Brynskov and Martin Ludvigsen injected some much-needed Danishness and intellectual vibes to our lab.

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The most recent set of Codelabbers are a vibrant community of weirdos and brainiacs. My thesis would not have happened without these people around: Zack Jacobson-Weaver, Deren Guler, Madeline Gannon, Hyunjoo Oh, Andrew Viny, Cheng Xu, Huaishu Peng, Kuan-Ju Wu, Rita Shewbridge, and Hiro Yoshida. In particular, Tobias Sonne (another Dane!), deserves credit for sparking the Codelab community, even though he was only around for one semester. Just as I was leaving, Nick Durrant and Gill Wildman entered the scene and gave me a final boost.

Very special thanks goes out to my committee. Mark and Ellen brought me to CMU and provided a great environment. Even after she went to Georgia Tech, Ellen was always available to collaborate or provide a much-needed jolt of reality. For the past two years, Jason has stepped up to play a central role in my PhD, by always being available to talk, and by bringing me into his weekly student meetings. Mark has been more than a thesis advisor: he changed the way I view the world. I'm pretty sure that is a good thing, but the jury is still out.

Of course I could not finish this without thanking Sputnik, the coolest Puerto Rican Beach Mutt in the history of the world. He's been with me throughout the entire development of my thesis system and has kept me sane (mostly) throughout. In fact, he's curled up next to me as I type this. Good boy.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Nearly everything around us has been *designed* and *built*. With mass production, a single design can be replicated many times. This keeps prices low and quality consistent, but users must be content with what the designer and manufacturer have done.

But what if the user could indicate exactly what they want for the same price and quality? Machines like 3D printers, CNC mills, and laser cutters are beginning to give a glimpse of what the future might hold. Today, a knowledgeable person can design and "print" parts on rapid prototyping machines. If the designer wants to change something, they simply print a revision. While this is currently not as cost-effective as buying an "almost good enough" mass-produced product, it does enable the user to directly engage with designing and making.

Rapid prototyping is a new technological phenomenon with economic and social consequences. The machinery that enables regular people to "print" objects at home was unavailable ten years ago: either it was too expensive, or it had not yet been invented.

Current prototyping machinery is still too expensive for most people to buy for personal use. But this will likely change in the coming years as more machines become available. The market for rapid fabrication machines is growing quickly: according to industry analysts, the market for laser cutters will exceed $3.8 billion by 2015, and the 3D printer market will reach $3.1 billion by 2016 [19, 77].

Today's machines produce adequate (but not typically compelling) output. This is quickly changing as price decreases while quality improves. We are witnessing the start of a technology that enables new activities—some that we can predict, but others that we can not yet clearly see. It is conceivable that we are witnessing the beginning of a shift from an economy entirely based on *mass production* to one that includes *mass customization*.

Rapid fabrication gives many people the ability to design and build things when there was no opportunity before. In the mass production model, people are merely consumers.

Figure 1.1: Using Sketch It, Make It on a Wacom Cintiq display tablet. The user sketches with their preferred hand, and uses a single button with their non-dominant hand.

Rapid fabrication enables people to play an active role in designing and constructing the world around them. *However, the machines, alone, are insufficient: a human must tell them what to make. To support this, people need adequate design tools*.

This dissertation addresses the observation that people need better design tools if they are to effectively use rapid fabrication machines. Current modeling software targets users who go to school to learn how to design and use design software. But most people can not dedicate that much time to learn the intricacies of design software.

While someone might find professional design software to be difficult, it is likely that person can *draw* with pencil and paper to communicate ideas with others. Even if the sketch is rough, it is an effective method to express ideas about form and function.

1.1 Thesis Statement and Contributions

Thesis Statement: Sketch-based interaction can provide the basis for a useful and usable 2D modeling tool for designing laser cut items.

Researchers have attempted to leverage sketching as a computational medium for at least half a century. But we have not seen this effort move beyond academic laboratories. A critical element missing from this body of work is the lack of a *system of interaction design* for sketch-based tools.

I offer several **Contributions** to support my thesis. First, I present a coherent set of sketch-based interaction techniques that enables users to make precise designs with a stylus. Second, I develop several new interaction techniques including Flow Selection [33]. Last, I offer a recognition and disambiguation architecture that supports fast and user-friendly interaction design.

These contributions are embodied in a *useful* and *usable* modeling tool called *Sketch It, Make It* (*SIMI*) that lets people design precise items for laser cutters.

1.2 Intended Audience

This work is aimed primarily at researchers interested in sketch-based modeling—particularly those developing sketch recognizers or interactive sketch-based software systems. This includes people working on topics traditionally found in computer science (e.g. artificial intelligence or computer graphics) as well the human-computer interaction and interaction design communities. Beyond motivating the work (sketch-based interaction) and domain (designing for laser cutters), a reader could implement any of the techniques described herein. The target audience may be in academia, but it is hoped that commercial software tools can start to incorporate some of the novel interaction exemplified by SIMI.

Further, members of the physical hacking or tangible interaction worlds may be interested in learning how their trade can benefit from improved design tools.

1.3 Motivation

This work is motivated by academic and practical perspectives. From an academic perspective, I am motivated to find a way to bring greater coherence to the field of sketch-based modeling with a compelling example of a useful and usable sketching system that exhibits a set of mutually harmonious interaction techniques. There are dozens of sketch-based systems that demonstrate recognition algorithms, corner-finding methods, and interaction techniques, among other topics. But as I have said, sketch-based tools don't exist outside research labs. Because researchers rarely share, or have complete documentation or working examples to use as a starting point, they must typically build their work from scratch. Consequently, researchers interested in one topic (e.g. making new interactive widgets for

sketching) must spend a substantial amount of time implementing functions that are not their research focus (e.g. ink parsing). Although it might occasionally be a useful learning strategy to re-invent the wheel, I view the focus on side-topics as a largely needless distraction.

The practical motivation behind this work is the observation (shared by many people) that current computer-based design tools are hard to use, and that "natural" techniques like drawing, speaking, and gesturing are potentially great methods to design with computers. It would be a wonderful turn of events if such a natural, easy-to-use tool were available to designers. I believe one of the critical steps to making this a reality is to develop an appropriate system of interaction. For example, such a system to interact with (drive) a car involves foot pedals, a steering wheel, and dashboard indicators and knobs. It would be inappropriate (and dangerous) to force automobile drivers to control their cars with a standard PC setup: keyboard and mouse, complete with software updates and dialog boxes. But this is the approach that many researchers take when developing sketch-based design tools. It is convenient, but inappropriate. This dissertation offers an example of an appropriate interaction for sketch-based design tools.

1.4 Thesis Structure

This chapter introduced the domain of rapid fabrication and the culture of hacking and making that is associated with it. I discussed the field of sketch-based modeling and introduced my tool, *Sketch It, Make It* (*SIMI*), a digital modeling tool for designing precise items for laser cutters. The following chapters are outlined as follows.

Chapter 2 covers background information about rapid fabrication and laser cutting, and provides a brief survey of the literature on computational support for sketch-based modeling in design. Next, in Chapter 3 I describe formative investigations that informed development of my tool: observations and interviews with designers, and an analysis of some of the artifacts made with current design tools and laser cutters.

Two chapters are devoted to discussing SIMI. Chapter 4 introduces the tool and presents usage scenarios: why and how somebody uses it. This is an overview of the system. Chapter 5 details individual interaction techniques and other technical aspects to the system likely to be useful to others.

Chapter 6 presents several evaluations of SIMI, including results of a quantitative evaluation involving 60 undergraduate architecture students. Last, in Chapter 7, I discuss the implications SIMI has on digital modeling tools and sketch-based design. I also describe some additional questions that warrant future work.

Chapter 2

Related Work

This chapter discusses design (focusing on rapid fabrication and laser cutting) and research on physical and computationally-supported sketching.

2.1 Design for Rapid Fabrication

A growing community of self-described *makers* design and build many kinds of physical things [18]. Some are electronic or robotic gizmos, while others are made from traditional craft material. These "new makers" [25] are empowered by rapid fabrication machines like 3D printers and laser cutters.

It is possible that we are beginning to see a shift from an economy based on mass-production (in factories) to one that includes mass-customization (in homes, schools, and community centers) [75]. Rapid fabrication machines continue to decline in price while improving in quality. A new sector of businesses use rapid fabrication to cater to the needs of hobbyist designers as well as people that need highly customized goods [58]. For example, companies such as Ponoko fabricate and send users physical output based on digital models uploaded over the web.

Rapid prototyping machines are used in many domains: mechanical engineering, architecture, craft work, industrial design—just to name a few. While many users of these machines are professional, a growing population of Makers are not necessarily educated (in a traditional sense) to design and build things. Instead, members of this group might be better described as hobbyists or semi-professionals. They are smart and motivated, but do not necessarily have a great abundance of time or money.

2.1.1 Rapid Fabrication Machines

The software modeling tool discussed later in this thesis targets laser cutters, which are one particular type of rapid fabrication machine. I will first describe the broader area of rapid fabrication to situate the specific machine in question.

There are several related (but not necessarily interchangeable) names for machinery to in this space. *Numerical Control* (*NC*) machines were introduced in the 1950s that ran programs encoded on punched tape. *Computer Numerical Control* (*CNC*) introduces a computer, capable of performing conditional execution soon followed. Modern CNC machines are found anywhere from large automobile factories (e.g. as sophisticated robots) to the home-brewed 3D printer set up in the hobbyist's garage.

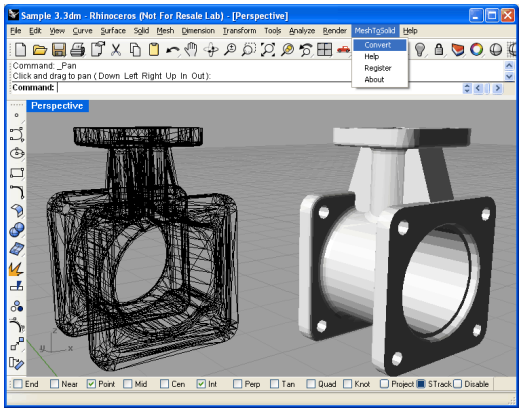
When applied to CNC machines, the terms "rapid fabrication" and "rapid prototyping" refer to their role in a design process. While industrial CNC robots are engaged in large-scale production work, rapid fabrication machines are used primarily by designers to explore ideas and construction (preceding large-scale production, if it happens at all). Because of their role in the design process it is critical that these devices are faster and cheaper than using human labor with manual machinery.

The type, quality, and composition of the output depends not only on the machine, but also on the designer's skill in creating suitable instructions. A CNC mill, for example, could be used to create a customized office desk. But in order to build the parts comprising the desk, somebody must give the machine a digital model that indicates not only where the mill will cut, but how the cut will be made.

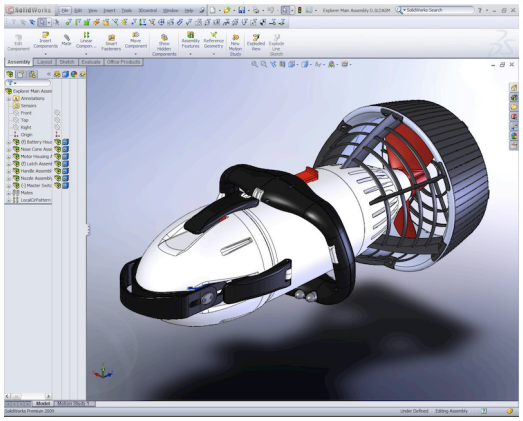
A mill may operate with 3 or more axes: it can move on the x/y plane, and up and down (z-axis). Some models have additional axes that allow the tool head to move in other ways, such as rotation. The tool path is therefore an important consideration when designing for most types of computer controlled manufacturing machines. In many (but not all) cases, software tools can compute tool paths automatically. Designers must consider a machine's capabilities.

Laser cutters can be thought of as a very fast, strong, and precise automated razor blade, cutting through flat material (paper, wood, plastic, metal, etc.) from directly above. Many items can be made entirely with a laser cutter, aside from the occasional screw or glue.

SIMI targets design for laser cutters. This tool was chosen for several reasons. First, problems related to tool paths are nearly non-existent. Second, a laser cutter executes quickly, which supports a faster loop of coding, testing, and debugging. Fabricating a toothbrush holder takes about five minutes on a typical laser cutter, but a 3D printer would take four hours to make a similar object. Last, laser cutters are among the more popular rapid fabrication machines.



(a) Rhino 3D modeling software.



(b) Solidworks modeling tool.

Figure 2.1: Rhino 3D and Solidworks are two commonly used 3D modeling tools and are often used by skilled users for various rapid fabrication purposes, including laser cutting.

Laser cutter users place material on the laser cutter's *cut bed*. Typical sizes for cut beds are in the range of 12″x 18″ to 48″ x 72″ (30 x 46 cm to 122 x 183 cm). A laser is directed through several mirrors mounted on robotic arms. These arms move to allow the laser to reach any location on the cut bed. A lens near the end of the path focuses the laser to the material to create an optimal cut. A 40 watt machine can cut $\frac{1}{4}''$ (6mm) thick wood; a 100 watt machine can cut up to 1″ (25mm) plywood.

2.1.2 Current Design Tools for Laser Cutting

Today, designers can choose among several modeling tools for laser cutter projects. The most commonly used tool is Adobe Illustrator, a general-purpose vector graphics editor. It is full-featured and has an interface new users find familiar, as it presents interaction with menus, tool bars, and persistent tool modes. However, participants in our formative study (presented later in Section 3.2) had a hard time using Illustrator quickly and effectively because they spent a great deal of effort looking for appropriate functions among the many features that are irrelevant to laser cutters.

Specialized CAD tools like Rhino or SolidWorks (see Figure 2.1) are perhaps more appropriate for this kind of modeling but they also have a substantial learning curve. If rapid fabrication is to become common, appropriate modeling tools must be made accessible to ordinary users [48].

2.2 Design Sketching

People commonly sketch when problem solving. Some sketches are personal, others collaborative. Some help people make quick calculations and are quickly forgotten while others serve longer-term purposes. For professional designers, sketching is a *process* to think about problems. Just as importantly, a sketch (the result of the process) is a *record* that communicates ideas [14].

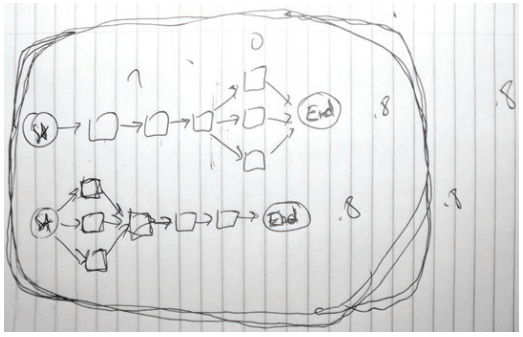
Design can be seen as an iterative process of problem-framing and exploring possible solutions within the current conception of the problem. A sketch is not a contract: it is a proposal that can be modified, erased, built upon. The rough look of hand-made sketches suggests their provisional nature.

Some theories of cognition give the human mind two distinct tasks: to perceive the world via our senses, and to reason about what our senses provide. In contrast, the late psychologist Rudolf Arnheim argues that perception and thinking are inseparable: "Unless the stuff of the senses remains present the mind has nothing to think with" [3]. Visual thinking is valuable in evaluating what is and designing what might be. Sketching allows people to give form to notions that are otherwise imaginary; the act of seeing fuels the process of reasoning.

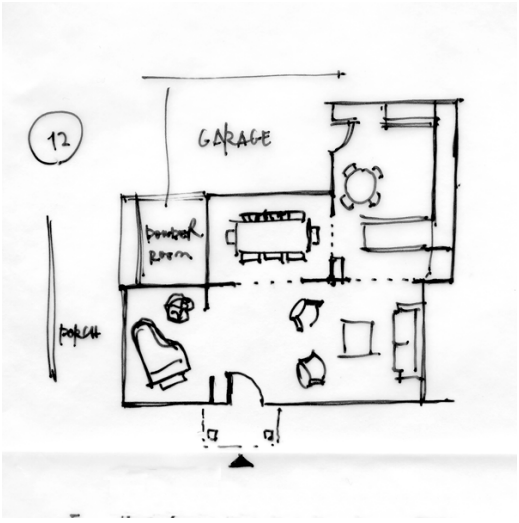
Sketching plays a crucial role in the practice of design. It helps people think about problems and offers an inexpensive but effective way to communicate ideas to others. The practice of sketching is nearly ubiquitous: One recent study of interaction designers and HCI practitioners found that 97% of those surveyed began projects by sketching [51]. We must understand the purpose and practice of sketching as it is done *without* computation if we hope to effectively support it *with* computation.

While designing, we iteratively explore and refine the problem definition and proposed solutions. Sketching supports this creative search process. We set out on our design task with some high-level goals. However, due to the ill-structured [70] and "wicked" nature of design [60], we encounter unforeseen opportunities and constraints as designing progresses. Those opportunities and constraints may be implicit in the original problem description, but designers expose them as they explore. The discoveries are incorporated into the understanding of the problem and potential solutions. Design problems are "not the sort of problems or puzzles that provide all the necessary and sufficient information for their solution [11]." So it goes with sketching. We draw different views of our model, which allows us to perceive the problem in new ways.

Designers engage in a sort of "conversation" with their sketches in a tight cycle of drawing, understanding, and interpreting [67]. Goldschmidt describes this as switching



(a) Project management diagram showing task precedence of two projects. Hastily drawn boxes and arrows represent abstract activities.



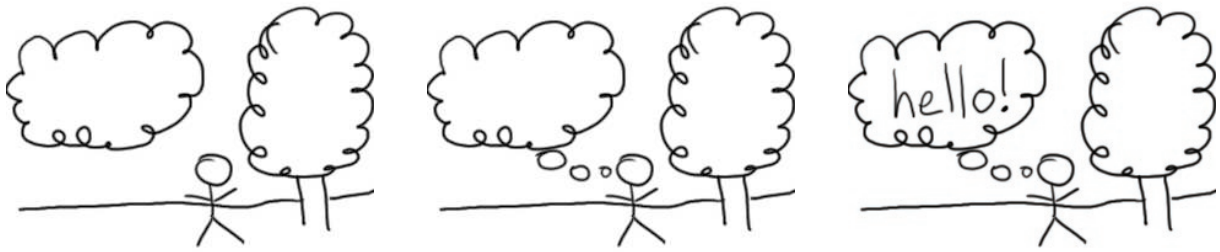
(b) An architect's floor plan sketch. It includes text, spatial information, and symbols representing household items like a piano or dining table.

Figure 2.2: Sketches vary in domain and in the visual characteristics of marks.

between two reasoning modes: "seeing that" and "seeing as" [21]. *Seeing that* is the process of recognizing the literal, descriptive properties of the drawing. *Seeing as* is figurative and transformative, allowing the designer to re-interpret parts of the sketch in different ways. Care must be taken to support this conversation when developing sketch-based modeling tools. If the system interprets drawings too aggressively or at the wrong time, it may prevent the human designer from seeing alternative meanings; recognize too little and the software is no better than paper.

2.2.1 Prototyping and Fidelity

Newman and Landay's ethnographies of web designers focused on how designers use informal techniques [53]. They found that designers always sketch at the beginning of a web design project, exploring numerous high-level options. Frequently this early sketching phase is accompanied with construction of low-fidelity prototypes made on paper or with simple software tools like Microsoft PowerPoint. As the design progresses and designers incrementally add details, they move to higher fidelity models. Client meetings are an important forcing function in web design projects. When meeting with clients, designers want to show polished prototypes produced with computer software. Therefore designers used electronic tools earlier in the process than they would otherwise have preferred.



(a) Overloaded semantics: The cloud and tree have similar shapes but different meanings due to context.

(b) Ambiguity: A small addition changes our interpretation. The object at left may be a cloud or a thought bubble.

(c) More information gives more confidence about object identity. Text in the cloud indicates a thought bubble.

Figure 2.3: Overloaded semantics and ambiguity.

Today most software tools support incremental refinement and specification of details but do not adequately support idea generation or exploration [73]. Designers who begin using software tools in the early phases of design tend to make superficial explorations of possible solutions. Further, because tools are poor for exploration but good for specifying details (font, line weight, and color), designers tend to focus on nuances that are not yet important. Observing that current tools are inadequate for creative pursuits, researchers have developed calligraphic tools such as SILK and DENIM, which aim to support the early phases of design [45, 46].

Paper sketches dominate the early phases of design as people generate new ideas, in a process Goel terms "lateral transformations" [20]. But as soon as the web designer believes he or she will make incremental revisions (which Goel calls "vertical transformations") they switch to a computer tool.

2.2.2 Sketches as a Symbol System

Goodman provides a comprehensive framework for analyzing the properties of various symbol systems, including sketches [22]. Goel places sketching in Goodman's framework, noting that sketches have *overloaded semantics*, they are *ambiguous*, *dense*, and *replete* [20]. These properties describe one particular sense of sketching in which the drawer's marks may be idiosyncratic. It is critical to understand these properties when developing sketch-based design software.

Sketches have "overloaded semantics": The same symbol may mean different things depending on context. Further, a sketched symbol may be "ambiguous", meaning that the symbol affords more than one plausible interpretation. Figure 2.3 illustrates these

Figure 2.4: Different instances of the same stick figure vary along a continuum (*dense*). However, the visual properties of individual symbols may (or may not) communicate additional information (*replete*). Is the figure at the right waving?

properties. A lumpy shape can be used to indicate many things including clouds, trees, or thought bubbles. We interpret the shape differently depending on context.

Sketched symbols are "dense", indicating there is a continuous range between instances of the same symbol. While there may be minute visual discrepancies between symbol instances, Goel claims that such symbols are also "replete": no aspect of the sketched symbol may be safely ignored (Figure 2.4).

The pen strokes constituting a sketch serve various functions. Ink may indicate abstract domain symbols (e.g. diode, treble clef), object boundaries, actions (e.g. arrows indicating containment or movement), dimensions and units, annotations, region texturing, and so on. Some parts of a sketch are more dense and replete than others. For example a diode's properties do not change if it is drawn with a slightly larger triangle. However, subtle variations in how a desk lamp is drawn might lead to substantially different esthetic responses to it.

Gross and Do discuss some properties of hand-drawn diagrams from the perspective of building tools to support design drawing activities [23]. The authors distinguish sketches from diagrams, noting that diagrams are "composed of primitive elements chosen from a small universe of simple symbols—boxes, circles, blobs, lines, arrows." This list is certainly not exhaustive, but it does illustrate the general idea that diagrams have a limited vocabulary. In practice, sketches and diagrams from various dialects may be combined (e.g. mathematical notation on the same page as circuit diagrams and hand written notes.)

Freehand diagrammatic drawings are abstract, ambiguous, and imprecise. *Abstract* symbols denote elements whose identities or properties are not (yet) important or known. For example, Figure 2.2a on page 9 shows a project management diagram of two hypothetical projects. The activities composing each project are abstract—they could represent anything. The value of the project sketch is that it shows the network structure and does not draw attention to what specific activities are.

An *ambiguous* symbol has many plausible interpretations. The floor plan sketch in

Figure 2.2b shows several rectangles indicating rooms, furniture, shelves, or counters. Human observers can confidently disambiguate the intended meaning of some rectangles, but others remain unclear. The bottom-right of the sketch shows two armchairs and a sofa with an ambiguous rectangle in the middle that could plausibly represent either a rug or a coffee table.

Last, freehand diagrams are *imprecise*. Imprecision allows designers to work with rough values (e.g. "about two meters wide") and avoid premature commitment. Imprecision also indicates that the design is by no means final.

The notational properties of sketches make them powerful tools for supporting visual thinking. Designers may leverage ambiguities in their sketches to see new meanings, for example. However, these same properties present challenges for accurate software recognition.

The degree to which a drawing is ambiguous, imprecise, and abstract varies among instances, and people might interpret them differently. A rough sketch is useful to designers, especially for brainstorming and incremental development of ideas. But in order for the sketch to be transformed into a finished product (e.g. as a digital model supplied to a rapid manufacturing device), it must be made unequivocal, precise, and concrete. The process of moving from the informal sketch to the formal specification involves drawings that are semi-ambiguous, partially precise, and with some abstractions given definite identities.

2.2.3 Summary: Traditional Sketching and Computation

If we hope to effectively support sketching with computation, we must first understand the practical aspects of traditional sketching.

Sketching is an important—perhaps necessary—tool for doing design. It gives a way to quickly make provisional drawings, which help us efficiently make sense of spatial, relational information. Sketches let us make marks that are as vague or specific as needed. Because sketched elements can be ambiguous, rough drawings have different interpretations. We may reflect on sketches to see new meaning in existing marks. People sketch in part because they don't know exactly what they are making: sketching facilitates exploration.

Low-fidelity prototypes are especially important as tools to test ideas during early design. This is because they are easy to make, allowing designers to quickly expose problems before committing to decisions. Sketching is a common method of creating such prototypes.

In order for computers to recognize sketches, we must develop techniques to transform imprecisely made marks into discrete symbols. However, some of the properties that make a sketch useful for a human (overloaded semantics, ambiguous, imprecise, etc.) complicate the task of computer recognition.

2.3 Hardware: Tablets and Pens

Now that I've discussed the role of sketching in design, and some of the cognitive aspects of freehand drawing, I will now present topics involved in supporting sketching with computers. This section discusses hardware people might use to give input to a sketching system, and the next enumerates software topics for processing it.

Researchers in sketch recognition and interaction typically use tablet devices such as a Wacom Bamboo or Cintiq. Some surfaces, like the Bamboo, simply sense stylus input but do not display feedback. These "blind" tablets require the user to look at one place (their computer display) but draw on another surface. This can lead to hand-eye coordination trouble. The Cintiq, and various Tablet PC computers, combine display and sensing surfaces. In this case, the user's pen comes into contact with a drawing plane that is separated from the display plane by only a few millimeters. When the user views the display at an angle, this parallax difference can be annoying, but it is certainly better than the situation with blind tablets.

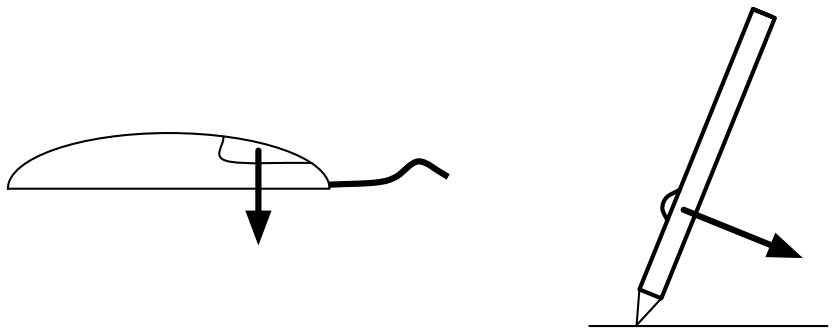
Input surfaces that are intended to be used with fingers or hands offer different interaction experiences than pen-oriented drawing surfaces. For example, users may trace shapes with a single finger, use two fingers to zoom in or out, or use whole-hand gestures for issuing other commands. These interaction techniques provide opportunities for developing innovative sketching applications, as demonstrated by work by Hinckley *et. al* at Microsoft Research [30].

Regardless of sensing technology, these devices allow users to provide input in a way that is much closer to handwriting and freehand sketching than a mouse allows. Although pen and mouse input share many properties (both allow users to interact with 2D displays) they have several key differences.

Mouse input affords *motion* sensing while pen input affords *position* sensing [29]. In other words, while mice produce the relative *change* in (x, y) locations, pens directly provide absolute (x, y) locations. Users can configure tablets to report relative position, thereby behaving like a mouse.

Form is also extremely important. A stylus affords people to use the fine motor abilities of their fingers to control the tip of the pen, whereas hand and forearm muscles dominate mouse usage. Fingers can be used to move the mouse, but not with the same dexterity possible with a pen. Depending on the type of work, a pen may be ergonomically superior to a mouse, or the other way around.

Some styluses have buttons. While buttons are an indispensable part of a mouse, they are often difficult to use on the barrel of a pen [59]. The force of a *mouse* button click



(a) Force vector for mouse button press is perpendicular to the plane the device rests on. It will therefore not move much.

(b) Pressing a stylus button is more likely to cause unwanted pen tip movement because it is at an acute angle to the drawing surface plane.

Figure 2.5: The force required to press a mouse button compared with a stylus button.

is orthogonal to the device's plane of use and has negligible effect on target accuracy. However, pressing buttons on a *stylus* can move the tip of the pen, making it difficult to accurately press the button while pointing at particular objects (see Figure 2.5). Further, pressing a button on a computer stylus usually requires the user to adjust the pen in hand. This action may be distracting and uncomfortable for long term use.

2.4 Sketching Systems for Fabrication

Sketch It, Make It is a sketch-based tool for rapid fabrication. This section discusses similar design tools that let people design objects for physical fabrication.

Makers of physical things sketch throughout their process. In the early phases, sketching is used to explore ideas, develop concepts, and gradually give detail as the final product comes into focus. Later, people annotate renderings and blueprints with freehand edits to indicate desired changes. An example of late-phase sketching is shown in Figure 2.6. There is a strong tradition in physical design domains to sketch throughout the process—from concept generation through fabrication.

Designers often create perspective drawings of 3D objects. This is a common activity on paper, so it is an appealing activity to support. There are two primary approaches to sketching 3D objects: either draw in perspective, or draw 2D planar diagrams that correspond to a 3D product. Some researchers combine these approaches.

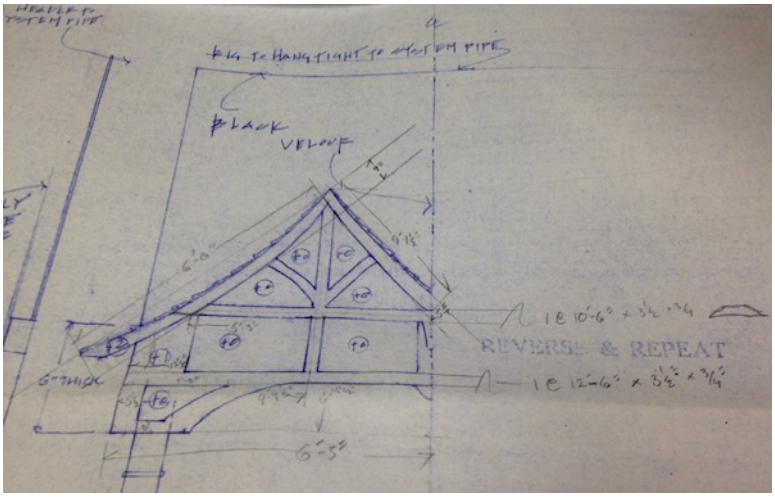


Figure 2.6: Designers, builders, and clients annotate a formal blueprint with desired changes during the final stages of production. The drawing serves as a context for stakeholders to communicate with one another.

In the first set (perspective drawing), some systems focus on giving the designer interaction techniques to form 3D shapes [6, 39], while others attempt to infer the 3D shape using statistics and perceptual rules [47].

The second set (convert 2D drawings to 3D objects) is a natural fit with domains where the finished product is composed of flat sheets. Oh's *Furniture Factory* [55], and Saul and *et. al*'s *SketchChair* [63] tools let designers draw and fabricate furniture. Sketching is done in a 2D window, and is mapped to a 3D representation that lets the user see their composition. In both systems, the system uses domain knowledge to make the process possible. For example, Furniture Factory will create appropriate joints where two parts meet. SketchChair does the same while adding a physics and ergonomic simulation to see if the chair will fall over and be comfortable to sit in.

A combined approach is demonstrated in *Plushie* [50]. The user designs plush toys in a 3D environment similar to Teddy [32] and applies textures as desired. The shape will eventually be fabricated from actual cloth, involving cutting and sewing. Plushie shows the user the 2D cutout patterns associated with the 3D model. These cutouts can't be edited directly, but it does give a sense of how much work is involved with physical production.

In contrast with the systems mentioned above, Song's *ModelCraft* [71] system lets designers sketch on physical objects to edit virtual models. The objects are covered in (or composed of) Anoto paper. This paper has a dot pattern that is visible to a special pen that identifies where the pen is drawing. ModelCraft users can annotate or edit virtual objects using different color ink.

Topic	Section	Remark
Recognition accuracy	2.5.1	Discusses how to measure recognition accuracy, and what acceptable error rates are.
When to recognize	2.5.2	Recognition is powerful but may also distract users from their task.
What to recognize	2.5.3	Sketches may represent objects (e.g. tables and chairs) and spatial or functional relationships between those objects (e.g. chairs positioned around table perimeter).
How to segment	2.5.4	Sketches contain many different symbols that may overlap. Recognizers must isolate groups of marks for consideration.
How to recognize	2.5.5, 2.5.6, 2.5.7	Many recognition techniques exist, and rely on segmentation methods.
Mediating recognition error	2.5.8	Recognition often results in ambiguous results.

Table 2.1: Topics in sketch recognition

2.5 Sketch Recognition

Recognition is the centerpiece of many software prototypes that support sketching. Although the research focus of many systems is not recognition, such systems use automatic interpretation of sketches to explore methods to interact with computers and new ways to design [24, 26, 46]. Such projects rely on reasonably accurate recognizers. Recognition is therefore a topic that affects nearly all aspects of research on sketch-based systems. For this reason, a substantial portion of this document is devoted to aspects of sketch recognition. This includes timing issues, determining what to recognize and how those elements can be recognized, and interaction issues (see Table 2.1).

2.5.1 Recognition Accuracy

Recognition accuracy is typically measured by the deviation between what the user intended and the machine's interpretation. *Error tolerance* refers to the recognition inaccuracy rate a user is willing to accept. One study using a typewriter modified to make occasional errors found that typists do not notice a word 0.5% error rate, 1% is manageable, but 2% is unacceptable [9, p. 79].

It is unclear if there are similar accuracy thresholds for sketching, though studies have been conducted for related recognition tasks. For handwriting recognition, adults find 3% minimally acceptable, with 1% considered "very good" [44]. Another study examining

user acceptance of hand gesture recognition error rates found users would tolerate misrecognition up to 10% when equivalent keyboard commands could be employed [40].

This is a substantial spread in acceptable error tolerance rates: 1% for typewriters, 3% for handwriting recognition, and 10% for hand gestures. One possible explanation is that people have higher expectations for typewriters (where there is a direct, deterministic mapping between input and output) compared with recognition based interaction, because we understand that it is possible the system might not understand.

2.5.2 When to Invoke Recognition

It is important that sketching systems *aid* design exploration and not simply *computerize* it [52]. For example, a sketch recognition system might zealously identify parts of the user's drawing as it is made, replacing the rough sketch with lines or curves. This removes the opportunity for reflection and re-interpretation that is so important to the early phases of design [21, 66, 73]. Premature recognition may interrupt the designer's flow of thought and interfere with the task at hand. Instead we may want the computer to eavesdrop silently, and provide help only when we need it.

A system can provide the user feedback of sketch recognition on different occasions: (1) in mid-stroke, (2) immediately after the pen is lifted, (3) when the system infers that feedback may be appropriate, (4) only upon request, or (5) never. Many interfaces attempt immediate recognition of gestures for invoking commands, such as with marking menus [42] or PDA device character input [56]. This is commonly called *eager* recognition [7]. Other systems [2, 23, 31] perform recognition in the background, deferring judgment until adequate information is available. This is termed *lazy* recognition. Most modern research prototypes take this approach. Last, some systems wait until the user explicitly requests recognition [45], or avoid recognition entirely [16]. Combinations of these approaches are common.

2.5.3 What Should be Recognized

Different kinds of design drawings ("model ink") in many domains might be recognized: artistic sketches, study sketches, drawings, diagrams, schematics, blueprints, and so on. In addition to model ink comprising those drawing types, user input may be interpreted as a command ("command ink"). The particular rules about what should be recognized depends on the domain (architecture or circuit design), kind of model (floor plan or timing diagram), and other application-specific requirements. Sketches often contain hand-written labels or annotations, which are common targets of pen based recognition.

Diagrams usually have a domain-specific grammar describing how vocabulary items relate [43]. For example, boxes may connect to other boxes via lines, those lines may have arrowheads to indicate direction. Diagrams are good candidates for recognition because the various elements and their relations can be described formally. Table 2.2 summarizes various recognizable classes.

"What" to recognize	**Examples**	**Remark**
Genre	Mathematical graph, architectural floor plan, web site layout, circuit design	It may be sufficient to recognize a sketch is of a certain kind without asking the user. The program could assume the sketch is in a certain domain.
Characters (writing)	Alphanumerics, math symbols	Usually with other characters, in words and sentences.
Geometric shapes	Dots, lines, rectangles, blobs	Geometric shapes are often drawn in relation to others.
Spatial features	A is contained in, is above, is larger than B	Spatial relations among elements may influence recognition.
Entities	Domain-specific notation such as diodes, transistors	Contextual clues can help disambiguate semantics of domain symbols.
Artistic nuance	Shadows, textures, color	Ink that modifies an existing element, perhaps suggesting 3D shape.
Commands	Object selection, delete, copy, move, etc.	Command ink specifies operations on the drawing.
Intention	Drawing's function or behavior, e.g. *circuit breaker*	Requires detailed domain knowledge and reasoning.

Table 2.2: Kinds of elements to be recognized

2.5.4 Segmentation and Grouping

Segmentation and Grouping are related processes of breaking down user input and finding related ink. Segmentation involves partitioning undifferentiated sketch input into parts (analogous to identifying word boundaries in speech recognition [9]). Grouping is the process of forming logical collections of data (analogous to determining which spoken words compose a phrase or sentence).

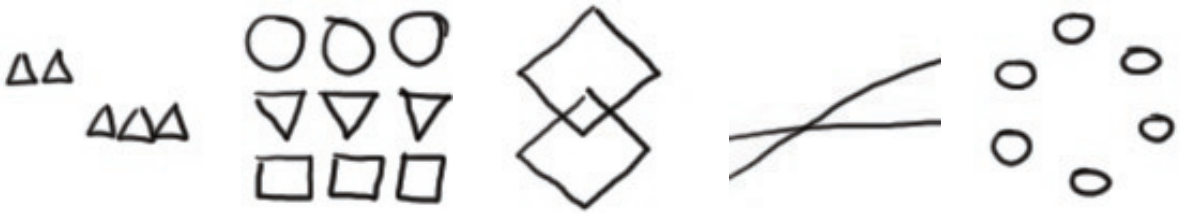
It is sometimes appropriate to break apart continuous pen strokes into multiple segments, for example in recognizing letter boundaries in cursive writing, or finding corners in continuous pen strokes. Alternately, it may be necessary to group related strokes to recognize compound objects such as a triangle drawn with three distinct strokes. To further complicate matters, there may be a number of reasonable ways to segment user input [49], based on information such as pen speed, stroke order, perceptual qualities, domain knowledge or curvature [41].

The technical challenge is simplified if the system requires users to complete each symbol before moving on to another, or if each symbol must be drawn using a conventional stroke order. However, such requirements work against the goal of supporting unconstrained, fluid sketching.

A common and effective method for segmenting ink incorporates time data. Sezgin's approach combines stylus velocity with curvature to identify locations of interest such as corners, or places where the drawer may be taking extra care to be precise [12, 68]. Wolin's MergeCF corner finder extends this approach by initially over-fitting the stroke with corners and iteratively removing them to arrive at a better fit. SIMI's ink processing algorithm is based on these.

It is often useful to organize drawn input at higher levels before performing semantic recognition. Gestalt psychologists offer the *laws of perceptual organization* to explain how people make sense of visual scenes. Humans perceive scenes not only using what is shown but also with "invisible extensions as genuine parts of the visible" [3]. The rules of perceptual organization include *proximity*, *similarity*, *closure*, *continuation* and *common fate* [37] (see Figure 2.7). All of these features are used by SIMI's sketch recognition system.

Perceptual organization supports grouping at many levels. At a low-level, we can use perceptual rules to analyze the relationship among individual ink strokes to find plausible groupings for recognition. PerSketch and ScanScribe explore how perceptual organization rules can be used at higher levels [64, 65].



(a) Proximity (b) Similarity (c) Symmetry (d) Continuation (e) Closure

Figure 2.7: Some principles of perceptual organization [37]. (a) Proximity: elements near one another are seen as belonging to a group. (b) Similarity: objects sharing features such as shape belong in the same group. (c) Symmetry: two shapes symmetric about horizontal and vertical axes, suggesting they belong together. (d) Continuation: the simplest explanation is two straight lines, not four lines meeting in the middle. (e) Closure: A large circle emerges from an arrangement of smaller circles.

2.5.5 Overview of Recognition Techniques

Regardless of the input device, we identify two broad categories of sketch recognition: *on-line* and *off-line*. On-line recognition knows how fast and in which order marks are made, and is performed as the drawing is made. Off-line recognition happens after the drawing is complete, irrespective of the order or speed strokes were made. SIMI uses on-line recognition.

On-line recognition strategies are further divided in two categories: single-stroke and multi-stroke recognizers. Single-stroke recognizers are appropriate for tasks such as interpreting freehand gestures. Single-stroke approaches are simpler to implement than multi-stroke strategies because user input is clearly divided into pieces. This process could be relatively simple: a multi-stroke recognizer might simply expect multi-stroke objects to be drawn in a prescribed fashion. Or, multi-stroke recognizers might be more complex, for example calculating the likelihood that distinct strokes (or segments) belong together. SIMI uses both single- and multi-stroke recognizers.

2.5.6 Hard-coded Recognizers

One common approach is to hard-code recognition routines directly. For simple or limited graphical vocabularies this may be appropriate. A circle (or a zero, or the letter 'O', or the sun, etc.) can be recognized with a short program looking for input points that are roughly equidistant from the stroke's centroid. However, ad-hoc, hard-coded recognizers are difficult to maintain and extend. For example, if we wished to extend our circle recognizer to interpret a sun with rays of light coming out of it, we would have to also recognize lines, then coordinate the recognizer to consider those particular lines together with the circle,

and ensure that the lines are positioned and angled correctly. Further, sketch recognition applications must be able to discern different kinds of elements. Recognizers for these elements may conflict. A new recognizer may cause an existing recognizer to stop working correctly, leading to maintenance, debugging, and testing problems.

SIMI uses hard-coded recognizers in situations when performance is critical (e.g. erasing and undo/redo).

2.5.7 Pattern Matching

Another strategy for representing classes is to create a library of pattern templates. These approaches can be separated into two groups: those that use *visual* templates, and those that use *textual* templates.

Template matching strategies are often *feature-based*. Features include properties such as stroke length, stroke path, minimum or maximum angle, or aspect ratio. The system holds a library of templates, each of which has feature values. The system computes feature values for user input, and compares those values with those contained in the library. SIMI uses textual templates, but not the visual kind.

Examples of the visual template method include the Ledeen recognizer [54], the Rubine recognizer [61], Kara's recognizer [38], and the $1 Recognizer [76].

Textual templates may be described using a programming language [5, 10, 27, 57]. These notations have two primary strengths. First, humans can read (and edit) them. For example, a television symbol may be described with natural language as "a square with a slightly smaller circle positioned at its center." A formal symbolic language for that statement is still quite legible (assuming one understands the function semantics):

```
(define television
        (and (centered square circle)
             (slightly-smaller circle square)))
```

Another strength of this kind of notation is that it allows the developer to describe entities at a level of abstraction that accommodates variability between entity instances. An *abstract* triangle is a three-sided, two-dimensional shape whose internal angles add up to 180°. A *particular* triangle may have side lengths of 3, 4, and 5, and be oriented so that its long edge is horizontal. We may define triangles and other entities as abstractly or concretely as the language allows.

Many of the recognizers in SIMI use textual templates roughly based on the approaches described by Hammond [27] and Alvarado [1, Chapter 4].

2.5.8 Managing Ambiguity

Futrelle's classification scheme of types of ambiguity in diagrams includes two high-level categories: lexical and structural ambiguity [17]. Lexical ambiguity refers to the "word" level, when the meaning of a particular symbol is in question. Structural ambiguity refers to confusion arising from the composition of symbols.

Shilman augments this scheme with two additional types of ambiguity that arise in sketch recognition: label and attribute ambiguity [69]. Label ambiguity is present when the symbol's identity is unclear. For example, a quickly drawn rectangle might be interpreted as a circle. Attribute ambiguity refers to the features of a sketched element: the exact location of a quickly drawn rectangle's corner may be unclear.

BURLAP [49] is a calligraphic application based on SILK [45] that enables people to draw user interfaces. As the user draws, BURLAP forms a list of plausible interpretations. At some point the system may need to pick one interpretation. Mankoff *et. al* call this process *mediation*, performed by agents called *mediators*. Some mediators may engage the user by displaying a pick-list of choices or visually indicating the ambiguity. Other mediators automatically execute and do not involve the user. SIMI uses this automatic way to disambiguate contending interpretations.

Another way to manage ambiguity is to prevent it from arising in the first place. Some sketching systems let designers model 3D objects. Recognizing 3D topology from a 2D sketch is difficult because of *Z ambiguity*: for any point on the (x, y) plane, there is an infinite number of possible z values. In Kara's automotive styling system [39], designers use specific sketch-based interaction techniques to achieve unambiguous z values. By contrast, Lipson's 3D modeling sketching tool [47] does not impose special techniques on the user, and instead attempts to derive z values by searching a space of possible interpretations weighted by past observations of 3D-to-2D reverse projections.

The two 3D modeling systems described in the preceding paragraph use different approaches to manage ambiguity: In Kara's system, the approach is interaction design; in Lipson's, it is based on perception and statistics. Researchers have found success with both approaches. SIMI is entirely based on interaction design.

Chapter 3

Formative Studies

The previous chapter covered background literature and prior work by other researchers. This chapter presents original work studying design culture, specifically related to rapid fabrication with laser cutters.

This chapter presents three studies. First, I give observations of people working at a professional design studio. It gives a firsthand account of processes that real designers use when practicing their craft. Second, to better understand the tasks and problems designers face when designing for laser cutters, I conducted two related formative studies. I interviewed people with experience designing laser cut artifacts and watched them work. In addition, I surveyed and analyzed laser-cut items found on community web sites to identify common features.

3.1 Tiny Ethnography

I arranged to "be a fly on the wall" at a MAYA Design, well-respected design firm in the Pittsburgh area. This was done to observe how designers work. I spent about twenty hours at the company observing and interviewing designers who work there. This study was inspired by Bucciarelli's ethnographies of engineers [8]. While this work pre-dates my focus on design for laser cutters, it does provide a solid connection between my narrow topic and the broader context of design practice.

A professional studio is notably different from an educational design studio. For example, companies face many issues that are not generally present in an academic institution. These include billable hours, interacting with paying customers, significant differences in age and experience level of collaborators, and so on.

This company's culture places high value on collaborative whiteboard sessions. At any time, the majority of the whiteboard surfaces throughout the office have some sort of

scribbling on them. Most whiteboard sessions were by two or more people gathered in conversation. The scribbles served to represent objects that are sometimes labeled with markers, but usually just described verbally. In this way, collaborative whiteboard drawings are multi-modal design artifacts, because part of their value is static (the sketch), while another part is transient (the conversation) [35]. Whiteboard sessions are consistent with Ferguson's *talking sketches* [14].

Four of the five designers I interviewed showed me their paper sketches. About half of these drawings were made when the designer was alone (Ferguson's *thinking sketch*), and the rest resulted from collaborative sessions like the whiteboard events described above. Some paper sketches were diagrammatic (using formal or semi-formal notation), while others were renderings of some physical object like a building or electronic gadget. Interestingly, those same designers were less inclined to show computational models (like Illustrator files) because they felt the sketches contained the "real" work.

While designers typically did not volunteer to show computational artifacts, they were inclined to show me printed versions of their computational models. Nearly all of these printed pages were annotated with handwriting and sketches, sometimes by more than one person. They use a process of iterating between virtual and paper representations of their work. The designers would edit a computational model with a high-functionality application such as Photoshop, then print a paper copy for personal or group use. Then they would draw or write directly on that page as they explored variations or made refinements. If a paper-based editing session was useful, the designers would then manually transfer these changes back into their application. The process of printing, editing, and manually merging changes was common. This pattern recurs in the following section on laser cutter users.

3.2 Interviews

Six designers were interviewed from different backgrounds, including mechanical engineering, graphic design, and architecture. This was done to learn about their work practices and to understand how they use their tools. All had experience designing objects to be made with a laser cutter.

Each session lasted approximately one hour, split evenly between an interview and using software. Meetings took place in participant workplaces, where they were asked to describe their design process and to show sketches, demonstrations, or videos of their work. Although there were differences in their process, each followed the same overall pattern.

The designers all said they began by thinking about a problem and sketching on paper. They made drawings to think about how to "frame" the project (what it is for). Other

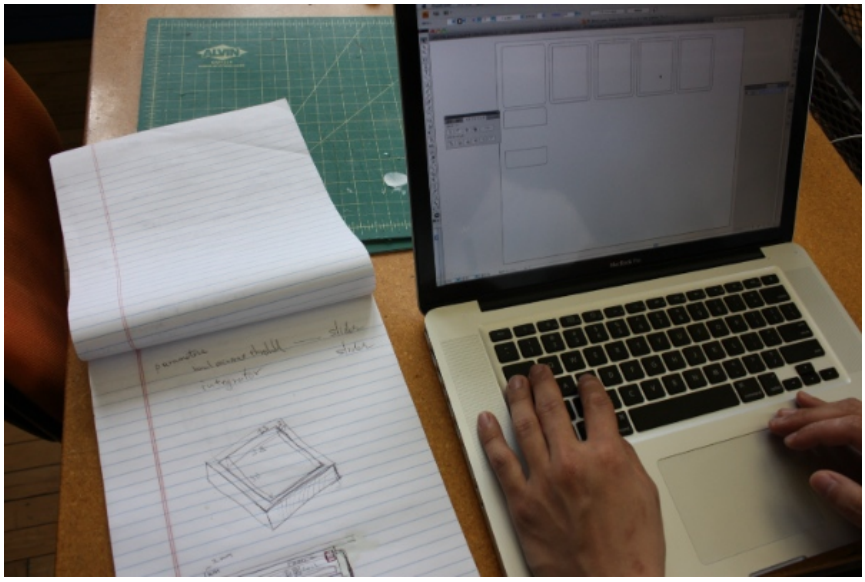


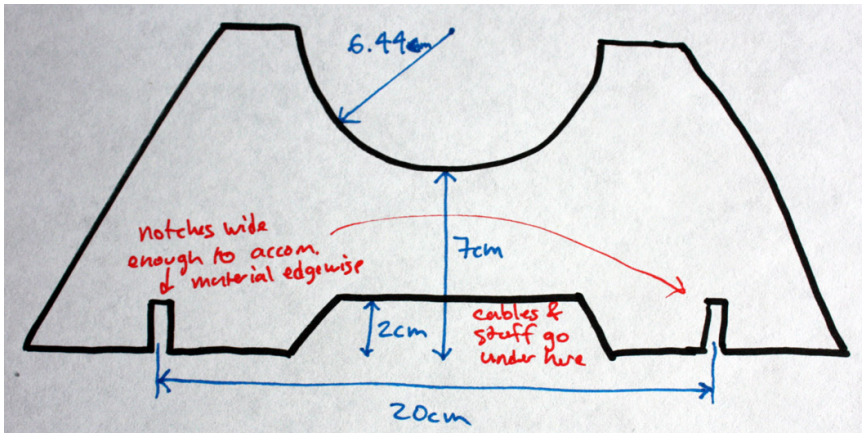
Figure 3.1: A common step of designing for laser cutters: translating a hand-made sketch to a computer modeling tool. The sketch includes a perspective drawing of the desired result, and 2D diagrams of individual parts with key dimensions indicated.

sketches helped reason about how to make it (how it works and fits together). Some designers explicitly noted that sketching is a necessary part of the process: they could not move forward without making freehand drawings. Only after the idea was well-formed were they ready to translate their hand-made sketch into a computer model (Figure 3.1).

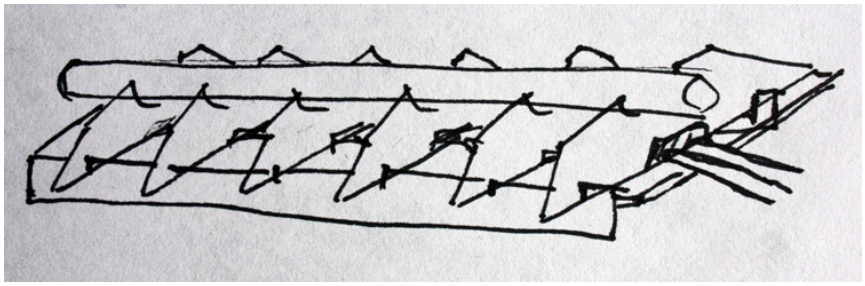
After the interview, participants were asked to copy the sketch shown in Figure 3.2 using a software tool of their choice. This was done to learn what problems people encountered when executing the common task of translating a sketch to a computer model.

Five participants chose to implement the sketch with Illustrator; one chose Rhino. All users were comfortable with their tools, but none were experts. Every designer's strategy involved common activities: creating and editing boundaries, aligning or snapping items, using guide lines or reference points, measuring distances, specifying or changing lengths and angles, and creating finished "cut files" to send to the laser cutter. They also engaged in the usual interaction management tasks—selecting and deselecting on-screen elements, and view port management such as zooming and panning.

Participants spent a good deal of time on operating overhead (approximately 50%, or about 15 minutes per interview). This included searching for appropriate tools for the next task, and recovering from errors. Consider the example of one designer who was an experienced Illustrator user. He was aware of the "Path Finder" tool and wanted to use it. He slowly searched the program's menu structure and hovered over toolbar buttons to read tool tips. Upon finding the Path Finder, he invoked various functions, using the keyboard



(a) Users tried to replicate this sketched part.



(b) Drawing of the part in context.

Figure 3.2: Participants were asked to model this using software of their choice.

shortcut (Control-Z) to undo after each failed attempt, as he searched for the correct mode within the subcommand palette. This process lasted approximately 80 seconds.

Occasionally participants used features in unorthodox ways. For example, to remove an unwanted segment of a polyline, one participant (a graphic designer) created an opaque white rectangle to obscure it, rather than erase it. ("Don't tell anyone I did this", he said).

Similar episodes are common: a person *should* know the 'correct' action, but takes an alternate approach. Although the alternative achieves the intended effect, it might be less efficient (more operations, longer execution time) or introduce unwanted complexity (e.g. the white rectangle).

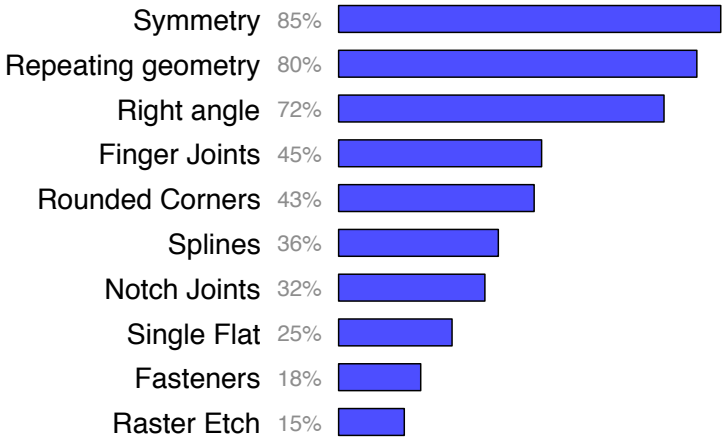


Figure 3.3: Frequency of features of 55 laser-cut designs found on Ponoko and Thingiverse.

In short, most common tasks and problems belong to three main groups:

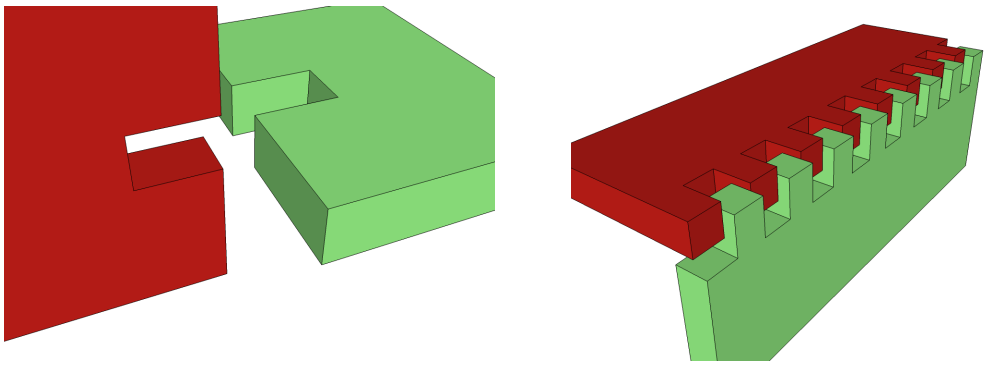
- *Defining geometry:* Creating/editing boundaries, aligning items, creating and using guide lines or reference points, measuring distances, and specifying lengths or angles.
- *Managing the editing tool:* Selecting/deselecting objects, view port management, finding and entering tool modes, and recovering from errors.
- *Cut file:* Finalizing the cut file by creating copies of items when more than one is needed, and positioning stencils.

3.3 Artifact Analysis

The formative study of work practices from the previous section helps us understand *how* people create laser cut items. To learn more about the characteristics of those objects (*what* people create), I analyzed finished items from two web-based communities of laser cutter users.

Many users are motivated by the opportunity to share their work with others. Ponoko and Thingiverse are two currently popular web sites for selling or sharing items that can be made with rapid fabrication machines. In early 2012, Ponoko offers thousands of user-designed items for sale, mostly produced by laser cutting. Thingiverse is a warehouse of digital models of 3D-printable objects and designs for laser cutters. From these two sites I selected a total of 55 laser-cut designs. On Ponoko, the most recent 45 laser cut items were chosen. On Thingiverse, ten objects with the "laser cutter" were selected. Figure 3.3 summarizes the feature analysis of these 55 projects.

Each project was characterized using ten properties, based on my own experience de-



(a) Notch joints. (b) Finger (box) joints.

Figure 3.4: Two common methods to join parts. Notch joints are used when parts intersect along part midsections; finger joints (box joints) join parts along edges.

signing objects for laser cutters, as well as observations from the formative study. They are:

- *Symmetry*: Radial/linear symmetry is present.
- *Repeating geometry*: Line work is repeated several times.
- *Right Angle*: Edges meet at 90-degree angles.
- *Notch and Finger Joints*: Parts join in one of the ways shown in Figure 3.4.
- *Rounded Corners*: Right-angle corners are slightly blunt.
- *Splines*: Curved line work (not counting rounded corners).
- *Single Flat*: The project is composed of a single, flat piece of material (e.g. a coaster).
- *Fasteners*: Use of glue, screws, or bolts.
- *Raster etch*: Patterns like words and images are etched in material.

This list of properties helped inform what SIMI should (and should not) do. However, it is important to note that the features provided by SIMI was not explicitly determined by this analysis; rather, the most common features were favored. Rounded corners, for example, were not included in SIMI because that feature did not support a substantially greater outcome. By contrast, Symmetry was not explicitly supported (e.g. by a 'mirror' tool or similar) but was implicitly made possible with a combination of angle and length constraints.

Chapter 4

Sketch It, Make It: Overview

The primary contribution of this thesis is the set of interaction techniques implemented in a single design tool called Sketch It, Make It (SIMI). SIMI is a modeling environment for laser cutter design that recognizes short sequences of drawn input made with a stylus. Using only freehand input, SIMI enables a designer to iteratively and incrementally create precise laser cut models.

I am inspired by the potential of freehand drawing as the basis for precision modeling for several reasons. Sketching is quick and can be easily learned. It is simple and modeless: unlike structured editing software, a designer need not set a pencil's mode to line, circle, or anything else. I will show that given an appropriate set of interaction methods, sketched input can provide enough information to make a precise digital model.

There are several principles that guided SIMI's design and development.

- **Democratized design**: Freehand drawing is a skill that most people already have. It follows that a tool based on sketch based interaction should be usable by a majority of people. For this reason I target avocational designers, not professionals.
- **Sketch based**: The user should never feel obliged to set down their pen. In the past, many sketch based design tools relied on keyboard input, or used interface widgets that are appropriate for mice, but are uncomfortable to use with a stylus (e.g. hierarchic menus).
- **Coherence of interaction techniques is key**: The tool presents a set of sketch based interaction techniques that work well together. Researchers commonly make toy systems that demonstrate one or two novel interaction techniques in isolation (e.g. my own prior work on Flow Selection [33]). But a useful tool has many individual techniques. The current system implements many techniques together to give an example of a way to make them work harmoniously.

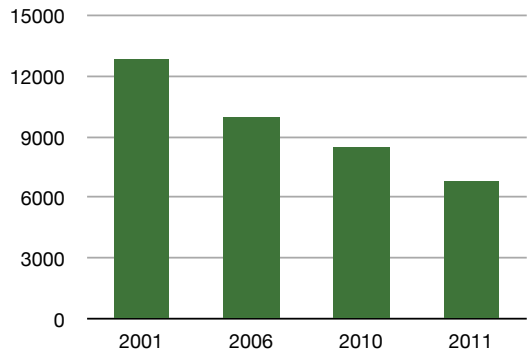


Figure 4.1: Declining cost (USD) of Universal Laser Systems 25-Watt 16x12 inch laser cutter.

- **Useful and usable**: Last, the system lets people make real things in a real domain (namely, laser cut objects). The current implementation of the tool is efficient and highly responsive. In informal demonstrations, more than one person noted that the system seems more like a commercial product than a research system. This is intentional.

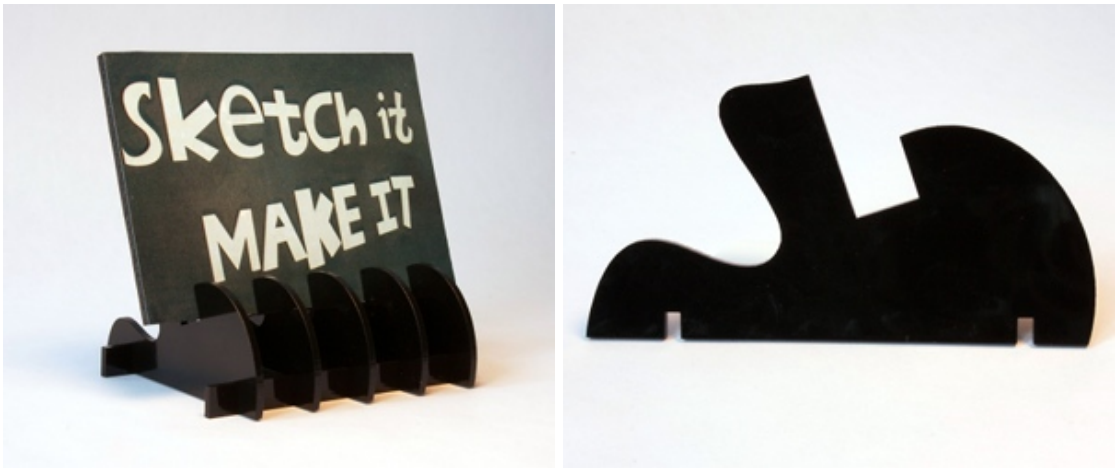
4.1 Rapid Fabrication and Laser Cutting

Laser cutters are among the more common and affordable fabrication machines. One can think of a laser cutter as a fast, strong, and precise automated razor that cuts flat material (paper, wood, plastic, textiles, etc.).

The price of laser cutters is quickly declining, making it possible that more people can access to them. Figure 4.1 shows prices for a comparable 25-Watt, 16″x12″ laser cutter model from Universal Laser Systems (these values were found on hobbyist web forums). While these data may not be exact, they do show the price of desktop laser cutting machines has been cut by almost half in the past ten years. While still out of reach for most people to afford, they are becoming inexpensive enough for schools and hacker spaces to own.

Laser cut designs are composed of parts cut from solid, flat material and assembled in various ways: laminated, notched, bolted, glued, *etc*. Various materials require different laser speed and intensity settings to achieve a quality cut. The designer uses a software application to specify part shapes for laser cutting. The software outputs vector graphics called a "cut file" that defines these shapes. As most joints have small margins of error, lengths, angles, and relative position must be specified precisely so parts fit together properly.

Tools for designing laser cut objects must allow users to precisely specify dimensions.



(a) (b)

Figure 4.2: A picture stand (a) drawn and fabricated using SIMI. A single copy of the primary part is shown in (b).

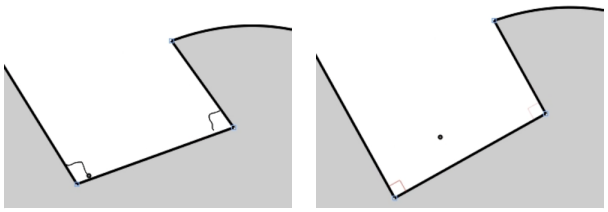
Like a physical saw, the laser leaves a gap in its wake, called a *kerf*, (between 0.2mm and 0.5mm on a 40 watt cutter). This is an important consideration when designing facets whose tolerances are small with respect to kerf. A notch joint, for example, is ineffective if it is 0.1 mm too large or small.

4.2 Motivating Scenario: Picture Frame Holder

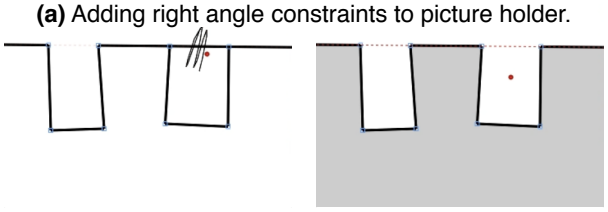
To introduce Sketch It, Make It I will explain how it could be used to make the picture stand shown in Figure 4.2. This narrative helps explain the overall user experience while exposing technical aspects (which are discussed in much greater detail in the following chapter).

We begin with the idea of a stand with two horizontal rails as a base and a five-part vertical support structure, joined with notches. Using SIMI on a tablet device like the Wacom Cintiq shown in Figure 1.1, we first draw the rough profile of the vertical support piece using curved and straight segments. After a brief period of user inactivity, SIMI recognizes and renders the drawing by straightening lines, smoothing curves, and connecting curved and straight segments. We may optionally press a button with our non-dominant hand to ask SIMI to do this immediately. If we make a mistake (or if we change our mind), we can recover quickly by scratching out the unwanted ink, or use an Undo gesture.

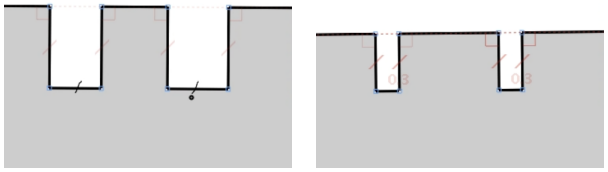
After sketching the rough outlines of our two parts, we begin to refine the design and make it precise. We square the corners by drawing right-angle braces (Figure 4.3a). Now as we adjust the shapes of the two parts by selecting and dragging endpoints and re-shaping



(a) Adding right angle constraints to picture holder.



(b) Erasing line segment to reveal a notch in the base rail.



(c) Constraining notch widths precisely in the base rail.

Figure 4.3: Key steps taken when making the picture stand.

curves, SIMI maintains the right-angle constraints we've established.

Next, we add notches to the two parts to make joints. We draw five small notches on the base rail. For each notch we draw three lines inside the outline of the part, and then use the erase gesture to remove the residual outline segment (Figure 4.3b). Then we indicate that both sides of the notch are to be the same length: We draw tick marks on each segment, and right-angle braces to keep the notch perpendicular to the edge of the part. The notches must have exactly the right dimensions: too wide, the top parts will wobble; too narrow and they will not fit. We size the notch by over-tracing its segments and entering fixed dimensions (Figure 4.3c).

We drag the base part (twice) and the support part (five times) to SIMI's cut file area to prepare a vector file, and then send it to the laser cutter. Finally we assemble the cut parts to make the picture stand in Figure 4.2.

4.3 Technical Challenges Met By SIMI

The above section describes the user's needs, and how the user interacts with the system. This section summarizes several categories of technical challenges the system has to meet in order to support those user needs. These categories are printed in bold text. Most of the following topics are described in great detail in the next chapter.

A fundamental task is **ink parsing**. While the pen is down, the system looks for gestures such as erasing. When the user lifts the pen, the ink is parsed to identify corners and segments, and other recognizable elements.

SIMI must be able to dependably **recognize user input**, which often depends on the ink parsing just mentioned. Input is often made quickly and inaccurately, so occasional recognition errors can not be avoided. There are several kinds of recognized elements. Input might be line work that specifies the model's geometry. Or, input might be identified as a gesture that edits the model by removing ink or adding constraints. Last, input might be as part of a multi-stroke phrase that controls the modeling environment (e.g. undo/redo, zooming, or panning).

There is one recognizer per recognizable pattern. Each recognizer has access to the model state, but they do not communicate directly with each other. Inevitably more than one recognizer will signal a positive result, so it is necessary for SIMI to **disambiguate (or resolve)** contending recognition results. For example, the user may draw two short strokes that are recognized as both a right angle symbol and a same-length gesture. To resolve this ambiguity, SIMI uses a series of tests that involve context (e.g. if the input is correctly positioned in a corner or not) as well as static precedence rules that defer to the interpretation that causes the least trouble in the event it is wrong.

The user's work is stored as a **data model** consisting of points, segments (e.g. line, arc), and high-level constraints (e.g. right angle, same length). SIMI lets the user edit the model to create, merge, or erase these elements. The **constraint engine** is closely associated with the data model. It lets the designer indicate geometric rules that the system will try to maintain, even as the user edits the model. SIMI's constraint engine is an iterative, numerical solver using a relaxation method in the tradition of Sketchpad [72].

When it is time for the user's work to be given to a laser cutter, the designer asks SIMI to **generate a cut file**. This is a 2D vector graphics file specifying geometry of cutouts. The current implementation is a rather simplistic "typewriter" algorithm—it uses the bounding box of each cutout, placing one next to the other from left to right, and moving to the next "line" when placing a piece would extend beyond the material bounds.

4.4 Coherent Sketch Based Interaction

Sketch It, Make It presents a fluid interface for making laser cut parts. The smooth interaction is made possible by combining many sketch-based techniques into a set of interaction methods that work very well together. The fluidity is *not* the result of any one technique, nor is it simply the result of throwing several existing methods together.

The interaction techniques offered by SIMI were carefully tuned to work with one another. Each gesture is as distinct from the others as possible. The distinction is either *syntactic* (e.g. a circle is distinct from two short lines) or *contextual* (e.g. a large circle around a closed shape is distinct from a small circle around loose segment endpoints.) This does not completely avoid recognition error but it does mitigate it because the gestures are not often confused with one another.

SIMI gives visual feedback when appropriate which helps to resolve possible conflicts. For example, a selected point is rendered as a colored dot, and changes the cursor to a hand symbol to indicate the can move the point by dragging. Without visual feedback that the point is selected, or that the pen is near enough, it was easy to inadvertently draw line work when the user intends to move the point.

The interaction techniques have conservative failure states. The automatic latching algorithm is a good example. The auto-latcher has parameters describing the maximum distance between points and relative segment angles. These parameters were set to err on the side of not latching segments together, because the consequences of latching inappropriately are worse than not latching when the user wanted. To recover from a missed automatic latch opportunity, SIMI provides a very simple latching gesture.

SIMI's interaction differs from standard design tools and other sketch based modeling prototypes in several ways. Some of these differences are discussed in the sections below.

4.4.1 "The Mode Problem"

A traditional design tool like Adobe Illustrator is built around the concept of input modes such as *select*, *draw line*, or *fill color*. Users activate modes by selecting a menu option, clicking an on-screen widget, or pressing a keyboard button. The program interprets user input in terms of the active tool. Sometimes users are unaware of which mode the program is in, or are unsure how to change to the desired mode. Managing modes often introduces cognitive load by forcing users to think about the tool rather than their work. This is called "the mode problem" [74].

SIMI lacks persistent mode. The user can always draw on any part of the drawing canvas, and the input's meaning is determined via recognition: an input stroke might be an erasure scribble or a right angle symbol or a straight line that completes a shape. There is no 'erase mode', no 'right angle mode', and no 'draw line mode'. Some operations, such as flow selection, include transient mode changes where the meaning of user input is interpreted differently based on recent interaction. For this reason it is not strictly correct to label SIMI's interaction as *modeless*.

4.4.2 Conversational Interface

One property that characterizes sketch based systems is *when* recognition is performed (see Section 2.5.2). Many sketch based design tools operate in batch mode, where a substantial amount of raw ink (e.g. dozens of strokes, or more) is analyzed at the same time. The rationale for this approach is that recognizers have more data (unrecognized ink) to work with and can use statistical methods to generate the most likely interpretations for the entire sketch. The larger the sample, the more statistical confidence the recognizer can have.

SIMI takes a different approach involving short sequences of input followed by recognition that fix the meaning of input by graphically representing results. Because the meaning of on-screen elements are known, the next round of recognition can use that knowledge to provide unambiguous contextual clues. As the user and system take turns on such a regular basis, I call this a *conversational interface*. The user and the system constantly check each other's states to ensure that meaning is shared.

4.5 Recognition Architecture

SIMI's recognizers operate at three different times. First, *Dynamic* recognizers (like Erase) operate while the pen is down. A second class of recognizers are invoked when the pen is lifted. If there are positive results from these *Pen Up* recognizers, action is taken immediately. An example of this kind is latching. The third kind of recognizer is triggered after a period of inactivity (currently 1.5 seconds). The user may optionally press a button with their non-dominant hand to recognize input as needed. The recognizers include those that establish constraints like right angles, or create line work like circles and splines. This last type is called *Deferred* because it does not happen immediately after the pen lifts.

Each recognizer class addresses a different need. Dynamic recognizers allow the user to make gestures that must be recognized (and possibly acted upon) as they are made, when timing is very important. Pen Up recognizers allow the user to make distinct gestures that are acted on immediately, eliminating lag and making the interface seem much more responsive. The Pen Up recognizers are reserved for common actions that are unlikely to interrupt the user when their associated actions are taken. By their nature, both Dynamic and Pen Up recognizers must work on single stroke gestures. Last, Deferred recognizers operate on one or more strokes. Their related actions might distract the user if they were invoked immediately upon lifting the stylus. The overall recognition architecture is illustrated in Figure 4.4.

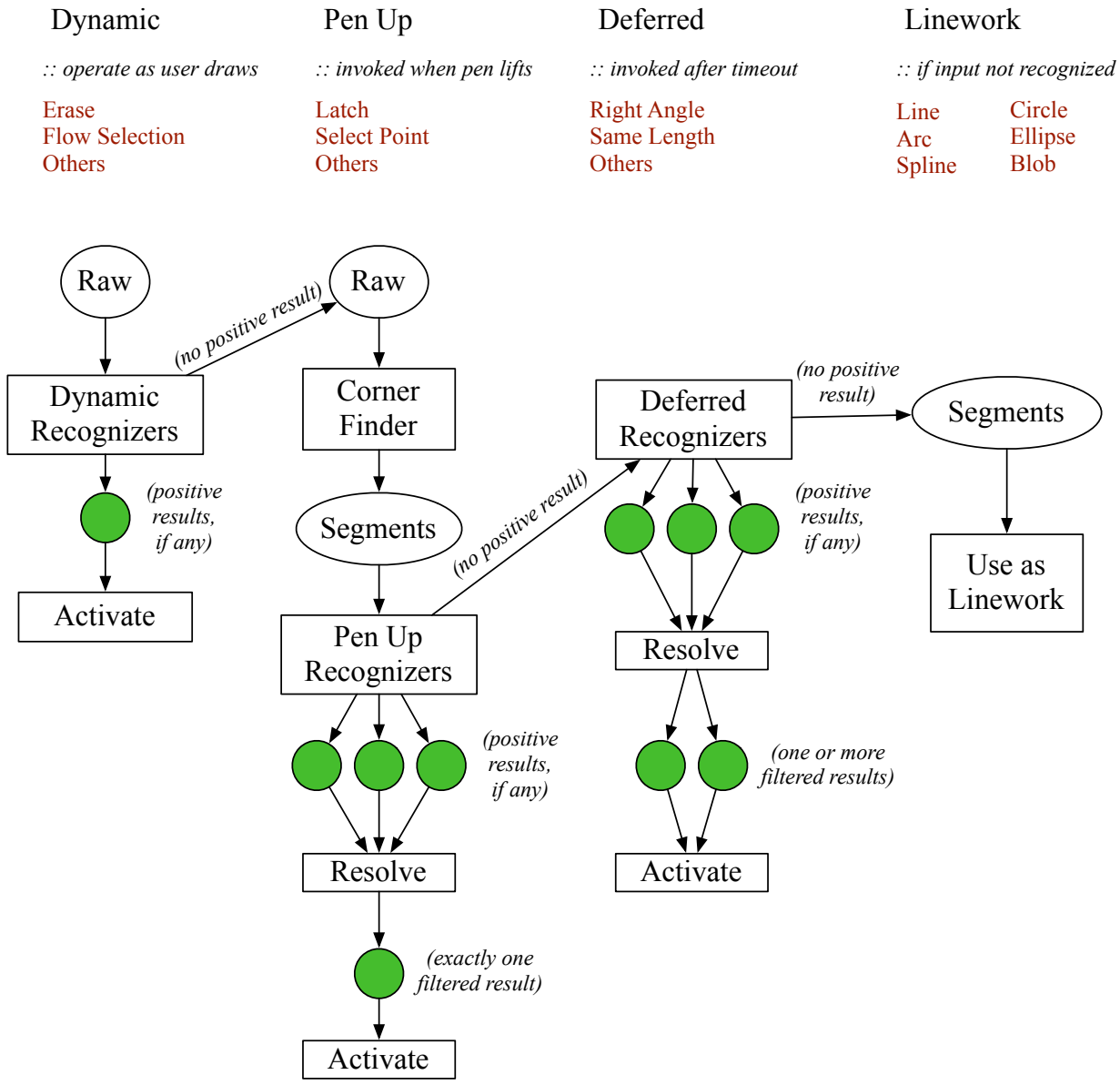


Figure 4.4: SIMI's recognition architecture includes three types of recognizers based on when they are invoked. Colored circles indicate positive results.

4.5.1 Dynamic Recognizers

Dynamic recognizers use raw pen data that is generated as the user draws. They are invoked after each new pen movement event, which typically happen at a rate of once per 15–20 milliseconds. They must execute very efficiently in order to avoid causing the interface to seem unresponsive. If the user interface is redrawn at 60 Hz, each frame must be drawn in less than 16 ms. Therefore it is very important that all dynamic recognizers execute in much less than this time period in order to give the graphics subsystem time to draw the screen.

When a dynamic recognizer finds a positive result, all other Dynamic recognizers are temporarily turned off, and the associated ink stroke will not be passed on to the Pen Up recognizers. For example, if the scribble recognizer determines that the user is erasing, it displays a visual indication that it recognizers the erasure. When the user lifts the pen, it will attempt to erase something. Further, the Dynamic recognizer might change how the current ink stroke is drawn, as is the case with Flow Selection.

4.5.2 Pen Up Recognizers

If no Dynamic recognizer claimed an ink stroke, it is processed by the Pen Up recognizers when the user lifts the stylus. The first step is to parse the raw ink to identify corners and segments. The implementation details of SIMI's corner finder are given in Section 5.1. The Ink Parser supplies a set of segments, which may be any of the following types: Dots, Lines, Elliptical Arcs, Splines, Circles, Ellipses, or Blobs (a spline that starts and ends at a common point).

Pen Up recognizers operate on this set of new segments. Each recognizer operates independently of the others. They test if segments comprising the most recent pen stroke match a pattern. It is possible for several recognizers to positively identify their gesture, but only one such gesture is valid. If any positive results are found, a subsequent process resolves conflicts.

The conflicts are mediated in two ways. First, sometimes a gesture makes more sense than others in context. A context checker will report how well a gesture matches the current drawing state with a Yes, No, or Maybe. If only one contending gesture receives a 'Yes' vote, the other interpretations are discarded. Second, if the context checker can not resolve the problem, then a static rule list is used. This list ranks each recognizer type, and the interpretation that is highest on the list is accepted (the rest are rejected).

The order of this rule list important. Recognizers that edit the model are lower on the list than recognizers whose effects can be ignored. For example, a Latch gesture edits the model, while the gesture to display the Pan/Zoom widget has only a temporary response. If

the wrong interpretation is made, SIMI will err on the side of the inconsequential or easily recoverable.

If a single positive result is found, it is activated immediately. The related action for a Latch gesture will combine points, possibly destroying or creating segments. This edits the model and causes the graphical representation to change.

Last, any ink associated with a positive result is removed from the model and will not be available to the deferred recognizers.

4.5.3 Deferred Recognizers

Deferred recognizers follow a similar process to Pen Up recognizers. The deferred recognizers are automatically invoked after the user has not interacted with the system for a short period (currently 1.5 seconds). The user may optionally speed invocation by pressing a button with their non-dominant hand.

It should be noted that the button press does not conflict with the guidelines presented at the beginning of this chapter. Because the button is pressed with the user's non-dominant hand, the stylus can remain comfortably gripped in the primary hand—they do not have to set it down.

By this point, ink that was positively recognized during the Dynamic or Pen Up stages is not available to the Deferred stage. When the pen is lifted, the ink is analyzed in the Pen Up recognition step, yielding a set of corners and segments. Ink and segments that are not recognized by the Pen Up step are placed in a data structure for the Deferred recognizers. This means Deferred recognizers operate on segments made in one, two, or (potentially) many more strokes.

As in the Pen Up stage, each Deferred recognizer operates independently of the others. *Unlike* the previous step, it is possible that several results are valid, as long as they are composed of different strokes. This makes it possible, for example, to issue two Right Angle gestures and a Same Length command in the same batch, all of which can be recognized. If two potential results involve some of the same segments, SIMI employs the same resolution process from the Pen Up recognizer step.

When conflicts are resolved, there may be zero, one, or more positive results. The positive results are activated in no particular order. This could theoretically cause problems (for example if one action renders another nonsensical), but this situation has not been relevant in the current system because the gestures (syntax and context) were designed to avoid such conflict.

Segments that are not associated with positive results are interpreted as geometry. This is how the user creates line work that define boundaries of laser cut parts. This geometry is

then included in the model and provide context for later recognition processes.

4.5.4 Discussion of Recognition Architecture

SIMI's recognition and resolution architecture provides a framework for developing other sketch-recognition applications. The staged approach allows recognizers to work in batches at different times. The properties of each stage suggests there are natural places for new recognizers to fit into this scheme. Future developers can use the following logic to determine the appropriate stage for new recognizers to operate.

If the gesture's effect should be immediate, Dynamic or Pen Up recognizers are apt. Actions that require visual feedback while the pen is down (e.g. Flow Selection) must be Dynamic; others (e.g. Latch) should be run with Pen Up recognizers.

Actions that are composed from several strokes must be implemented with a Deferred recognizer. The Same Length gesture, for example, can be composed of two or more hash marks.

Actions that are composed of a single stroke may be Dynamic, Pen Up, or Deferred. Because Pen Up recognizers activate immediately it is best to reserve this stage for operations that are made quickly and with minimal potential for ambiguity.

4.6 Model: Geometry, Constraints, Cutouts

The data model underlying SIMI is fairly simple. It contains *named points, segments, constraints, and cutouts*. All these data are the result of sketch recognition—no raw, unprocessed ink is stored. *Named points* are time-stamped 2D locations. They are named because they are given textual labels that allow other entities to refer to them by name. This makes it easier to debug and to store the model to disk.

Segments are a patches of line work. They must be one of the types listed in Table 4.1. All segments are composed (at least partly) by named points. If the named points change locations, the segment's geometry is automatically changed as well. More than one segment can refer to a named point (e.g. if two lines meet, they share a common point). Some segments are open, while others are closed. Figure 4.5 illustrates all supported segment types.

A *Constraint* establishes geometric relationships among named points or segments. Constraints refer to named points directly. Like segments, several constraints can share named points. Table 4.2 lists all SIMI's constraint types.

The final output of this design tool is a *cut file* that contains *cutouts*. A cutout is a 2D

Segment Type	Remark
Line	Straight line connecting two points.
Elliptical Arc	Elliptical arc that passes through two points on an ellipse. The ellipse is defined with a centroid, a major and minor radius, and an angle of rotation. The endpoints are defined with angular offsets.
Ellipse	An ellipse defined like the elliptical arc, except it is a closed shape.
Circle	A circle is a closed shape defined by a center point and radius. SIMI does not include a corresponding circular arc.
Spline	A cardinal spline made of start/end points, and a parameter list determining control point locations relative to the start and end.
Blob	A Blob is a closed spline.
Dot	A Dot is represented as a single point. It is recognized when the input stroke is very short.

Table 4.1: Segment types in SIMI.

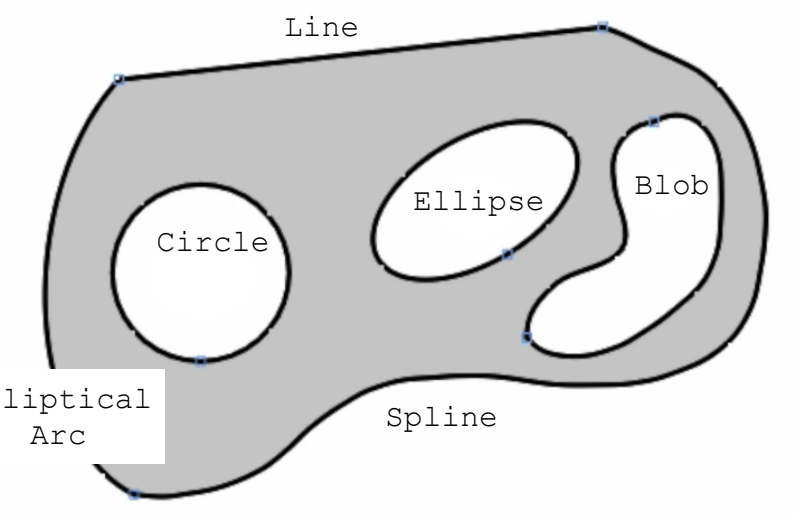


Figure 4.5: SIMI supports six segment types: lines, elliptical arcs and splines are open-ended, while circles, ellipses, and blobs are closed 2D shapes.

Constraint Type	**Remark**
Same Length	Constraints two or more segments to be the same length. On each step, it calculates the mean segment length and expands or contracts segments to conform to the mean.
Specific Length	Like the Same Length constraint, this can refer to two or more segments. It uses a specific numerical value for the expected segment length.
Right Angle	Constrain two line segments to form a 90 degree angle. As there are two possible orientations (e.g., $\perp$ vs. $\top$), it chooses the nearest solution when calculating error and change vectors. It rotates each point about its line segment midpoint.
Same Angle	Like Right angle, this constraint rotates points about their line segment midpoints. It operates on two or more angles, polling its constituent angles to find a mean value to calculate error and change vectors.
Colinear Points	Constrains three or more points to be on the same line.

Table 4.2: Constraint Types in SIMI.

shape defining the boundary of a part to laser cut. SIMI identifies cutouts automatically by analyzing the model, searching for closed paths. Cutouts are graphically shaded. Users may place a cutout in the cut file region on the screen to add one or more copies to cut file.

4.6.1 Constraint Solving

Many user actions trigger the constraint solver. This section describes how the SIMI's solver works.

Figure 4.6 illustrates the relationship between points, segments, and constraints. In the first pane, the system has recognized the user's input as two lines that meet at a common point. Further, the user has added two constraints indicated the lines should meet at a right angle, and the lines should be the same length.

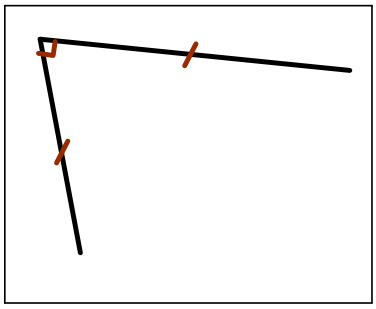
Initially, the constraints in the figure are not satisfied. Lines meet at about an 80 degree angle, and the top line is longer than the other. If constraints are not satisfied, the *constraint solver* (sometimes called a constraint *engine*) is called on to make corrections.

SIMI uses an numerical, iterative solver similar to Sutherland's relaxation method used in Sketchpad [72]. Each iterative step follows the process shown in Figure 4.6. Before iterating, the constraint engine determines if it should proceed. It polls each constraint to compute its error, which is a measure of how much change is needed to satisfy the constraint. In SIMI, a system of constraints is *satisfied* if its error value is less than some small threshold. It is important to note that *the satisfactory solution is not necessarily exact*, but rather that the constituent constraints are satisfied to within engineering tolerances.

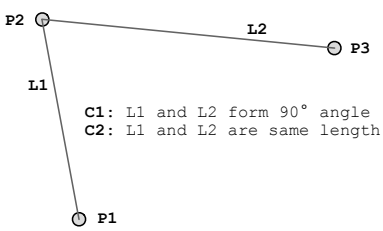
Each constraint type calculates its error differently, so it is not appropriate to directly compare error values from two kinds of constraints. For example, the "Same Length" constraint calculates the mean length of all its segments, and reports error as the sum of absolute deviation from that mean. A "Right Angle" constraint reports error as the absolute difference between expected and actual angles. While these numbers are clearly not directly comparable (radians vs linear distance), they both have the property of becoming very small when the constraint is reasonably satisfied.

If the total error from all constraints is greater than some threshold, the solver will proceed, beginning with Figure 4.6c. Each constraint calculates *change vectors* for each related point. A change vector describes both a direction and the desired distance to move in that direction.

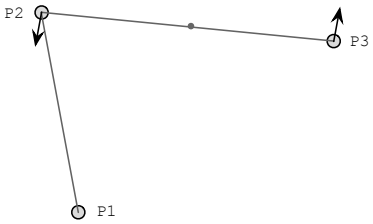
Each constraint computes change vectors differently. For example, the Right Angle constraint is composed of two *low-level constraints* that work together to achieve the desired effect. For Right Angles, they are Orientation constraints that rotate a line (e.g. L1) about its midpoint. The high-level constraint coordinates the low-level constraints on each iteration



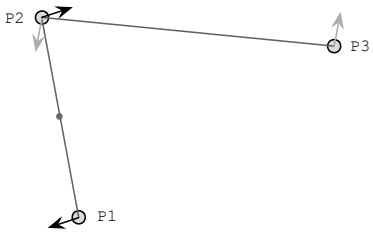
(a) The user draws two lines that meet at a common point. The lines should be the same length and form a 90 degree angle.



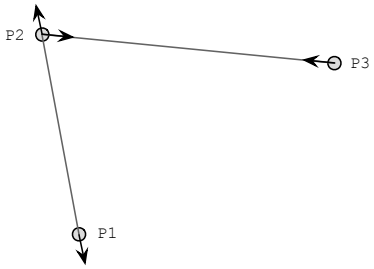
(b) Data is stored as three points (P1, P2, P3), two segments (L1, L2), and two constraints (right angle, same length).



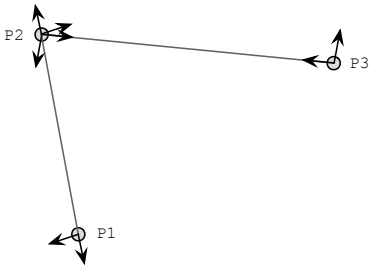
(c) Constraints form a *change vector* for each point. For right angles, they rotate about line midpoints (P2 and P3 here).



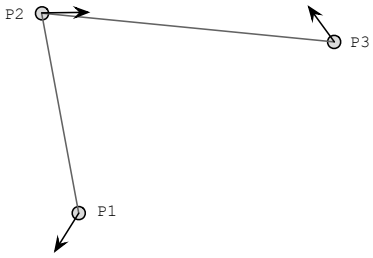
(d) Rotating the other line in the right angle constraint. Note that a second change vector is calculated for P2, as it is in both lines.



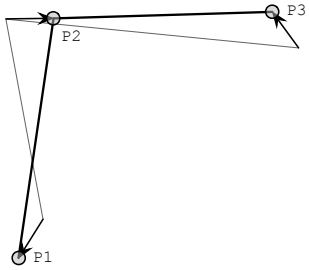
(e) Change vectors for points in the same length constraint. Again, P2 has two change vectors as it is in both lines.



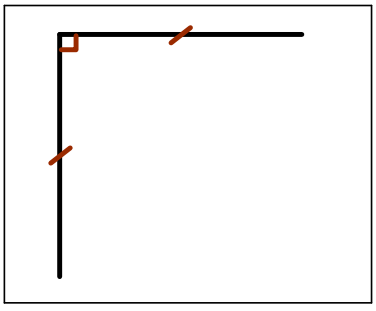
(f) Finally, add all change vectors to form each point's *total change vector*.



(g) Total change vectors for all points.



(h) Translate each point along its total change vector.



(i) Repeat *c* to *h* until the constraints are satisfied within tolerance. This is the final result.

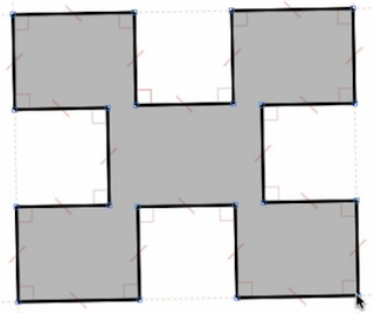
Figure 4.6: SIMI's constraint solving process. The first and last panels show the initial and final state as the user sees it. The panes in between illustrate a single step in the solving process. The solver will iterate this process many times to find a satisfactory solution.

by supplying a rotation parameter based on their current and desired angles.

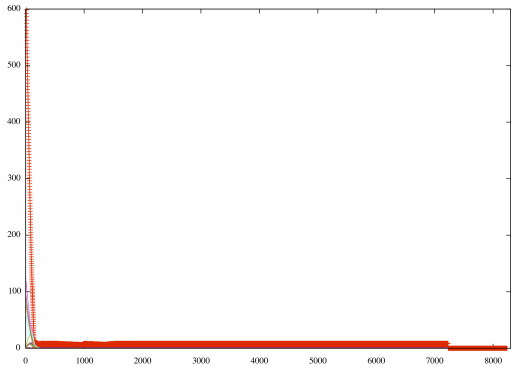
In this case, the low-level constraints operate on L1 (points P1 and P2) and L2 (P2 and P3). Because P2 is involved in both L1 and L2, it will be rotated *twice*, as shown in panel *d*. Named points accumulate related change vectors. The accumulation process continues until panel *f*, when all constraints have computed change vectors. P2 has a total of four—two from the Right Angle constraint, and two from the Same Length constraint.

The next step is to add each point's change vectors into a *total change vector*, which describes the direction it could move (panel *g*).

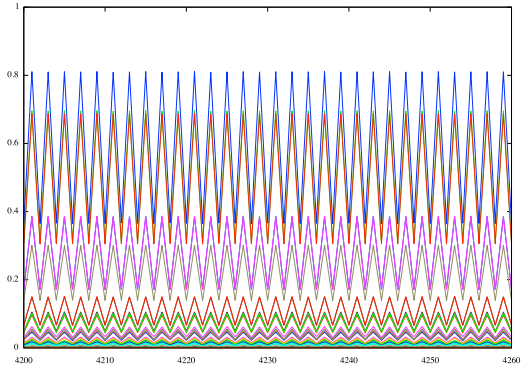
The last step is to translate each point along its total change vector (panel *h*). It is likely (and common) that the iterative process will get 'stuck' in a loop where points oscillate between two or more states. To avoid this, SIMI moves each point a random distance by multiplying its total change vector by random number between zero and one.



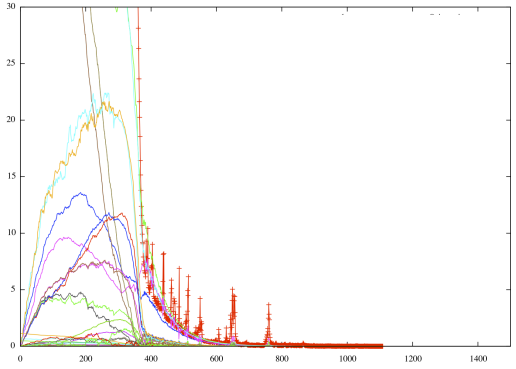
(a) initial state with 20 vertices, 20 line segments, and 45 low-level constraints. The user will move a corner, which violates many constraints. The following graphs illustrate error over thousands of constraint solving iterations.



(b) Total error graph with weak randomness. It quickly comes close to a solution after 200 iterations, but does not fall below tolerance until after 8000 iterations.



(c) Zoomed in portion of weak randomness Figure b. States are 'stuck' (iterations 4200 to 4260) oscillating between two states.



(d) Total error graph with full randomness converges below acceptable threshold after only 1100 iterations.

Figure 4.7: SIMI's constraint solver with minimal randomness (panels *b* and *c*) compared with full randomness (panel *d*). In each graph, the red line at top is the total error. All other plots indicate error of individual low-level constraints.

Figure 4.7 illustrates the need for randomness in SIMI's constraint engine. The user has drawn a cutout that contains 20 vertices, 20 line segments, and several high-level constraints comprising 45 low-level constraints. When the user moves a corner, the constraint solver is invoked to satisfy the system. The upper right graph shows the solver approaching a solution fairly quickly, but getting 'stuck' for several thousand iterations, taking about five seconds to settle down. During this time, the on-screen representation jitters. In this case, *weak randomness* is used, and it is applied only to the total change vectors. The effect of the randomness increases over time. However, this approach was not satisfactory because it took too long and caused visual jitter.

This problem was addressed by modifying the constraint solver to apply randomness to each individual change vector. For vertices with more than one change vector, this means the total change vector's *direction* is subject to randomness, as well as its magnitude. The overall results are satisfactory, as the system of constraints is satisfied in about 1/8 of the number of iterations compared with the weak random case.

Chapter 5

Sketch It, Make It: Details

The previous chapter gave an overview of SIMI's architecture, including an introduction of SIMI's recognition process. (Section 4.5). This chapter gives details on how each recognizer works.

First, SIMI's corner finding and segmentation strategy is described. This process is necessary to most recognition, and is what produces geometric output like lines and arcs. Next, the three types of recognizers are described: including Dynamic, Pen Up, and Deferred recognizers. All sketch based interaction techniques are detailed in these sections.

5.1 Ink Parsing

Ink parsing is the process of identifying useful characteristics of freehand digital input, hereafter referred to as 'raw ink', 'rough ink', or simply 'ink'. Characteristics include the locations of corners, curvature at specific points, and the likely identities of segments like lines or curves. Raw ink points are recorded as (x, y, t) coordinates that specify where a point is and it was created.

In the following sections, there are two different ways to measure distance: Euclidean and Curvilinear (see Figure 5.1). Euclidean distance is the measurement most people are familiar with: this is how far apart two points are on the 2D plane. Curvilinear distance follows the ink stroke path. In the figure, points A and B are close together in the Euclidean sense, but are farther apart in the Curvilinear sense. The Euclidean and Curvilinear midpoints are also depicted in Figure 5.1.

SIMI's ink parsing strategy is simpler than many other approaches found in literature on sketch-based interfaces and modeling (SBIM). Others, like the strategies taken by Sezgin [68] or Wolin [78], combine both *time* and *curvature* information when corner finding. SIMI's approach for corner-finding relies only on curvature, but still achieves good results.

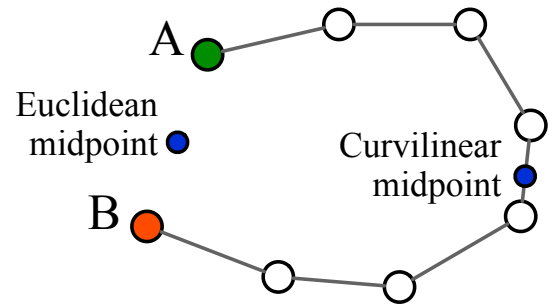


Figure 5.1: Two ways to measure distance: Euclidean vs. Curvilinear. The Euclidean distance from A to B is direct (*length* = 18). Curvilinear distance from A to B follows the path indicated (*length* = 86). Each measurement approach has a related midpoint, indicated as smaller dots.

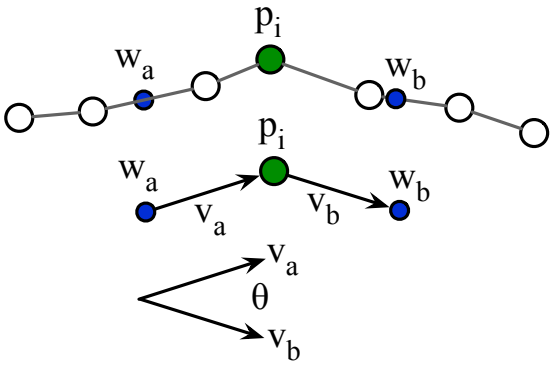


Figure 5.2: Illustration of how SIMI computes curvature about point p_i. Interpolated window boundary points w_a and w_b are equidistant (curvilinear-wise) from p_i and are shown as dark dots. These window points let us create vectors v_a and v_b. The curvature at p_i is the signed angle between these vectors.

When the user completes a stroke, the ink parser is invoked. First it assigns a curvature value to each point. Next, a corner finder uses this data to identify which (if any) points along the stroke are corners. Last, the system analyzes the regions between corners to determine the most likely segment type. The output of this process is the set of segments formed in the last step. I will detail each of these steps now.

5.1.1 Curvature

Figure 5.2 illustrates how curvature is calculated. A raw ink stroke is composed of a series of unevenly distributed points. Sometimes, points may be very close together (as when the user draws slowly). To determine the curvature at an individual point, the algorithm uses a surrounding region called a *window*, rather than only the immediate neighbors. Without this window, the curvature would be unreliable when points are very close together.

The window's size w is measured in pixels, and is determined by the current zoom factor. When the zoom factor is 1 (meaning there is a 1:1 ratio between model and screen coordinates), the window size is 20px. To calculate the window boundaries at point p_i, the corner finder begins at p_i and traverses the stroke backwards and forwards by half the window size ($w/2$). It computes interpolated points w_a and w_b that are exactly $w/2$ units

along the stroke to p_i. It then forms two vectors: v_a from w_a to p_i, and v_b from p_i to w_b. Note that all distances in this part are measured with Curvilinear reckoning.

The signed curvature θ for p_i is computed directly from these two vectors. The magnitude is determined by their dot product; the sign is determined by the cross product.

$$\theta_{unsigned} = \arccos \frac{v_a \cdot v_b}{|v_a||v_b|} \tag{5.1}$$

$$\theta = \begin{cases} \theta_{unsigned} & \text{if } v_a \times v_b \geq 0, \\ -\theta_{unsigned} & \text{otherwise} \end{cases} \tag{5.2}$$

It is tempting to use arctan to calculate curvature because it is a simple calculation. However, this leads to discontinuities when the vertical change is zero. The approach described above is valid for any orientation.

5.1.2 Isolate Corners

Now that each point's curvature has been calculated, we can identify corners. This is a two-step process illustrated in Figure 5.3. First, clusters of high curvature are identified. To be a member of such a cluster, the absolute value of a point's curvature must be greater than some threshold. In the current version of SIMI this value is 45 degrees.

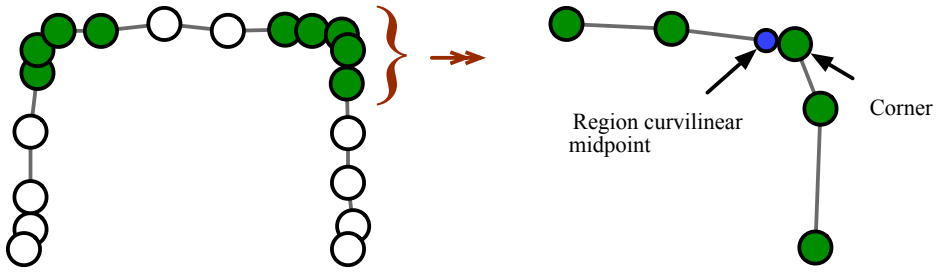


Figure 5.3: Corner finding begins by clustering nearby points that have high curvature. At left, the stroke has two such clusters indicated with dark circles. At right, one cluster is shown up close. The cluster's curvilinear midpoint is found, and the point nearest that midpoint becomes the corner.

Once clusters have been computed, a corner is found for each. A cluster's corner is simply the point closest to the curvilinear middle. In other words, if the distance along stroke from the beginning to the end of the cluster is 9, the corner is the point in the cluster that is nearest to the interpolated point 4.5 units from the cluster beginning.

In addition to the corners discover in this process, the stroke's first and last points are also included as 'corners'. This is for the convenience of the next step where segments are identified.

5.1.3 Identify Segment Types

The last step in ink parsing is to identify segment types. Table 4.1 in the previous chapter describes the possible segment types. For each segment type there is a corresponding segment finder. The segment finders for 'open' types (Line, Arc, Spline) operate on regions between corners. The remaining segment finders are identified by examining the raw ink directly, and do not use corner data.

Like semantic sketch recognizers, it is possible for multiple segment finders to positively identify ink—e.g. a segment might be an arc, or it might be a line. To mitigate this, segment finders operate on a priority system. The priority is: Dot, Circle, Ellipse, Blob, Line, Arc, and Spline. In other words, if the Dot finder identifies a dot, there is no possibility of the associated ink being identified as a Circle.

Dot Finder

The dot finder examines the entire ink stroke. If the entire stroke was made in less than some threshold value (currently 180 milliseconds), it is always considered a dot. Otherwise, it continues by computing the convex hull of all stroke points. Two properties of the hull are used next: the area and the aspect ratio. If the ratio defined by $ratio = area/aspect$ is less than 120, it is a dot. If not, there is one final check to make. The stroke's point density is computed. This is the number of points in the original ink stroke, divided by the hull's area. If $ratio/(0.3 + density)$ is less than 120, it is a dot.

Circle and Ellipse Finder

Circles, Ellipses, and (in the next part) Blobs are the three *closed* segment types. A segment is closed if the beginning and end points are close, relative to the overall length of the stroke. More formally given start and end points p_{start} and p_{end}:

$$\begin{aligned} closeness &= \frac{EuclidianDistance(p_{start}, p_{end})}{CurvilinearDistance(p_{start}, p_{end})} \\ closed &= \begin{cases} true & \text{if } closeness \leq .1, \\ false & \text{otherwise} \end{cases} \end{aligned} \tag{5.3}$$

Circles and Ellipses are identified with the same finder. If the input stroke is closed, the input is fit to an ellipse. To avoid placing restrictions on how users draw, they may draw ellipses at arbitrary angles. SIMI implements a least squares approach described by Fitzgibbon *et. al* [15]. It is an efficient algorithm whose complexity grows linearly with the size of the input. The output of the ellipse fitting algorithm is a rotated ellipse, defined by a centroid, a rotation, and major and minor axis magnitudes.

An error value is calculated to determine how closely the raw input matches the derived ellipse. This is done in a modified *least squares* fashion that requires the calculating the minimum distance between a point and the ellipse. Unfortunately this is an involved process (for example, see [13]). SIMI approximates the shortest distance between a point p and an ellipse by discretizing the ellipse boundary into a list of points d, and computes the minimum distance between p and d.

The error value measuring the closeness between raw input points $p_i, i \in [0..n)$ and the discretized elliptical surface D is given with the equation:

$$Elliptical\ Error = \frac{\sqrt{\sum min^2(p_i, D)}}{n-2} \tag{5.4}$$

In order for the input to be considered a Circle or Ellipse, the total error must be less than 1.0. This value was determined experimentally, given a discretization of 60 points. To distinguish between a Circle and an Ellipse, the fit ellipse's eccentricity used. Eccentricity describes how flattened the ellipse is as defined by its major and minor radii:

$$Eccentricity = \sqrt{\frac{major^2 - minor^2}{major^2}} \tag{5.5}$$

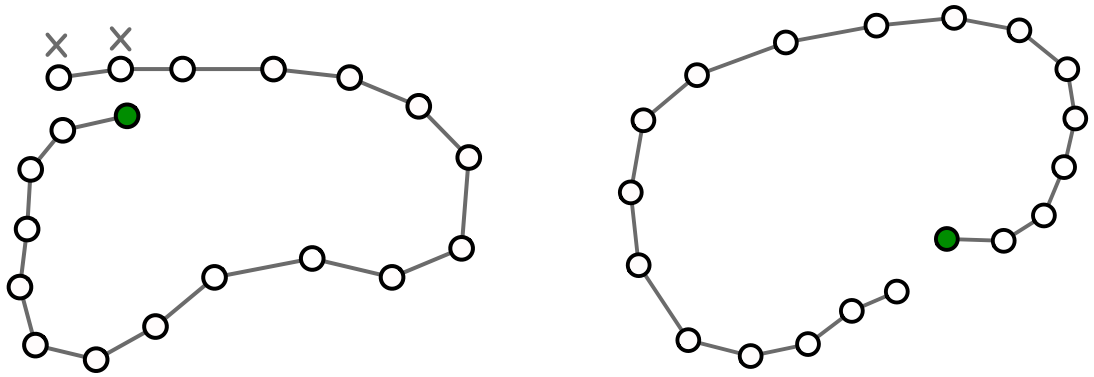
If the eccentricity is less than 0.7, the input is a Circle; otherwise it is an Ellipse.

Blob Finder

A *Blob* is a spline than wraps around on itself to form a closed loop. Recall that SIMI identifies a closed shape when a stroke's start and end points are close relative to stroke length (as given by Equation 5.3). To transform rough input into a smooth shape, additional processing is necessary because the start and end of the stroke are discontinuous.

There are two possible situations: there is a *gap* between the stroke's start and end, or there is an *overlap*. These cases are illustrated in Figure 5.4. The Blob Finder identifies a gap when the first point p_0 is closer to the last point p_{n-1} than it is to the last point's neighbors p_{n-i}, where i is in the range [2..10]. An overlap is when p_0 is closer to one of the p_{n-i} points.

In case of a gap, the next action is simple: the first and last points are connected. When



(a) A Blob with an initial overlap. To resolve, remove points at the end of the stroke marked with X's.

(b) A Blob with an initial gap. No further action is needed.

Figure 5.4: Two Blob shapes just before adjusting the start/end to match. The first is an overlap, the second is a gap. In case of an overlap, remove points from the end of the sequence until it becomes a gap. These define the initial spline control points.

an overlap is detected, the algorithm removes points from the end of the stroke until there is no overlap (e.g. there is a gap). Then the Blob's start and end are connected as before.

The control points for Blob and Spline types are computed and stored in the same manner. This representation is discussed in the Spline section.

Line Finder

Lines are typically the most common segment type. Like arcs and splines, lines are an open segment type. A single ink stroke may contain any number of open segment types. All open segment type finders operate on regions between (and including) corners—they do *not* operate on the entire stroke, unless the stroke happens to contain no corners.

The line finder fits a region of points to an idealized line, and measure its error. If the error is below some threshold, it reports a positive result. The idealized line begins and ends at the corners on either side of the region. A raw point's individual error is calculated as the shortest (orthogonal) distance between the point and the idealized line. The total error for the region is:

$$Line\ Error = \frac{\sqrt{\sum OrthoDistance^2(p_i, line)}}{n-2} \tag{5.6}$$

If the error is below the threshold (currently 1.5), the region is identified as a line segment.

Arc Finder

Arcs in SIMI are portions of ellipses. If a region is not a line, the Arc Finder attempts to identify an elliptical arc. It does this by using the same math as Ellipse shapes, including the error metric in Equation 5.3. If the total error is less than 0.5, the region is identified as an elliptical arc.

Note that the arc is only a portion of the ellipse. The portion is recorded using the start and end angles, and (to determine which direction the arc traverses the ellipse) a median angle.

Spline Finder

Splines are the fall-back segment type: if nothing else fits, a region is classified as a spline. SIMI uses natural cubic splines to render these curves.

As mentioned earlier, Blobs are modeled in the same way as Splines. Both variations are composed of two primary points A and B (for splines, the start and end points; for blobs, the start point and initial centroid point). Using these two points, a third point C is found by rotating B about A by 90 degrees. These three points form the basis for a barycentric coordinate system that identify locations of the Spline/Blob's control points. This way, when A or B move, the control point locations are easily recalculated.

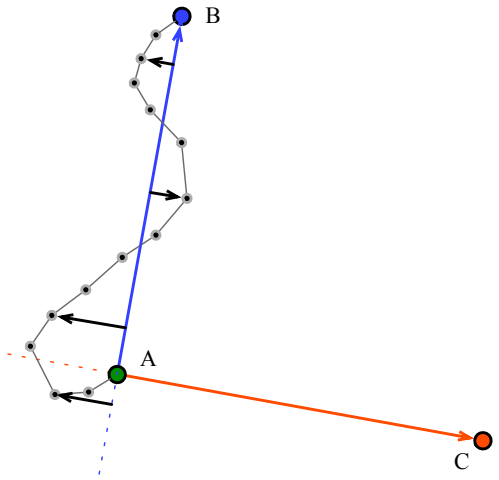
A control point is defined with a pair of numbers: one in the $A \rightarrow B$ direction, another in the $A \rightarrow C$ direction. A value of one indicates full movement from the start to end point.

5.2 Dynamic Recognizers

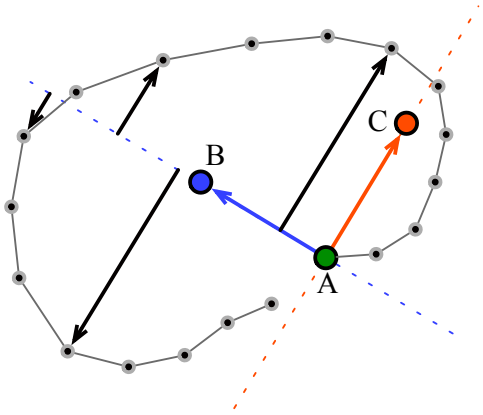
As mentioned in 4.5.1, Dynamic recognizers attempt to identify gestures as the pen is down. In order to maintain a responsive user interface, these recognizers must execute very quickly because they are invoked at high frequency. When any dynamic recognizer has a positive result, the others are suppressed until the next stroke. They each give distinct graphic feedback to let the user know that the recognizer has triggered.

5.2.1 Erase

The *Erase* gesture allows the user to delete segments. It lets users recover from errors or lets them change their minds. Unlike Undo (discussed below), Erase gives access to any line work in the model. Erase can also be used as part of a deliberate process, for example to cut away segments to create notches (as in [79]).

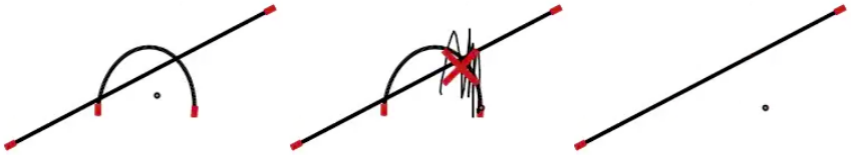


(a) Spline primary points defined by stroke start (A) and end (B).

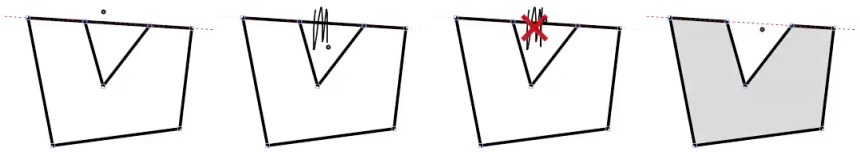


(b) Blob primary points defined by stroke start (A) and initial centroid (B).

Figure 5.5: Spline and Blob control points are defined in terms of two primary points, A and B. A third point C is simply B rotated 90 degrees about A. These points form the basis of a barycentric coordinate system. Control points are computed as a vector offset from A in this coordinate space.



(a) The erase gesture picks the most specific segments. This makes it easy to target short segments that are near or overlapping longer ones.



(b) Erasing can also be used as part of a deliberate process to subtract linework that exposes new shapes.

Figure 5.6: The erase gesture is made by vigorously scribbling. When the dynamic recognizer identifies an erase gesture, it gives visual feedback (the red 'X').

SIMI users depend on being able to erase quickly and easily. While it may seem that an efficient and easy to use gesture recognizer would be easy to write, this is not the case. During development, the Erase gesture went through a number of design iterations. Initially, it was implemented as a Deferred recognizer (executing after the pen was lifted). Users were only able to successfully execute the gesture about half the time. When it failed, the scribble was interpreted as line work, requiring users to erase or undo the unwanted line work. This was a common and frustrating event. The recognition algorithm was only part of the problem. Proper visual feedback was also a necessary part of the solution.

Erase was reimplemented as a dynamic recognizer so it would operate as the pen was down. It identifies erase gestures in mid-stroke, showing a colored 'X', indicating the user's erasure will succeed. This gives users confidence the system understood, and reduces the number of recognition errors substantially.

The dynamic erase gesture is implemented as follows. It involves several parameters that may be tuned for different circumstances. These parameters are summarized in Table 5.1 after the description.

First we assign each point P_i with a time stamp T_i, a path distance D_i, and a heading vector H_i. Path distance is measured as the curvilinear length from the initial point: $D_0 = 0$, and the rest are $D_i = D_{i-1} + distance(P_{i-1}, P_i)$.

The heading H_i is a normalized vector from P_{i-k} to P_{i+k}, using a window size k. The first k points use H_k for their heading.

Next we add points to a list of sample points S. If the path distance between D_i and the most recently added sample point is greater than min_{sd}, P_i is added to S. When a new sample point is added, a sub-list R is assembled containing recent sample points that occurred within t milliseconds. If the angle between the new sample point's heading and any point heading in R is greater than some angle threshold value min_θ (we use π radians), it increments a 'corner' count value for the current pen stroke.

When more than min_c corners are found in a stroke, the stroke is a strong candidate to be interpreted as an erase. When the corner count has reached min_c, the system checks to see if the input resembles a circle. This final check is necessary to avoid confusing a latch gesture as an erase gesture.

If the circle check fails, the stroke is interpreted as an erasure. The system provides visual feedback to alert the user that the gesture has been recognized and halts recognition until the pen is lifted.

Because the sample list depends on a relatively short duration, the user must scribble vigorously to activate the erase gesture. Erasing is a destructive process. Even though the Undo command lets the user quickly recover from an unwanted erasure, they are

nonetheless disconcerting. Scribbling vigorously helps to avoid false positives.

When the user lifts the pen after successfully issuing an erasure, SIMI determines which (if any) segments should be removed from the model. The simplest approach would be to identify any segment that intersects the erase gesture's convex hull. However, this leads to poor results because users often want to erase items that are near other items that should be kept. If this strategy were applied, both the line and the arc in Figure 5.6a would be erased.

When activating an erasure, the first step is to collect all the segments that are under the erase gesture's convex hull. Next, SIMI calculates the percentage of each segment's length that is under the hull.

It is common that users would like to erase several items with the same gesture. To support this, SIMI chooses the segment that has the highest percentage and any segment whose coverage is at least $C\%$ of that value. In Figure 5.6a about 10% of the line is under the hull, while about 50% of the arc is. In the current version of SIMI, $C = 70$, so any segment that is at least 70% of 50 (in other words, 35%) would be erased. Since the line is only 10% under the hull, it remains.

This set of segments are then removed from the model. Further, any constraints that are no longer relevant are also removed.

5.2.2 Undo and Redo

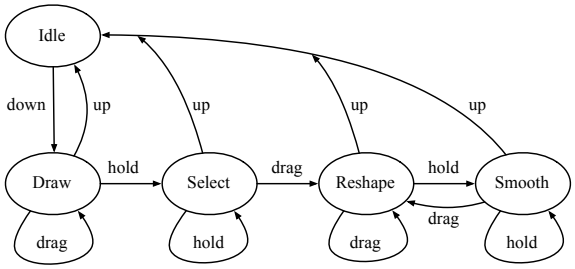
There is very little *recognition* involved with SIMI's *Undo*/*Redo* recognizer. The user presses the button with their non-dominant hand and then drags the stylus left (to undo) or right (to redo). It is the only technique that can not be performed entirely with the pen. While it might not require recognition like the others, it does have to fit into the same framework.

The undo/redo events are triggered with each 40 pixel change in the x dimension. Each event shows a preview of what the model looked like at some point in time. Releasing the external button commits the change by replacing the current state with the previewed state. The user may lift the pen, reposition their hand, and continue gesturing. This allows the user to smoothly 'scrub' through their model's design history. Each 'page' in SIMI's user interface has a separate design history.

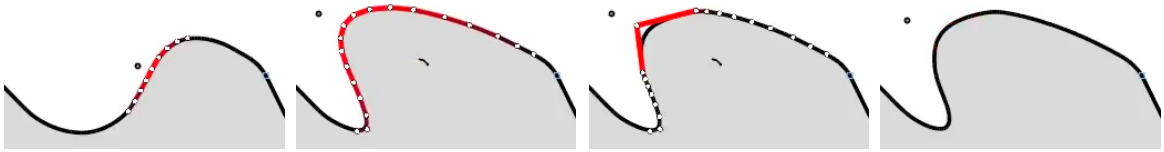
Each state in the design history stores a complete snapshot of the model (containing points, segments, constraints, and cutouts) as well as a cached graphic. This is a fast memory-intensive strategy that requires only minimal computation. Snapshots are made when the user adds, modifies, or removes geometry or constraints.

Param.	Value	Remark
k	1	Number of points in heading vector window. For higher resolution input surfaces k should be larger because the input points will be much closer together.
min_{sd}	20	Minimum curvilinear distance between sample points. Smaller values allow users to make smaller erase gestures, but might also introduce false positives.
t	100ms	Limits the sample history so only the most recent samples are used. Samples older than this may be discarded.
min_{θ}	$\pi/2$ rad.	Minimum corner angle between a recent sample heading and the current sample heading.
min_c	5	Minimum number of corners required for a stroke to be an erasure.
C	70	A percentage value in the range [0..100] describing how strictly to choose erasure targets. A low value indicates few targets. Using zero means only the most specific segment is erased; 100 means all segments that intersect the erase gesture would be erased.

Table 5.1: Parameters involved in detecting erase gestures.



(a) Finite state machine that models flow selection. Most of the time, users simply press the pen down, draw some ink, and release. But if they hold the pen down, the flow selection states are reached. The user holds down the pen to select a region, moves the pen to move the selection, and holds it still once again to smooth the selection. Lifing the pen ends the process.



(b) Example showing the user deforming a curved segment. The user holds the pen to heat a region, and moves the stylus to move that region. Next the user dwells to smooth region. The final state is at right.

Figure 5.7: Interaction and implementation of Flow Selection.

5.2.3 Flow Selection

Flow selection is a time-based selection and operation technique that lets users deform *regions* of curved segments [33]. It is useful for fixing errors, or simply playing with curves to achieve an esthetically pleasing effect.

Flow selection is triggered by holding the pen still for a brief period (e.g. 800 milliseconds). Once triggered, it begins selecting points on segment nearest the stylus (see Figure 5.7b). The selection slowly grows along the curve, as its points begins to 'heat up' near the stylus. The longer the pen is held down, the more strongly points are selected (e.g. they become 'hotter'), and the selection size gets bigger. Next, the user can move the stylus without lifting. This moves selected points—the more strongly selected, the more they move. The process is illustrated by the finite state machine in Figure 5.7a.

Flow selection is graphically presented by highlighting the affected region. Points that have positive selection strength are drawn as small white dots, and the line work connecting them is drawn in a shade of red. The stronger the surrounding points, the brighter red the curve is drawn.

(a) Raw ink with hooks. (b) Processed ink after hooks removed.

Figure 5.8: Removing 'hooks': accidental short lines at the start and end of a stroke.

5.3 Pen Up Recognizers

If no dynamic recognizer claimed a user's stroke, the *Pen Up* recognizers are invoked. There are two pre-processing steps before this happens. The first is Ink Parsing—corner finding and segment identification. This was discussed at length earlier in the chapter. The Pen Up recognizers have access to both the structured data including corners and segment types, as well as the original raw data. The second pre-processing step is called *hook removal*.

5.3.1 Removing Hooks

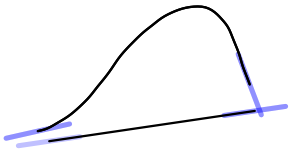
A *hook* is a short region of ink made accidentally as the user presses down or lifts the stylus from the digitizing tablet. Many tablet surfaces are smooth, so there is little frictional resistance to prevent this from happening. Unless hooks are removed, they frustrate recognition efforts. Hook removal is shown in Figure 5.8.

Hook removal occurs after ink parsing but before recognizers are invoked. The hook remover receives a set of newly made segments. A hook is a segment that has two properties: (a) it was made from ink appearing at the beginning or end of the user's stroke, and (b) its curvilinear length is less than 10% of the longest segment from the same ink stroke. Hooks are simply removed from the model and not passed on for recognition.

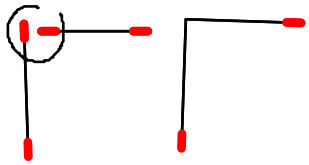
5.3.2 Latching

Users often want lines to meet at a common point. In the formative work practices study, we observed Illustrator users struggling to make lines co-terminate. Sometimes the designer would simply extend lines past each other to ensure that the laser will correctly cut the corner.

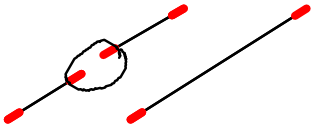
Latching is the process of adjusting adjacent segments to meet at a common point [28]. All line work in SIMI is meant to compose cutouts, which are closed sequences of latched



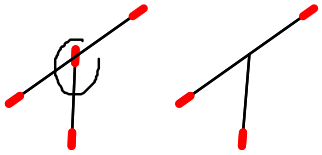
(a) Automatic: latch where endcaps intersect.



(b) Endpoint latching.



(c) Continuation latching.



(d) T-Junction latching.

Figure 5.9: Automatic and manual latching merges segments at a common point.

segments. The designer must therefore be able to find and fix non-latched segments to form cutouts. SIMI draws a red marker at 'lonely endpoints' (endpoints associated with only one segment) to make it obvious when there is a latching opportunity.

SIMI will automatically latch segments (shown in Figure 5.9) under fairly conservative circumstances. Users may also manually latch endpoints in three orientations (Figures 5.9b–5.9d). Both automatic and manual latching is performed as a result of a Pen Up recognizer.

Automatic Latching

The automatic latching process examines line work for cases where the user likely meant their segments to connect, and adjusts one or more segments to meet. However, this can pose problems if it is too zealous because users must erase or undo to recover, which interrupts the flow of work. Therefore the automatic latcher is intentionally conservative to avoid frustrating users.

The auto-latcher is *not* activated with the Pen Up recognizers—it is actually a Deferred recognizer. It is discussed here because it is closely related to the manual latching techniques, which are Pen Up recognizers.

The auto-latcher iterates through all newly made segments, and compiles a list of those with lonely endpoints. For each lonely endpoint, an *endcap* formed. This is a short line segment centered at the lonely point. The endcap length is X% of its associated segment (SIMI sets this parameter at 10%). The endcap orientation is tangent to the segment at the lonely point. They are represented as the light blue shaded regions in Figure 5.9a.

The endcap length and orientation are parameterized in this way to avoid latching seg-

ments that do not visually appear to meet. This approach was inspired by the gestalt principle of common fate.

Next, each endcap is intersected with nearby endcaps from either new or existing lonely point endcaps (with their own length and orientations). When two endcaps intersect, the auto-latcher reports a positive result, and the two related segments will merge. The merging process is discussed below, after the manual latchers.

Manual Latching

There are three ways users manually latch segments together, illustrated in Figure 5.9. They are activated by the same recognizer, but the action taken is distinguished by the particular configuration of segments below the gesture.

The three kinds of manual latching are: *endpoint*, *continuation*, and *T-Junction*, but the gesture (a small lasso, discussed shortly) is the same for all of them. The meaning of the latch gesture depends on what the user targets: in other words, what elements are beneath the user's input? If the user targets two endpoints, it is either an endpoint latch (when the two segments are not close to the same orientation) or a continuation latch (when they are about the same orientation). If the user targets an endpoint and the mid-section of another segment, it is a T-Junction.

The encircle gesture is recognized as follows. The gesture curvilinear length must be less than a threshold (currently 200 px). This helps distinguish line work (which tends to be large) from latch gestures (which are small). Second, the input must be *closed* using logic similar to the closed segment type finders (e.g. Blob Finder). In this context the input is closed if any of the last 10% of points were within 7 pixels of the initial point.

Merging Segments

If either the automatic or manual latching algorithm found a positive result, two segments must be merged. Table 5.2 summarizes the inputs, where the merge occurs, and the results. In each case, two segments are merged, but the output depends on the latch type. Automatic and endpoint latching result in two segments that have been joined at segment ends. Continuation latching results in a single segment—the two original segments are replaced by one longer one. With T-Junction latching, one segment is split in the interior region into two segments, and the other segment is merged with them where the split occurred.

Points and segments are created and destroyed in this process. This must be reflected in the model. Any constraints that referenced a deleted segment must be re-evaluated to see

Latch Type	Input	Merge Point	Output
Automatic	Two segments with endpoints	Endcap intersection	Two segments
Endpoint	Two segments with endpoints	Endpoint centroid	Two segments
Continuation	Two segments with endpoints	None	One segment
T-Junction	Segment + endpoint, Segment + inner point	Inner point	Three segments

Table 5.2: Four variations of latching with different input, merge point, and output.

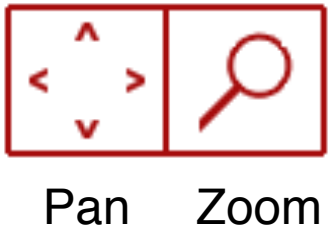


Figure 5.10: The pan/zoom widget is invoked by double-tapping the pen. Dragging in either square changes the viewport by panning (left square) or zooming (right square).

if (and which) new segments apply. If constraints depend on segments that are removed, the constraint is deleted.

5.3.3 Pan and Zoom

SIMI lets users control the view port. Tapping the pen twice displays a pan/zoom widget shown in Figure 5.10. To pan, drag starting in the left square in any direction. To zoom, start in the right square: up to zoom in, down to zoom out (the horizontal dimension is not used). The controls disappear after two seconds of non-use.

Many parameters used in other recognizers are sensitive to the zoom factor. When the user zooms in or out, distance factors must change accordingly because there is a disparity between physical and model coordinate distances. For example, if the zoom factor is $2x$, the latch gesture considers the input closed using $7/2 = 3.5$ model units rather than 7 as it would without zooming.

5.3.4 Select Points and Segments

Users can move points by selecting and dragging them. To select a point, users make a quickly made swirling gesture that is recognized as a *Dot* segment type. If the dot is made within 9 pixels of a segment endpoint, the closest endpoint is chosen to be selected. Once a point is selected, hovering the pen nearby shows a hand cursor, letting the user know that dragging the stylus will move the selected point.

Selected points can be de-selected by drawing a latch gesture around it (discussed above). The point is de-selected if no latch recognizer would have an effect.

Segments may be selected as part of the process to specify Same Length constraints. To select a segment, the user over-traces a portion. It is not necessary to over-trace the entire segment. To recognize a segment selection gesture, the system compares the rough input with the segments nearby. To be a segment selection gesture, the average orthogonal distance to the segment must be less than 5 px, the maximum distance less than 15, and (for line segments) the orientation must be within 20 degrees.

A selected segment is graphically with a thick blue line weight. Additionally, the segment's length is displayed nearby. Users deselect segments by over-tracing again.

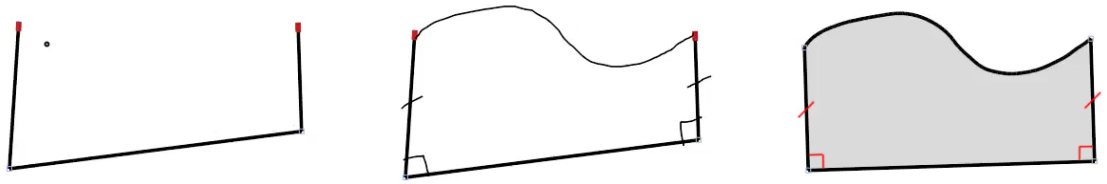
Users establish *specific length constraints* by selecting a line segment and then *typing* a value on the keyboard. This is the only interaction technique the violates the guidelines of not depending on the keyboard. It was necessary to implement to enable users to make items with specific dimensions, which is a common need. Ideally users would employ a pen-centric approach to set specific length constraints via handwriting recognition. Because that is an active and well-developed topic it was appropriate to focus effort elsewhere.

5.4 Deferred Recognizers

The deferred recognizers activate after one of two events has occurred: either the user has pressed the button with their non-drawing hand, or there has not been stylus activity for a brief time period. Deferred recognizers are invoked only on input that was not positively identified by either Dynamic or Pen Up recognizers.

Like Pen Up recognizers, Deferred recognizers could operate on either raw ink data or the set of segments found in Ink Parsing. However in practice, the three recognizers in this category only use segment data.

Unlike Pen Up recognizers, Deferred recognizers must be able to handle several ink strokes. The input might be anything: line work, a constraint, line work and constraints, two Same Length and two Right Angle constraints, and so on.



(a) Initial state.

(b) Five strokes must be recognized.

(c) Input identified as linework and constraints.

Figure 5.11: Delayed recognizers must be able to handle several ink strokes that could compose any number of elements. Here the user makes five strokes that must be recognized at the same time. This input is identified as four distinct items: a Spline, two Right Angles, and a Same Length constraint.

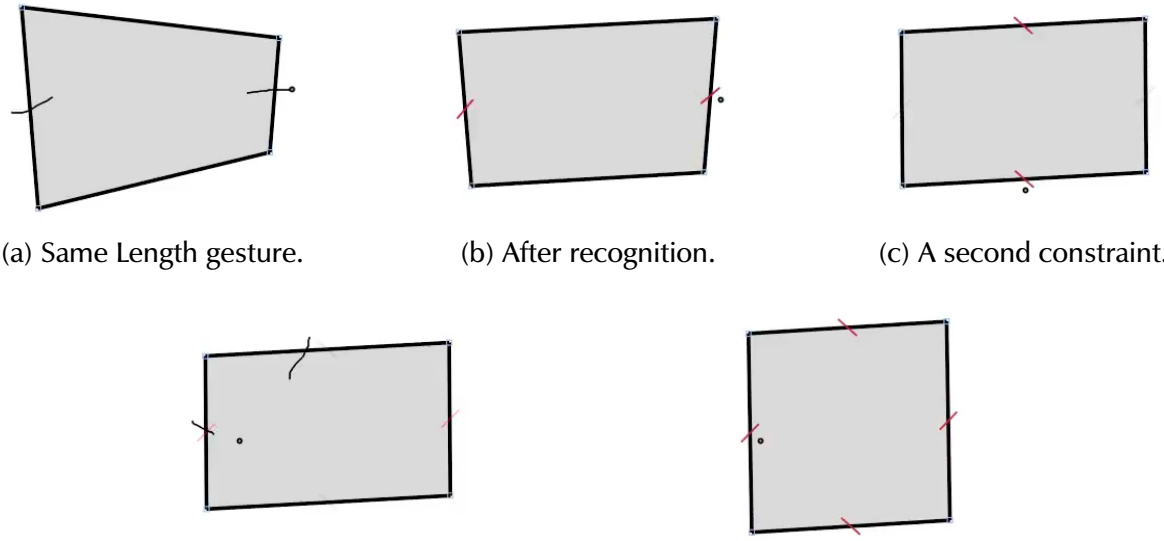
For example, consider the scenario pictured in Figure 5.11 where the user draws a spline, two right angles, and a Same Length gesture. The ink processor found seven segments: the spline at top, and six short line segments in the other strokes. Each recognizer receives these seven segments as input and must identify as many instances of its type as it can. The Right Angle recognizer, for example, looks for two short line segments of approximately the same length that appear to meet at roughly a 90 degree angle.

Given this input set of $n = 7$ strokes, the Right Angle recognizer has $n^2 = 49$ possible pairings to examine. Each pairing has four possible relative orientations. A recognizer that requires more segments has vastly more combinations. This process is also fraught with subjective noise: it looks for *short* line segments of *approximately* the same length that *appear* to meet at *roughly* 90 degrees. When finished, several recognizers may claim segments that belong to other positive interpretations.

In sum, there are three main challenges in this situation: (1) the search space is potentially very large, (2) subjective assessments like *approximately* must be made computable with numbers, and (3) conflicting results must be mediated.

Alvarado addressed these problem in her thesis work [1, Ch. 4]. I have re-implemented her approach to address the first two problems. It prunes the search space considerably, and fixes the meaning of vague measurements. The third problem—determining which interpretation is most likely—is handled differently.

Recognition mediation in SIMI uses two processes to determine which is correct. The first process ranks contending results by how relevant they are in context. The next process is invoked only if the first is inconclusive. Second is a list that ranks recognizers in order of most to least common.



(a) Same Length gesture. (b) After recognition. (c) A second constraint.

(d) Combining constraints. (e) Result is a rhombus.

Figure 5.12: Examples of making two separate Same Length constraints, then combining them into a single Same Length constraint.

5.4.1 Same Length

The *Same Length* gesture establishes a constraint that keeps two or more line segments the same length. The exact value for this length is not specified directly. Instead, the constraint computes the average length and will attempt to lengthen or shorten line segments to that length. Users may add segments to an existing Same Length constraint, or combine two such constraints.

Figure 5.12 shows how the Same Length gesture is made and how it can be used. In panel *a* the user draws the gesture on two sides of a quadrilateral to make those sides the same length. The Deferred recognizer identifies this, and the system creates and enforces the Same Length constraint (panel *b*. The user creates a second constraint by waiting until the first has been recognized, and drawing the gesture over the remaining lines of the quadrilateral (panel *c*). Next the user decides to combine these constraints by drawing a hash mark over one constrained line from each existing Same Length constraint (pane *d*). Panel *e* shows the result. This shape could have been made in a single recognition phase by hashing all four line segments. That would be equivalent to the state shown in the last panel.

A Same Length gesture is recognized when it finds two or more short input line segments ($in_0, in_1, ...$) that cross corresponding existing line segments ($S_0, S_1, ...$). All input lines in_i must be at least 40% the length of the longest one. In addition, each in_i must be within 30% of

Figure 5.13: The Same Angle constraint can be used to create symmetric shapes. Here the top angles are the same (about 135 degrees), and the lower corners are also constrained (about 45 degrees). Because the sides are constrained to be the same length, the top and bottom line segments are parallel.

S_i's length to S_i's midpoint. Users tend to naturally follow these rules without prior tutoring: the hash mark is a convention in pencil-and-paper sketching, and it is consistent with the Same Length constraint's visual appearance.

Graphically, any existing Same Length gesture is drawn as a set of short red lines passing through the midpoint of each S_i at a 45 degree angle (relative to S_i). Like other constraints, the constraint is drawn in a brighter red when the stylus hovers nearby. This serves two purposes. First, it reduces the visual clutter of the whole screen. Second, it lets the user see which linework is related to a single Same Length constraint.

5.4.2 Same Angle

Designers can constrain angles to be the same. This is particularly useful for creating symmetric parts. The gesture is the same as the Same Length gesture, but the user draws the hash marks over line segment intersections. A Same Angle constraint is indicated with a red arc symbol near the related corners. In Figure 5.13, the user has created a symmetric trapezoid. The pen hovers near the upper left corner, so the visual feedback for the upper Same Angle constraint is prominently displayed.

5.4.3 Right Angle

The Right Angle constraint allows designers to make 90 degree angles. Right angles are one of the most common geometric features of the artifacts surveyed in Section 3.3. Right angles are used to define not only the esthetic shape of a cutout, but also for making joints for combining parts.

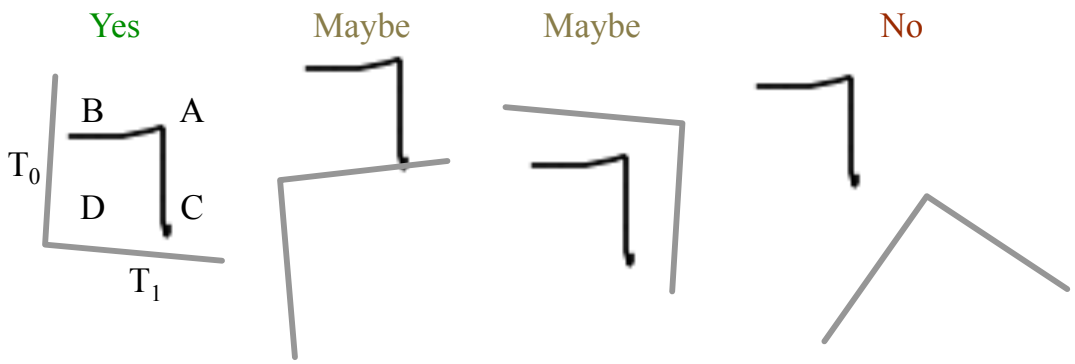


Figure 5.14: Context check for Right Angle recognizer. The user's input (black) is compared with the position and orientation of nearby line segments T_0 and T_1 (gray) to compute a liklihood that the gesture applies to that particular line pair. It outputs *Yes*, *Maybe*, or *No* depending on how well the context matches the input.

The gesture for making right angles looks like a half-square symbol. It is commonly used in pencil-and-paper sketching. The Right Angle recognizer looks for two short segments that meet at roughly a right angle.

The gesture can be made in one or two strokes. It does not require users to draw these strokes in any particular way—only that the result looks like a half-square. Once it identifies two line segments that meet the requirements, corners are labeled as shown in Figure 5.14 (left panel). This checks context around the gesture to determine which (if any) lines the right angle applies to.

The context check looks for nearby line segments that are in the correct location and orientation to supports recognition of a right angle constraint. The following description uses tunable parameters summarized in Table 5.3.

The context check finds nearby lines T_0 and T_1 that share a vertex and form an angle that is $90 \pm \theta_0$ degrees. This requirement might cause the system to miss the intended target, but it also reduces the search space. If the user tries to constrain a line pair that meets at an overly obtuse angle, they may move vertices until they are approximately 90 degrees before applying the Right Angle gesture.

The line pair's common vertex must be within d pixels of corner D (depicted in Figure 5.14). The lines must also have the appropriate position and orientation. Point B must be within d px of T_0, C within d px of T_1, and the angles formed by $(T_0, line(AB))$ and $(T_1, line(AC))$ must be $90 \pm \theta_1$ degrees.

The context checker reports one of three confidence levels for each nearby line pair: *Yes*, *Maybe*, or *No* (see Fig. 5.14). It reports *Yes* if all constraints hold, *Maybe* if all but one hold, and *No* otherwise. If there is a tie (multiple Yes results, or multiple Maybes when there is

Param	Threshold	Remark
θ_0	20	Maximum angle formed by target segments T_0 and T_1.
θ_1	20	Maximum angle formed by a target segments and part of the right angle gesture.
d	10	Maximum distance between feature points.

Table 5.3: Parameters used in Right Angle context checking.

not a Yes result) the one whose T_0–T_1 intersection is closest to point D is chosen.

Chapter 6

Summative Evaluation

I evaluated Sketch It, Make It in two ways. First, I tested SIMI with 60 undergraduate architecture students. The objective was to test if (and how well) SIMI's sketch-based interaction could be used to make precisely-defined designs for fabrication. Second, a task-tool analysis compares the strategy of an experienced SIMI user (me) for making an object with that of an experienced Illustrator user. This was done to compare how these starkly different tools require designers to work.

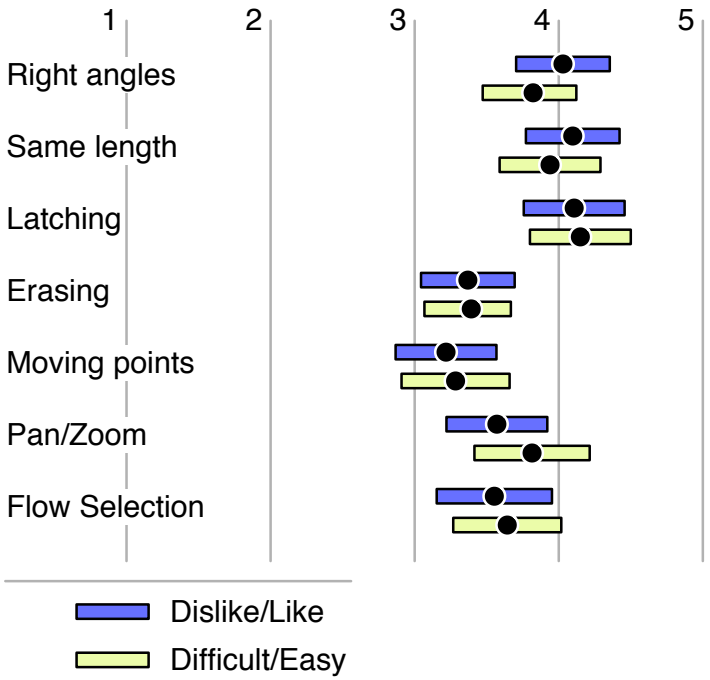
6.1 Workshop

I held a workshop with 60 undergraduate architecture students to gather qualitative feedback about how easy or difficult SIMI is to learn and use. The workshop was held in 30-minute sessions over two days in a room equipped with iMacs and Wacom Intuos tablets. Regrettably, these tablets do not display output, so users' eyes are not focused on the same physical location as the pen tip—leading to significant hand-eye coordination challenges. More costly display tablets like the Cintiq (Figure 1.1) avoid this problem, but were unavailable for the workshop.

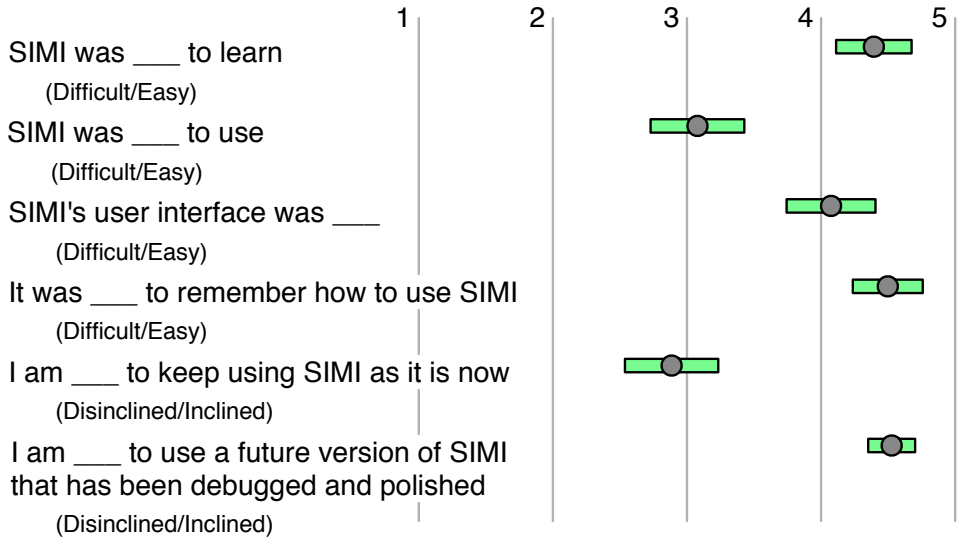
Initially, students complained that the tablet hardware was difficult to use, but most of the tablet-related trouble went away after about ten minutes. Then they quickly learned to make line work and constraints. At first they had trouble erasing and selecting points, but soon learned to make these gestures.

I expected students to have difficulty using SIMI because the hardware (tablets) and interaction paradigm (sketch-based modeling) were both new to them. However, by the second day, most questions and comments regarded missing features, not about how to use the system.

After the workshop, students were offered an extra credit assignment to complete a short



(a) Questions about features: attitude and ease of use.



(b) Questions on the system as a whole.

Figure 6.1: Survey results from the workshop with undergraduate architecture students. 40 students responded to the questionnaire.

survey. This generated 40 responses, summarized in Figure 6.1. The survey had three sets of questions, all on a 5-point scale. The first set asked how easy (or hard) each interaction method was to use. The second set of questions measured the student's attitude about the techniques. This line of questioning was borrowed from [4].

Only the Erase and point selection gestures seemed to give participants trouble. These are the only gestures that depend on timing. Erasing must be done with a quick, vigorous shake of the pen. Selecting points must be done quickly, or SIMI will interpret the input as the beginning of a flow selection.

The last set of questions polled students about their perception of the program as a whole: e.g. how easy it was to learn, to use, and remember. Although the students reported the system was easy to *learn*, their responses indicate they found it difficult to *use*. This might be explained by the limited time available (one hour), and the novelty of the hardware.

Finally, we asked (1) how much people would like to continue using the system as it is currently, and (2) how likely they would be to try it again when it was debugged and nicely tuned. The responses are in stark contrast: most would not continue using SIMI as it is today, owing to bugs and lack of features. Despite this, the response to the second question was very positive.

Enthusiasm about the interaction paradigm of sketching was evident in comments by respondents. For example:

- "This is the start of a great program, and once it is polished it will be extremely useful."
- "The program seems like it could be really cool to use in the future. I really enjoyed using a tablet and stylus. It made designing fun."

Not all commentary was positive. Aside from complaints about bugs, most negative comments concerned missing features (for example, a constraint to make lines parallel).

6.2 Task-Tool Analysis

A second method to evaluate our system is to compare the actions required to make an object with SIMI compared with those of a conventional tool such as Illustrator.

An expert Adobe Illustrator user was asked to describe the sequence of discrete actions necessary to model the table shown in Figure 6.2. This designer has used Illustrator to make dozens of laser-cut items.

Action Type	Description
Persistent mode change	Change the tool input state so subsequent input is interpreted in context of that tool (e.g. line drawing mode). User must enter another persistent mode to exit the first.
Specify value	Specify a dimension or location.
Specify target	Indicate (select) an element for a subsequent operation.
Transformation	Apply an operation that changes existing model elements beyond simply specifying numeric values. Transformations include moving or erase items.
Transient mode change	Temporarily change the tool mode so input is interpreted differently. This kind of mode change is part of a phrase, and will revert to another mode when the phrase is complete.

Table 6.1: Action types used in the task-tool protocol analysis.

For example, the first three actions were:

1. Press the M key to enter rectangle drawing mode.
2. Type rectangle dimensions.
3. Place the rectangle on the drawing canvas.

The first action is a persistent mode change, while the second two specify values. A similar transcript was recorded for SIMI. Five categories were used to code the verbal protocol. They are listed in Table 6.1.

Action type	Illustrator	SIMI
Persistent mode change	12	0
Specify value	17	7
Specify target	7	4
Transformation	6	27
Transient mode change	2	0
	44	**38**

Table 6.2: Action frequency in the design protocol of Adobe Illustrator and SIMI users.

The action frequency (listed in Table 6.2) shows how the two tools are used to create the same output. Roughly the same number of actions was taken (Illustrator: 44, SIMI: 38).

Figure 6.2: A laser-cut table for sale on Ponoko. Expert designers were asked how they would replicate this object using either Illustrator or SIMI.

To make an object using Illustrator, an expert issues a series of *Select, Specify* actions: either activate a persistent tool (e.g. line mode) or select a modeling element (e.g. a line on the screen), then specify a value or position by typing a number or moving the mouse.

In contrast, most discrete actions with SIMI involve transforming geometry that is already on the screen, for example, constraining two existing lines to meet at a common point or form a right angle. A single sketched gesture fluidly performs both *Select* and *Specify* operations that require two distinct actions in Illustrator. For example, right angle gesture necessarily indicates the line segments to be constrained.

The Task-Tool Analysis discussed here is limited. Because there is only one expert SIMI user (the author) it is not possible to gather more than one protocol for that tool. However, if several users were trained in SIMI, it would have been possible to collect more data. The classification scheme summarized in Table 6.1 not been vetted by researchers in other contexts. Further, the protocols were rated by only one person, leading to concerns with inter-rater reliability.

Chapter 7

Conclusion

Rapid fabrication—3D printing, laser cutting, and many other processes—can support designers in ways that were not possible even ten years ago. But to realize this promise, machine access is not enough. Users need effective and appropriate design tools.

Sketching is often cited as a common and necessary part of the design process in many domains. Beginning in the early 1960s with Sutherland's Sketchpad system [72], researchers have developed sketching systems in many areas, like mechanical engineering [47], web site design [46], and furniture production [55, 63]. During this time there has been a great deal of work on sketch recognition and on isolated sketch-based interaction techniques. But there has been little effort in exploring how all this fundamental work can be integrated and presented as a coherent and useful whole to address real-world design.

This thesis explored the role of sketch based interaction techniques as a basis for rapid fabrication design tools. I bridged the gap between an academic treatment of sketch-based design and a real-world useful and usable system. This work has included a literature review in design and computational support for sketching (Chapter 2 and the survey with my committee [34]). Chapter 3 explored the domain of design for laser cutting by studying both artist and the artifact. Last, Chapters 4 and 5 detailed my *Sketch It, Make It* system that provides a solid example of how a sketch based system can present a set of sketch recognizers and (most importantly) interaction techniques to enable real people to do real work in a way that was previously not actualized.

While I have made a prototype that many observers find compelling, there is still more work to do. It raises interesting ideas about what else is possible with this form of interaction, and questions remain unresolved.

In this chapter I discuss how my work with SIMI can serve as a starting point for further work. First I discuss the rationale for providing the particular feature set embodied in this software. Next I discuss the implications SIMI has on several areas of research. Last, I

describe the most obvious next steps that I would like to take.

7.1 Justification of Feature Choices

SIMI includes a set of interaction techniques that let users perform actions to create, edit, and build precision models for laser cutting. This particular collection chosen because it (a) provided a minimal set of features to be useful, (b) it covered a range of functions and (c) demonstrated a variety of sketch recognition types.

Some traditional software features were intentionally left out. For example, *Copy and Paste* is nearly ubiquitous in interactive systems, but it is not found in SIMI. It is often beneficial to discard long-standing assumptions of what is necessary to explore alternate ways to proceed. By omitting Copy and Paste, I had to focus on making it as easy as possible to create geometry and constraints. It is possible to create a 'copy' of geometry using standard SIMI actions. This helps to keep the application simple.

7.2 Implications to Related Areas

This research has implications to several areas, including rapid fabrication hardware and surrounding communities, interaction design, and research on sketch-based interaction and modeling.

7.2.1 Rapid Fabrication and Maker Communities

Laser cutters, 3D printers, CNC mills and so forth are called *rapid* prototyping machines because they facilitate fast machine-work. Often, software design tools are the bottleneck in a designer's work/build process. While experienced professionals might master the software to use rapid fabrication machines quickly, the majority of current (and certainly potential) users have not. Sketch based interaction might be one part of a new kind democratized design software that lets hobbyists and amateurs design and make with rapid fabrication machines.

Inexpensive, widely available, and *easy-to-use* rapid fabrication hardware and software has interesting consequences. Economically, it suggests a future where people can simply "print" new objects like door knobs as needed—obviously a topic of concern for hardware stores and manufacturers. Socially, it gives regular people the ability to play an active role in the design, function, and production of everyday things—which is concerning to professional designers and engineers. While it is difficult to envision a world without hardware stores (or

designers and engineers), desktop design and fabrication will have serious, unpredictable, and positive consequences.

7.2.2 Interaction Design

Sketch based interaction may be paired with other input paradigms to achieve unique results that would not be possible in isolation. While sketching, the user's non-dominant hand is free to perform other tasks. This can be leveraged to develop new ways to design.

Touch input is a current topic of importance, with touch-sensitive devices like tablets and smart phones dominating the consumer electronics market. Sketching, paired with touch, has recently been shown to give compelling results [30]. New technologies, such as voice recognition or Microsoft's distance-sensing Kinect, offer additional avenues that might be appropriate to mix with sketch-based input. Virtual reality hardware—special glasses that simulate 3D projection, volumetric displays, *etc.*—could be used to immerse designers in augmented reality design tools that let people draw anywhere in physical space [36]. These topics have been covered to various degrees, but the sketch interaction component has always been ad-hoc. This thesis gives a solid example of one way to support such interaction. Input paradigms that pair sketching with something else (touch, gesture, VR) have hardly been explored enough to consider them known topics.

Currently, sketch interaction is limited to devices that explicitly support pen interaction. But ongoing advances in sensing technology (e.g. Touché [62]) may allow arbitrary surfaces to accept sketch and touch input. Further, projection and display technology continues to advance. When every available wall and tabletop can display graphics and recognize sketch input, that has serious consequences for the future of interaction and design.

The recognition and resolution architecture from Chapter 4 might be useful to researchers and developers working on other kinds of recognition-based systems. For example, multi-touch devices or Kinect-style hand or body recognition could use the staged approach to simplify the recognition process. However, because there are multiple contemporaneous sample points to consider, future developers might have to extend the architecture discussed here.

Perhaps most importantly, the staged recognition architecture lets designers interact with computers using easy-to-make gestures that richly specify *an action*, *to which objects*, and *in which way*. This seems to reduce users' cognitive load by removing the need to enter persistent modes or the needs to set up sequences of atomic operations to achieve a desired outcome. Additional work on this topic is warranted.

7.2.3 Sketch Based Interaction and Modeling

This thesis claims that SIMI exemplifies sketch-based interaction techniques that work well together. However, the particular set is tuned to the laser cutter domain and to the features SIMI provides. How can future researchers generalize this contribution?

The recognition and resolution architecture from Section 4.5 guides programmers and interaction designers to develop new techniques and applications. While a programming structure is helpful, there are other important aspects to consider when designing new sketching gestures.

I provide several heuristics for developing sketch-based interaction techniques in other applications:

Leverage context. Gesture syntax can be overloaded by letting context determine meaning. For example, a circle drawn around two unlatched end points is semantically different from a circle drawn around a cutout. Overloading gestures means less work for the programmer, and fewer gestures for the user to learn and remember. However, care must be taken to ensure that the contexts are separate enough that they will not be confused.

Substantial shape differences improve recognition and user experience. Strive to develop gestures that are substantially different from one another. It is tempting to create many gestures that are different in subtle ways because it is easy to program the related recognizers. However, users will have a difficult time remembering and executing these subtly different gestures.

Rely on visual reinforcement and physical metaphors. SIMI's right angle constraint appearance echos the gesture used to create it. When there is not a visual, the gesture should make physical sense: the circle gesture used to latch points together feels like tying the points together with a string; the erase gesture is based on scratching over unwanted marks on physical paper.

Make use of the staged recognition architecture. Some gestures should be acted upon immediately, while others could (or should) be deferred until later. For dynamic recognizers, effective visual feedback is critical. While the staged architecture eases programming, its true purpose is to improve user experience.

7.3 Future Work

The most interesting research leaves more questions than it answered. Having built a useful and useful system for laser cut designs, much of the feedback I receive focuses on additional features. Observers commonly would like to see a tool like SIMI for some other domain,

such as for 3D modeling.

7.3.1 Common Feature Requests

It is likely that Sketch It, Make It (or something like it) will be made into a commercial product soon. We have accumulated a long list of feature requests that can serve as a starting point for the next set of additional features.

Users like the paper-like feel of the tool, and would prefer to have the ability to add ink that is not recognized. This enables designers to explore freely, as they would on paper, while still having the ability to use these unrecognized portions in future work.

Handwriting recognition is another commonly requested feature. This was intentionally not included in the current prototype because it would have required a substantial time investment without a correspondingly substantial pay-out. Handmade numbers and text could be applied to give dimensions and labels to parts of a drawing.

Users also request additional constraints, for example making two lines parallel, or making an object appear at the midpoint between two others. This would allow a wider and richer range of output.

Another feature that would likely make SIMI much more useful is the ability to assemble 3D constructions from 2D parts. This would let users see the relationship between the 2D parts they have designed and the final 3D output. This can be useful, for example, to identify stylistic or assembly problems before spending time and material on the laser cutter.

7.3.2 Machine Learning Improvements

SIMI was built on the idea that it is generally better to give users interaction techniques to state their intentions, rather than using machine learning routines to deduce what the user wants. However, there are a number of cases where machine learning could be used to make the overall user experience better.

Each user has a drawing style that is different from any other. The differences can be subtle, or might be substantial. In keeping with the paper-like interface, an intelligent agent could watch the user draw and learn their particular style and preferences. For example, if a user consistently fails to make the erase gesture correctly, their preferred erasure gesture could be learned and applied (without asking). The user could also teach the system new gestures entirely, providing new syntax directly.

Sometimes companies or other organizations adopt conventions. These conventions may be common within that community but not typically found outside. SIMI could learn these social norms, and understand when to apply them.

7.3.3 Domain Specific Improvements

Laser cutters and similar machines (water jet, plasma, CNC mills) share common properties. If the software could account for these properties, the user could incorporate them into their designs. An obvious property of laser cutters is the *kerf*—the width of the cut path. The laser cutter used throughout SIMI's development typically leaves a kerf of approximately 0.4mm. When designing press-fit notches for rigid material that is 3mm thick, the kerf size is a significant concern. If the tool understood that certain geometry was sensitive to kerf thickness, the software could save the user time and material costs by making more accurate cuts.

The press-fit notch just mentioned is just one type of joint. Currently SIMI does not include a concept of joints. If it did, the user would be able to indicate where joints should exist, between which parts, what the material properties are—and the software would take care of the rest.

Using material is another important consideration, both because it costs money, and because supplies are often limited. For example, Ponoko sells 15"x15" squares of acrylic for between $8 and $28 depending on thickness. To make more efficient use of material, the software could perform intelligent cut file layout with a shape-packing algorithm. If the system knows where a piece of material has holes, the algorithm could also place new parts on used material, saving a lot of money.

Assemblies often have a lot of parts, and it can frustrate users when trying to determine which part goes where. The tool could etch part numbers (or joint labels) into the material to aid assembly.

7.3.4 Beyond Laser Cutting

In this work, I set out to demonstrate how a set of interaction techniques designed to be used together to make a useful and usable system, and show that sketch-based interaction should be taken seriously, particularly as a paradigm for doing design. To do this I picked a specific domain—laser cutting—but there are other domains that would have been appropriate as well.

3D modeling is an obvious choice. Physical objects are necessarily three dimensional, and designers often sketch them in perspective. There are interesting challenges associated with "3D sketching", and many others are working on these research topics.

2D applications will be easier to write based on SIMI's current implementation. Graphic design applications for illustrations, diagrams, logos, T-shirt designs, or cartooning are appropriate areas for SIMI's interaction.

Teachers famously draw on chalk boards or whiteboards to illustrate concepts in many areas, from physics to mathematics. A sketch-based education system might be a useful tool for teaching STEM topics at all levels—primary, secondary, and post-secondary education.

The techniques presented in this dissertation could potentially be used in any domain that makes use of structured or semi-structured diagrams. It could be used to think about ideas, generate concepts. Or it could be a communication tool used to work with others in ongoing design projects. Or sketch-based design could simply be used as a fast, efficient method of specifying the designer's intent to create finished output.

7.4 Looking Forward

Nearly everything in our environment was deliberately designed and built by a human being. An artifact's users are not often the same people that designed or built it. The recent introduction and success of affordable, fast fabrication machinery suggests the gulf between *designers* and *users* may narrow as desktop manufacturing lets ordinary people design and build things on their own. One remaining bottleneck is software: access to fabrication machinery is not enough. Democratized fabrication requires democratized design tools. People need design software that is easy to use and gives the means to express ideas. But for ordinary people, current CAD software is not an option. It is expensive, hard to learn, and hard to use.

The sketch-based interaction presented in this thesis explicitly supports design for laser cut items. This is provided as an example of a (potentially) much larger space of sketch-based modeling tools. Many other application areas were mentioned above, such as STEM applications for students, 3D modeling, animation, and business diagrams. This line of research is important not simply because it enables users to do one thing marginally better than before. It is important because it will empower people to design and make many kinds of things that were previously impossible. Democratized design is a powerful idea, and the consequences are far-reaching.

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