Building Information: Means and methods of communication in design and construction.

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by

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Submitted to the Department Of Architecture on May 23, 2008 in Partial Fulfillment of the Requirements for the Degree of Masters Of Science In Architecture Studies.

Abstract

Architects are trained and practiced in the means and methods of design. These are distinct from the physical means and methods of construction, which have traditionally been in the hands of contractors. The successful realization of construction does not necessitate or rely on a direct link between the processes of design and construction. However, the constructability of a design is dependent on an effective means of communicating between the two. This thesis illustrates that the perceived complexity of constructability is often predicated on the efficacy of communication between the designer and the contractor. I present three models of communication: a linear transmissive model similar to that of Shannon and Weaver, a "speech-circuit" model based on that of Saussure, and a semiotic-constructionist model derived from Peirce and Papert. Through interviews, observations, and experiments with practicing architects and architecture students, I investigate the implications of these models on the perceived and contractual roles and responsibilities of architects and contractors. My findings suggest that in design, communication is also an act of design and construction. Best illustrated by the constructionist model of communication, acts of making and re-making are fundamental to the way that architects and contractors relate to design information. The automation of these acts through emerging technologies - such as BIM - lead to increased reliance on fixed data constructs in lieu of dynamic, individual interpretations of information. This can result in the loss of expert knowledge which does not fit a standardized model, and the dis-integration of meaningful communication between design and construction information.

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Professor of Design and Computation

Contents

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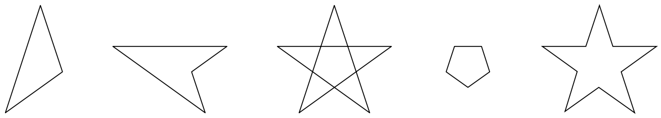
And thank you to Kate, whom I will soon marry. Without you I never would have made it in the front door…or back out.



1. Introduction

> "First, the taking in of scattered particulars under one Idea, so that everyone understands what is being talked about…"
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> - Plato, Phaedrus, 265D

Architects are trained and practiced in the means and methods of design. These are distinct from the physical means and methods of construction, which are typically in the hands of contractors. The successful realization of construction does not depend on a direct correlation between the process of design and the process of construction. However, the constructability of a design is predicated on an effective means of communicating between the two.

Increased demands have been placed on the Architectural, Engineering, and Construction (AEC) industry to design and build projects that consume fewer material and economic resources, conform to tighter construction tolerances, display greater formal complexity, remain operable for longer time periods at lower costs, and have a smaller overall environmental impact. Similar demands and advances in other industries, such as the automotive and marine industries, have been cited as successful examples upon which the AEC industry should be remodeled[1]. Much of this remodeling effort focuses on the adoption of the technological means and methods of these industries. In particular, the AEC industry has subsumed the particular use of computer aids to design and manufacture from these industries as a generic approach to designing and making. Proponents at the forefront of this movement claim that

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[1] See Kieran, Stephen, and Timberlake, James. (2003). *Refabricating Architectre: How Manufacturing Methodologies are Poised to Transform Building Construction.* (McGraw Hill Professional).

digital technology can provide the means and methods for translating design into building information[2]. Currently, the favored method for achieving this is by explicitly associating textual and mathematical information to digital geometry through parametric[3] software and relational databases. These methods are adopted directly from the automotive, marine, and manufacturing industries. By superficially adopting the means and methods of other industries, architects also adopt their embedded terminology and metaphors. These metaphors shape not only how computer aids to design are developed, but also our mental models of their purpose and usefulness. A problem occurs when these metaphors become so commonplace that they go unchallenged. An excellent example comes from the design of the operating system for the One Laptop Per Child (OLPC) project. Recognizing the implications that familiar desktop metaphors have upon what and how children learn, the OLPC team designed their interface using the metaphor of a 'neighborhood'. The change of metaphor in this case was not just symbolic, but a powerful method for opening up entirely new ways of thinking about how a computer designed for children should function. Commenting on this approach Nicholas Negroponte, the creator of the OLPC project and an early pioneer in computer aided design in architecture, stated "…one of the saddest but most common conditions in elementary school computer labs…is the children are being trained to use Word, Excel and PowerPoint…I consider that criminal, because children should be making things, communicating, exploring, sharing, not running

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[2] See Shelden, Dennis. (2006) "Tectonics, Economics and the Reconfiguration of Practice: The Case for Process Change by Digital Means" in *Architectural Design*, v76-4, July/August: p82-87.

[3] The use of the term parametric with respect to digital design software is a poorly understood term and is regularly conflated with history-based software. The details of this will be discussed in Chapter 6.

office automation tools."[4] Should the development of computer aids for design be any different?

There is an implicit assumption in the use and development of contemporary Computer Aided Design (CAD) technology that being able to generate, and having access to, more information will increase the ability of designers and contractors to manage increasingly complex projects. At the same time, this also demands increased attention to the management of such substantial amounts of information. In *Getting complexity organized: Using self-organisation in architectural construction*, Fabian Sheurer of the architectural consulting firm DesigntoProduction states, "…when it comes to actual construction of a complex building, the question arises: What is a reasonable quantity of explicit information for a specific design, and how does one communicate it in a reasonable fashion?"[17 p79]

This thesis shows that in architecture the perceived complexity of a design is a measure of the difficulty that a particular project team (architect, contractor, and consultants) has in translating the design information into construction information. Every design-construction problem can be represented in multiple ways.[18] The clarity and comprehensibility of intention and meaning in the representation of design and construction information is a function of human perception. Because any medium of human communication is open to interpretation, the amount of ambiguity in any representation is always greater than zero. The constructability of a project is therefore predicated on the efficacy of communication between

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[4] Associated Press, "Novel Software Drives '$100 Laptop", *CNN.com*, January 2, 2007, http://www.cnn.com/2007/TECH/01/02/hundred.dollarlaptop.ap/index.html?eref=rss_tech (last accessed January 3, 2007).

design and construction information. The feasibility of a project may be in doubt as a result of mismatched interpretations of information. Interpreting design information as a discrete set of physical elements and fabrication / assembly procedures is not an easy or reliable process. I present three models of communication: a linear transmissive model similar to that of Shannon and Weaver, a “speech-circuit” model based on that of Saussure, and a semiotic-constructionist model derived from Peirce and Papert. Through interviews, observations, and experiments with practicing architects and architecture students, I investigate the relevance and implications of these models on the development of computer aids to design.

Design is an act of seeing, thinking, and making. It is a construct involving the use of the eye, the mind, and the hand. Beginning in the 1960’s digital computer technology was developed to aid architectural design under the auspices of “a man-machine graphical communication system”.[25] Given the underlying bit-wise structure of digital technology, the majority of computational tools employed in architecture since then have been variations of canonical production systems[5]. The evolution of computational tools has also tended to conform to advances in technology, leaving the responsibility of determining their usefulness to designers[6]. In the 1970’s George Stiny and James Gips introduced an algebra for visual calculating known as Shape Grammars.[21][22][23] Fundamental to the algebra behind Shape Grammars is the use of visual perception in design

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[5] “A production says how, from one statement, string, or “enunciation”, of such and such a form, one *may* derive another string of specified form. A canonical system, which is a set of such productions and some initially given statements, does not even describe a *process*; instead it specifies the extent of a set of strings by (recursively) specifying how to find things in that set.” [13 p220]

[6] Such tools include: Lindenmayer systems (L-systems), genetic algorithms, and cellular automata.

and computation. The development of shape grammars differed significantly from other computational systems because it did not rely on a predetermined or fixed set of elements. While most computational systems were (and are) aimed at explaining and eradicating ambiguity, Shape Grammars embraced it as an inherent and necessary aspect of any design process.[2, footnote 8 to Chapter 9][19][24] The field of Shape Grammars and my work with George Stiny over the past two years has played a major role in my research, and provided a touchstone by which my work was guided.

Methods. The problem of communication in design and construction will be presented through both theoretical and empirical investigations. The theoretical investigations are presented within the framework of various models of communication. These models include the mathematical theory model of Claude Shannon and William Weaver, the speech-circuit model of Ferdinand de Saussure, and a semiotic-constructionist model based on the work of C.S. Peirce and Seymour Papert. The empirical investigation begins with an analysis of the contractual obligations of architects and contractors with respect to the production of documentation, as stipulated by the American Institute of Architects (AIA).

Next, the results of a series of experiments into design communication are presented. The subjects for these experiments were several graduate students in the Department of Architecture at the Massachusetts Institute of Technology (MIT) and practicing architects in the United States. To study the difficulty of communicating geometric design information, individuals were asked to translate a set of dimensioned drawings of a single shape into a set of written instructions. Those written instructions were then given to other individuals with which to re-derive the shape[7]. Full documentation of the experiments and results are provided in the Appendix.

Following the shape experiments, notes from a series of case studies conducted with individuals at several architecture firms is presented and discussed. The goal of these case studies was to determine how design information is communicated in practice along with how, why, and what computer aids are currently being employed. I followed an 'unstructured interview' methodology in order to encourage the individual expression of interviewee's ideas. The interviews were conducted with one individual from each of the following firms: Foster + Partners, London office, individual with the Specialist Modeling Group; SHoP Architects PC, New York City; and SOM (Skidmore, Owings & Merrill LLP), New York City, individual with the Computational Design Group.

The next section begins with a distinction between the *act of design* and the *result of design*. The verb design implies certain associative leaps and intuitive calculations that are made based on seeing and thinking and doing.[24][18] The noun design indicates the outcome of a process that can be analytically rationalized into a series of discrete procedures. In the Architecture, Engineering, and Construction (AEC) industry digital technology is employed in the service of both the process and product of design. There may or may not be a direct link between the design process and the construction product. I provide an overview of the general data

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[7] The geometry of the shape was developed based on a similar example created by Paul Hamilton which he reported on in his article, "A Primer on MCAD Modeling Technology, Part 2: Design Intent is Not Necessarily in the Eye of the Beholder." CADCAMNet, July 26, 2007. (Ash Bridge Media LLC). Available online at http://www.newslettersonline.com/user/user.fas/s=63/fp=3/tp=47?T=open_article,959682&P=article (last accessed May 5, 2008).

structures upon which most CAD systems are developed to better understand how these systems influence acts of communication in design and construction. I then discuss the advent of Building Information Modeling (BIM) within the context of interoperability, and compare it to Michael Reddy's *Toolmakers Paradigm* fable of communication. By juxtaposing statements made regarding the potential of computers to aid in design from the 1975 and 2007, I argue that the development of design technology has been stifled. I propose that the problems are to be found in our mental models, not our digital models. My contribution is the development of criteria with which to determine the usefulness of computer aids to design. These criteria are the degree to which design technology facilitates wasteful versus productive acts of repetition in design.

In conclusion, I provide a critique of the current standards-based approaches to design communication which rely on the disambiguation of information through a fixed data model. The danger of using such models is that expert knowledge which is not accounted for in the standards could be lost. Furthermore, a rigid and inflexible vocabulary could lead to the dis-integration of meaningful communication between design and construction information. I discuss several reasons for why these approaches continue to fail. First, they have in the past. Second, they are built on the assumption that meaning can unambiguously be connected with symbolic information. Third, these models assume and that individual interpretation is not necessary in the communication of design and construction. And lastly, these approaches assume that the solution must come from the formulation of a new model, rather than a new mindset.

2. Models of Communication

In the 1940's Claude Shannon and Warren Weaver developed a linear transmission model of communication while working at Bell Telephone Labs. They were most concerned with maximizing the speed, efficiency, and clarity of information transmitted over telephone lines and radio waves. The success of their model was measured in "bits per second".[20] Their model reduced the problem of communication to the technical issues involved with the transmission of information across a physical medium. This model proved valuable for such research and became the basis for their "mathematical theory of communication". [20] This model was quickly adopted as the basis for more generic models of communication other than those of a purely technical nature.

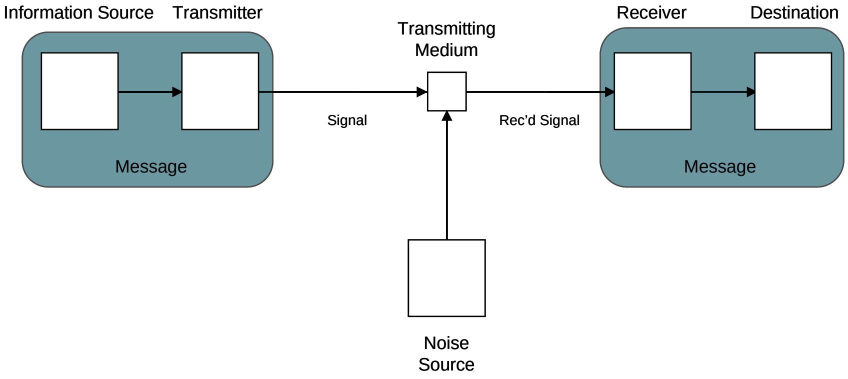

Figure 1. Linear transmission model based on Shannon and Weaver (1963).

In communication theory a message is a discrete and unambiguous set of information where *information* should not be confused with *meaning*. According to Weaver, information "…relates not so much to what you *do* say, as to what you *could* say. That is, information is a measure of one's freedom of choice when one selects a message." Weaver continues, "The concept of information applies not to the individual messages (as the concept of meaning would), but rather to the situation as a whole…"[20 p9]. As the diagram of the model (Fig. 1) indicates, each message is a discrete element, the contents and meaning of which are assumed to be preserved. Each message is encapsulated and unambiguous with respect to the information source, transmitter, transmitting medium, receiver and destination. All messages in this model of communication are literally passed through some medium, where any distortion or "noise" is solely dependent on the physical properties of the transmitting medium.

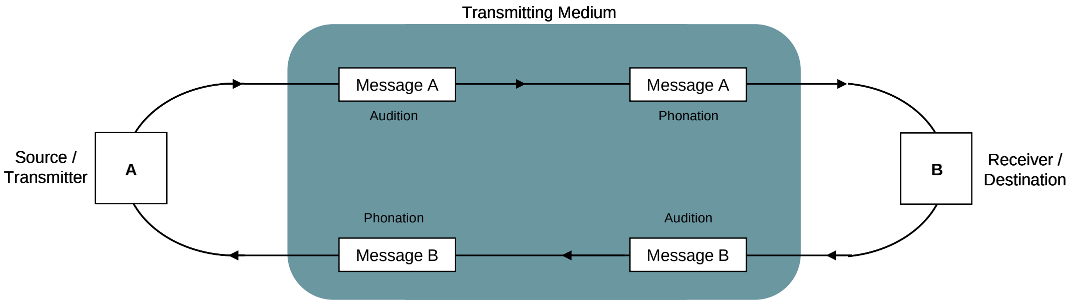

Figure 2. 'Speech-circuit' model of communication based on Saussure (1972).

In 1972 Ferdinand de Saussure introduced the "speech-circuit" model of communication.[16 p11-12] The speech circuit model differed formally from Shannon and Weaver's transmissive model in that it directly addressed communication as a cyclical process, and was based on human verbal interactions. In his explanation of the model, Saussure states, "The starting point of the circuit is in the brain of one individual, for instance A, where facts of consciousness which we shall call concepts are associated with representations of linguistic signs or sound patterns by means of which they may be expressed. *Let us suppose that a given concept triggers* *in the brain a corresponding sound pattern*." (my emphasis).[16 p11-12] The concept and sound pattern are what Saussure terms the signified and the signifier.[16 p67] This first statement would seem to indicate that Saussure, like Shannon and Weaver, assumed that spoken messages were unambiguous and remained unchanged as they passed back and forth through each subject. Saussure's model modifies this assumption slightly by further distinguishing between *meaning* and *value*. In defining value, Saussure recognizes the importance of context in communication[8]. However, he retains the idea that meaning (albeit arbitrary) consists of pre-determined, constituent elements, and rules out the possibility of ambiguity in language[9].

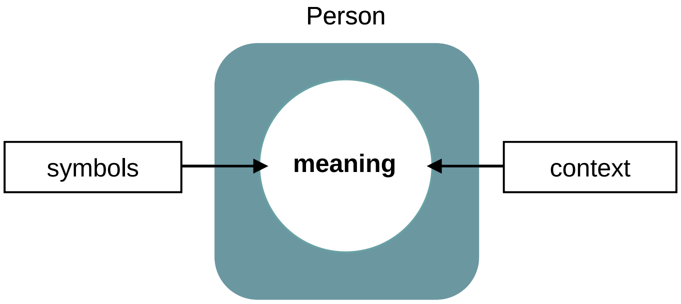

Figure 3. Constructed model of communication based on Peirce.

Around the same time, Charles Sanders Peirce introduced a contrasting model which highlighted the ambiguity of communication. For Peirce, communication was based on individual interpretation, and any one

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[8] "A language is a system in which all the elements fit together, and in which the value of any one element depends on the simultaneous coexistence of all the others."[16 p113]

[9] "A language might also be compared to a sheet of paper. Thought is one side of the sheet and sound the reverse side. Just as it is impossible to take a pair of scissors and cut one side of paper without at the same time cutting the other, so it is impossible in a language to isolate sound from thought, or thought from sound." [Saussure p111] Here Saussure is referring to spoken language, but I believe he would maintain this assumption for other forms of communication as well, for instance, visual.

person’s interpretation could be re-interpreted by another. Peirce states this notion clearly (using ambiguous terms) when he writes, “A sign...is something which stands to somebody for something in some respect or capacity.”[30, 2.228] Peirce emphasized the process of communication in contrast to the structured models of Saussure, and Shannon and Weaver.

The production of meaning was also noticed by those studying how people learn. Piaget’s constructivism and Papert’s constructionism presented models of learning that stressed the contextual construction of meaning. In writing about the subject, Edith Ackerman refers to the ability of children to instantaneously interpret and re-interpret (construct and re-construct) relationships between symbols and meaning. Ackerman writes, “We know from research on early pretense play that children’s abilities to treat a stick *as if* it were a horse requires a decoupling between signifier and signified. In other words, a child who uses a stick “as if” it were a horse also knows that it is not “really” a horse. What is less obvious is the notion that decoupling has to go hand in hand with its opposite, fusion, for the symbolic transform to be complete.”[1] External artifacts in such acts of “creative symbol-use”[10] are necessary to stimulate feedback processes that allow for the seeing, thinking, and doing cycles that are fundamental to the interpretation, understanding, and communication of information. In this context, feedback is considered to be the return or re-introduction of information in the form of a message to the information source.

The theories of Peirce and Papert show that when modeled as a dynamic process, communication can be seen as an act of designing and constructing meaning. This happens through a continuous coupling and

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[10] See [1] p25.

de-coupling of the meaning-symbol relationship. Ambiguity is managed through individual interpretation and validation.

In the case of architectural design, the design document[11] is meant to communicate project information. There are several national standards that are meant to govern the organization of information in architectural drawings[12]. This potentially indicates the reliance on a structured model of communication. According to communication theory, the amount of information present in the design document would be measured by the number of possible messages or meanings that the document can be shown to contain. How many messages can be found in a given document is related to the definition of what constitutes a valid message. Given just a small amount of ambiguity or uncertainty with respect to the constitution of a valid message, the receiver of a design document has the freedom to interpret the informational content of the document in any number of ways.

This notion of ambiguity raises several important questions with respect to the communication of design and construction information: First, how can the sender have any assurance that the intent of their message is adequately represented in the document? Second, to what degree can the sender be certain that the receiver will be able to adequately identify and interpret their message? Likewise, how can the receiver be certain of the fidelity between their interpretation of the message and the (unknown) intent of the sender? For Shannon, Weaver, and Saussure, ambiguity does

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[11] In this instance, the term design document is meant to be inclusive of all representative media including physical and digital models in addition to typical orthographic drawings.

[12] ConDoc, the U.S. National CAD Standard (NCS), the AIA CAD Layer Guidelines, and the Construction Specification Institute (CSI) Uniform Drawing System (UDS), just to name a few.

not exist, and neither do such questions. For Peirce and Papert, and anyone who has ever practiced in design and/or architecture, this is not only normal, it is to be expected. This is also clearly reflected in the contractual roles and responsibilities established by the AEC industry.

3. Roles and Responsibilities :: Means and Methods

The professional obligation of an architect is to produce a set of documents at a level of detail sufficient to communicate design through a set of design documents[13]. These documents may take the conventional form of two-dimensional drawings of plans, sections, and elevations, or increasingly, of three-dimensional computer models. Regardless, these documents do not comprise a set of instructions for building. The physical means and methods of construction reside in the hands of the contractors[14]. However, the successful realization of a construction does not necessitate or rely on a direct link between the processes of design and those of construction. This does not imply that the two are not related, or that it is not beneficial for one to inform the other. Rather, these conditions make clear that *the constructability of a design is dependent on an effective means of communicating between design and construction.* Put another way, the determination of whether or not a design can be built, and how difficult it will be to build, depends upon the ability of those responsible for building to *see* (interpret and understand) the means and methods of construction within the design documents. It is important to stress here that this type of seeing is not purely the visual perception of information, but also the cognitive processing of that information into a series of logical procedures, and the manual discretization of the whole into a series of parts that can be fabricated and assembled[15]. It is the role

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[13] See AIA document A201-1997 section 3.12.4.

[14] As noted in the AIA document B101-2007 (*Standard Form of Agreement Between Architect and Owner*, section 3.6.1.2.) the designer is barred from explicitly specifying the means and methods by which their projects are to be built. Regardless of the design methodology, the discretion is left to the builder to choose their preferred methods of construction so long as the final outcome reasonably matches the design documents.

[15] Lionel March stated this idea well in the forward to *The Architecture of Form*, “The nature of the environment is that of a complex system: the whole not to be understood as

of the contractor and various sub-contractors to produce another set of documents (shop drawings and coordination drawings) which represent the actual construction elements and how they will be assembled.

Due to the fact that the determination of the means and methods of construction are at the discretion of the contractor, how the design will be sub-divided into discrete elements cannot be assumed in advance (as Saussure and Shannon and Weaver might expect). Rather, because the design and construction are carried out by two separate entities, the elemental constitution of any design must necessarily be an arbitrary derivation based on the particular context of the design project (a la Peirce and Papert). The context includes not only the physical characteristics of site, and material, but also the logistics of budget and schedule, and the specific personalities and expertise of the various trades and professional domains involved in the project. All these variables, and more, are inter-related in a dense web of associated dependencies that influence the constructability of a project. If constructability were not a function of communication, and communication were not itself an act of design and construction, then designing a building from the outside-inwards and then building it from the inside-out would not be possible[16]. Herbert Simon

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a configuration of irreducible atomic elements, but the elements themselves constantly being redefined according to our approach to the system as a whole."[10 viii]

[16] For example, in Foster + Partners' Greater London Authority (GLA) City Hall and Swiss RE projects, the overall exterior form of the building was designed first and all the structure derived to match this form. In the computer models of these buildings, the perimeter shape of the floor slabs are derived by intersecting transverse planes with the 'skin' of the building along its height. This makes the shape of floor slabs associatively dependent on the skin of the building. However, in the actual construction the floor slabs are poured first, and the skin of the building hung from them, creating a dependency reversal. See [27], as well as any Gehry project from the last two decades. This is a common practice in architecture. The construction industry has developed very specific means and methods for managing construction tolerances in order to make these types of dependency-reversals possible and manageable (constructible). For more on construction tolerances and allowances see: Cole, Kevin C. "Aluminum Cladding on Multistory Steel

nicely generalizes this process in *The Architecture of Complexity*: “We pose a problem by giving the state description of the solution. The task is to discover a sequence of processes that will produce the goal state from an initial state. Translation from the process description to the state description enables us to recognize when we have succeeded.” Simon summarizes, “The general paradigm is: Given a blueprint, to find the corresponding recipe.”[31 p211]

My research shows that in design, communication is also an act of design and construction. Best illustrated in a feedback model of communication, acts of making and re-making are fundamental to the way that architects and contractors relate to design information.

Frames” in *Modern Steel Construction*. May 1997, http://www.modernsteel.com/Uploads/Issues/May_1997/9705_01_cladding.pdf (last accessed May 18, 2008.)

4. Shape Experiments

> "How complex or simple a structure is depends critically upon the way in which we describe it."
>
> – Herbert Simon, *The Sciences of the Artificial*, p.215

A general request was made via email for subjects to participate in a study on the effectiveness of procedurally-based design communication. Subjects included several students from the Architecture Department at the Massachusetts Institute of Technology (MIT)[17], an alumnus of the Computer Science Department at MIT (who currently holds a position in the Computer Resources Office in the Architecture Department at MIT), and several professional practitioners from various architecture firms in the United States. The experiment consisted of two parts. Subjects participated in only one part of the experiment, and each part of the experiment was carried out with the subjects individually. Subjects who participated in the first part of the experiment will be referred to as Group *A* and those that participated in the second part, Group *B*.

Subjects in Group *A* were presented with a perspective rendering and three orthographic projections of a single shape[18]. The orthographic projections included a dimensioned plan, section, and elevation of the shape. This was assumed to be a typical amount of design information necessary to fully describe the parameters for (re)making the shape. No explicit dimension was given for the height of the shape. This was an unintended omission,

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[17] Volunteers included Masters of Architecture (M.Arch.) students as well as Masters of Science in Architectural Studies (S.M.Arch.S.) students. It should be noted that some of the M.Arch. students had a background in architecture prior to MIT while some did not, but that all S.M.Arch.S. students had at least a professional degree in architecture, along with varying amounts of professional work experience.

[18] The design of the shape was based on an example presented in an article by Paul Hamilton of PHusion Engineering Solutions LLC.[7]

but the results suggest some very interesting and valuable insight on design communication. Certain details were specifically added to the shape as controls whose unintentional reproduction was considered unlikely. These details included fillets (rounded edges) and centering the circular opening on the inner faces of the shape rather than the outer faces.

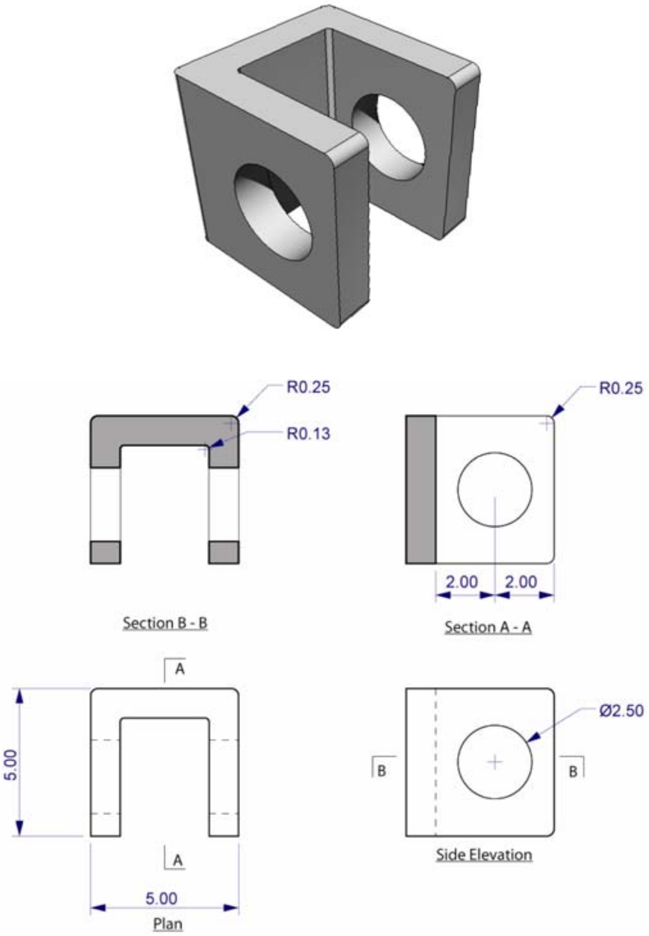

Figure 4. The shape drawings.

The instructions included with the drawings indicated the following:

- Your goal is to write a procedural description for the derivation of the geometry shown using written text only, no pictures or diagrams.
- This description will be given to another person and used to recreate the geometry.
- You may assume that the recipient has access to and may use CAD software with which to create the geometry, but you cannot assume which software they will use or what platform they will be using (i.e. Mac or Windows)
- Please be as explicit about the process as you feel necessary.

Some of the responses to the first part of the experiment were received via email, and others were returned as hand-written hard copies. All responses were re-formatted for the sake of conformity; however, no changes or corrections were made for spelling or grammar[19].

In the second part of the experiment, subjects in Group *B* were given one of the procedural descriptions from Group *A*. The instructions included with the procedural descriptions stated:

- Your goal is to derive the geometry described by the process below. Please follow the instructions explicitly.
- Please indicate – via written notes - ***any*** issues, additional steps, or deviations you make from the instructions below in your derivation of the geometry.

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[19] All the results are presented in the Appendix.

- You may use any CAD software you like; just indicate the program and platform below. If you do use CAD software, please email me a copy of the digital file.
- If you are unable to complete the derivation, please indicate how far you were able to get and why you were unable to continue.

Results. Six procedural descriptions were returned. From three of those descriptions, a total of nine derivations were created. Each set of instructions differed significantly in the number of steps and the approach. The shortest procedure was six steps and approximately 125 words, compared to the longest at over 30 steps and almost 1050 words. All the procedures indicate the height of the shape to be 5 inches (or "units" where the explicit unit-measure was not given), even though no dimension was given. The formal derivations produced by students were clearly distinguishable from the initial shape and from each other. The derivations of the practicing architects were all very similar and almost indistinguishable from the initial shape. Each of the student derivations was three-dimensionally modeled using either AutoCAD or Rhinoceros. Of the four results received from practicing architects, two were sketched by hand, one was modeled three-dimensionally in AutoCAD, and one was an isometric drawing produced using 2D lines in AutoCAD.

Students who were unable to complete all the steps of the derivation they were given indicated difficulty in comprehending and following the instructions. These problems were based both on the language used in the procedural descriptions as well as on the software they chose to use:

"In Rhino…you should specify which window to begin the sketch in. When you begin in a window which is not the horizontal x,y plane the

sketch accepts your co-ordinates relative to the plane you're sketching in. Does that make sense? This creates orientation issues when you extrude the sketch in z.” – regarding derivation of description 01-2.11.

“The Cylinder wouldn't cut (remove) from my solid. I guess its because it [Rhino] *couldn't calculate the cut due to two of the surfaces being planer.”* – regarding derivation of description 01-2.11.

“I was not sure what fillet the surfaces AH, A'H' etc, (number 13) meant. Did it mean fillet the surface between A', H', A, H?” – regarding derivation of description 01-2.11.

“I made it through step 14. I was not able to complete step 15. Through step 14, I had no problems. For step 15, I tried the following: BooleanDifference, BooleanSplit, Trim, Split… In the end, no matter what I did, I couldn't figure out how to remove the cylinder from the solid.” – regarding derivation of description 01-2.11.

The two practicing architects that returned computer-based derivations indicated that they had difficulty with the experiment because they were either unfamiliar with how to 3D model, or because it had been a long time since they had last modeled in 3D. The subject who produced the 3D model stated:

“I haven’t created a 3-D object for years, and so struggled a bit remembering how, and remembering what views to use.”

The subject who created a 2D version of a 3D axonometric drawing using CAD drafting software gave this rationale:

“For several reasons (a. I am retarded with modeling software and like to do things by hand b. we are short on Form-Z keys and c. I don't know how to fillet an edge in Sketch-up) I did this manually in Vectorworks (in 2D).”

When the two professionals who returned scanned copies of their hand-drawn derivations were asked why they had not used CAD software, they responded:

“I chose to go by hand for expediency. Typically, for me, it's easier to model something once I have a general understanding as to the overall shape. Different modeling techniques lend themselves to different forms and in some cases the sequence of modeling operations is critical.
After starting to figure it out on paper, it just seemed unnecessary to model the piece.”

“I choose to do the exercise by hand because I thought it would be faster. Given my [current project], *it's been awhile since I've worked in Autocad, and quite awhile since I worked in 3D autocad.”*

Discussion. The cumulative results are too few to be conclusive. However, I believe this investigation shows that the communication of design information both graphically and textually is non-trivial and fraught with ambiguity.

Based on strict formal conformance, none of the derivations can be shown to match the initial shape. However, is formal conformance the only criterion with which this experiment should be judged? While each procedural description is unique, they are, in Goodman's terms[20], all scripts on the performance of a common score. Likewise, even though the resultant derivations of a given procedural description differ formally from each other and from the initial composition, they are, again, individual interpretations of a common script. This is similar to the processes involved in the design and construction of actual buildings.

In practice, the architect produces a set of documents which represent a state description, of a desired concept[21]. The contractor, or those responsible for construction, must interpret and translate that composition into a set of explicit, actionable scripts. These scripts may take the form of Shop Drawings, Coordination Drawings, and other submittals. The contractor's scripts dictate the means and methods of the work to be performed. These scripts also act as validation of the ability of the contractor to accomplish the work within acceptable limits. Architects cannot enforce any particular means and methods of construction, regardless of the level of detail in their design documents[22]. Industry standards explicitly indicate that the contractor should assume that design information may be in conflict with construction requirements. However,

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[20] See [5] p218-221.

[21] In an article titled "Drawing the Line" James Atkins and Grant Simpson recall the decision of Gyo Obata, one of the founding partners of Hellmuth, Obata + Kassabaum Architects (HOK) to produce their construction drawings using freehand sketching. The intent was to emphasize the conceptual nature of the drawings, and to force the contractors to rely on their ability and that of their sub-contractors to produce construction documents demonstrating their comprehension and intended approach for the manifestation of the design concept. See Atkins, James B. and Simpson, Grant A. "Drawing the Line", in *Best Practices in Risk Management* AIArchitect September 5, 2005. http://www.aia.org/aiarchitect/thisweek05/tw0902/tw0902bp_riskmgmt.cfm (last accessed May 21, 2008.)

[22] As noted in AIA document B101-2007 (*Standard Form of Agreement Between Architect and Owner*, section 3.6.1.2.) the designer is barred from explicitly specifying the means and methods by which their projects are to be built.

the construction industry also provides detailed specifications for the legally acceptable limits, or tolerances, that physical construction may deviate from the design documentation[23]. With respect to the shape derivations from the experiment, the main determinant of acceptability is a direct result of the conformal tolerance desired and imposed. The less strict the tolerance is made, the greater the number of derivations considered acceptable.

The translation of design information into construction information is not a single-step process, nor is it unidirectional. The means and methods applied to the use of technology in communicating between design and construction are not static, but in continual flux. The dynamics of this process cannot be represented by Shannon and Weaver's nor Saussure's fixed-meaning models of communication. Bill Mitchell made note of this issue with respect to the limitations of CAD in 1995, "The content, format, and graphic style of construction documents should be based on rigorous consideration of what contractors and construction workers really need to see, not on the constraints imposed by now-obsolete document-production technology."[14 p401]

The following section documents several case studies on the various ways in which digital aids to design and construction are being used by contemporary architectural and consulting practices to communicate both internally and externally.

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[23] The AIA has developed a proprietary master specification for the construction industry known as MasterSpec.

5. Case Studies

Following an unstructured interview methodology, I conducted a series of three architecture firm case studies. At each of the firms, I interviewed one person. The goal of the interview was to determine how the firm communicated design information. I was interested in how these firms communicated both internally and with outside consultants.

Technological interoperability with respect to design and construction communication was a major issue common among all the firms. The database-driven BIM (Building Information Modeling) approach to interoperability requires adherence to a predefined set of standardized means and methods for generating and recording design information. For this approach to be viable, I should have been able to discern a common model of communication at each of the firms. Instead, each firm addressed the problem in its own unique way. The firms which participated in the case studies represent a distinct demographic of architectural practice. This suggests that a standard model does not exist in architectural practice upon which a BIM approach could be based. The case studies were conducted with individuals from the firms of: Foster + Partners, Specialist Modeling Group, London office; SHoP Architects PC, New York City; and SOM (Skidmore, Owings & Merrill LLP), Computational Design Group, New York City.

Foster + Partners.

Starting in the late 1990s the Specialist Modeling Group (SMG) was formed at Foster + Partners. Beginning with the Greater London Authority (GLA) building in London the SMG, under the direction of Hugh

Whitehead, began employing a technique termed the *Geometry Method Statement*[24]. The intent of the Geometry Method Statement was to facilitate better coordination during construction by actively involving contractors in the derivation of the overall building geometry[25]. Since then, this technique has been repeated on a number of other projects[26].

Geometry Method Statements rely solely on "first principle" descriptive geometry, and intentionally avoid the use of CAD-based terminology.

"It's a very clear way of communicating; they [the contractors] *don't have any* [technological] *problems translating it."*[27]

By eliminating the technological dependency that would be inherent to the use of CAD software, the SMG believes the use of Geometry Method Statements gives them a strategic advantage over competing firms such as Gehry Partners. In the opinion of the SMG, Gehry Partners use of their own proprietary CAD software, Digital Project[28], limits Gehry Partners to working with a smaller number of consulting and contracting firms. The SMG believes the step-wise diagrams of the Geometry Method Statements communicate to contractors and consultants a clear understanding of the relatively simple procedures to derive what might otherwise appear a

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[24] For an example of a Geometry Method Statement, see "Laws of Form" [27] p90.

[25] "By requiring contractors and fabricators to develop their own models from first principles, the problems that typically occur in data translation between different CAD systems were avoided. More importantly, the process transfers accountability from the design team to the suppliers, because each works with a digital model built specifically to fabricate and assemble their own components."[27] p91.

[26] Because the Geometry Method Statements rely on 'pure' geometry, they can only be used on projects whose overall geometry can be composed of lines, planes, and arcs.

[27] Interviewee, Foster + Partners

[28] Digital Project was developed from CATIA (Computer Aided Three-dimensional Interactive Application). CATIA is a CAD/CAM/CAE suite of software originally developed for the aerospace industry by the French company Dassault Systemes.

complex shape. The SMG believes the statement makes the project “less scary”[29] resulting in a greater number of contractors and consultants willing to bid on the project. And with more people bidding on the project, competition is increased, and the resulting construction cost is assumed to be lower.

The learning-by-doing approach has also proven to be an important aspect of the Geometry Method Statement.

“If we don’t give a [completed] *model…we will actually force whoever is on the other side - the receiving end - we will force them to draw it themselves and to start to understand the geometry, and its kind of an educational process that you make sure that your contractor...whoever has to build this building has a clear understanding of what the geometry is....we think that's actually quite important."*[30]

The pedagogy of this approach is now also being used internally at Foster + Partners. The SMG feels it is equally important for the design teams at Foster + Partners to have mastery over their respective projects. This requires the ability to rationalize and understand the geometric foundations of the work they are doing. Therefore, rather than having the SMG produce the Geometry Method Statements, each design team is tasked with producing their own Geometry Method Statement. Quoting again from my interview with the SMG:

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[29] Interviewee, Foster + Partners
[30] Interviewee, Foster + Partners

"We often want the [design] *team to do it because then…it forces them to think about the geometry and to 'pure it out' even more."*[31]

In addition, the ability to validate a derivation is embedded in the process. By asking for certain dimensions not explicitly given, Foster + Partners can verify the conformity of a completed derivation. If a contractor returns dimensions which match those of Foster + Partners, the derivation is considered to be accurate. Given the similarity to the experiments I had conducted, I asked if and how the Geometry Method Statements were verified for comprehensibility prior to being issued to outside parties. The interviewee indicated that each Geometry Method Statement was tested in-house by at least one other person. Typically this test subject would be someone who did not have prior knowledge of the project. The test subject would attempt a derivation of the Geometry Method Statement and provide feedback regarding any confusion or additional information they felt necessary. In the opinion of the SMG, a proper Geometry Method Statement should provide clear diagrams and just the right amount of dimensioning and textual annotations to be fully constrained[32].

SHoP.

SHoP Architects PC is an 80-person office in New York City that was founded in 1996 by five partners. The goal of the office is to establish a new model of practice in architecture that leverages design, finances, and technology "…not only to produce innovative architectural forms but to streamline the design and construction process and create new efficiencies

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[31] Ibid.

[32] In a fully constrained system, the outcome of the system is determinate and unique based on the constraining requirements. An under-constrained system is indeterminate because it does not fully resolve all of the degrees of freedom present in the system. An over-constrained system is also indeterminate because of the presence of two or more contradictory constraints (i.e. a line is assigned two length dimensions).

and cost-savings."[33] SHoP uses several different CAD packages on any given project. I began the interview asking about why they take this approach:

> *"…it's really just understanding at which scale each* [software] *platform operates, and then taking advantage of that. That's really how we try to use the software. We think about it as tools, I mean, I always make the comparison - I'm not going to try and hammer a nail with the back of chisel, I'm going to figure out what works best and that's what we're going to use."*

The intent is also to eliminate any communication gaps between design and construction. SHoP will "…find out what the industry is using, find out what the fabricators use...so we can communicate, so there isn't a language barrier there." [34] SHoP will also regularly consult with contractors and fabricators during the design phase of a project. This is done in order to determine the likely means and methods that will be used during construction and incorporate this knowledge into the design process. This is referred to as a 'design-assist'[35]. If SHoP gets geometrical or other quantifiable feedback during the design-assist they may encode those rules directly into the CAD models as parameters. This process was explained with respect to one of their current projects:

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[33] SHoP website: http://www.shoparc.com/ (last accessed May 13, 2008).

[34] Interviewee, SHoP.

[35] This is not a binding relationship that guarantees that particular fabricator will be hired when it becomes time to bid the project. However, given their familiarity with the design elements and the overall design goals through their interactions with the designers, SHoP is more likely to trust their bid price and recommend the use of that fabricator to the client and general contractor.

“In Revit, we have our levels and our grids, and then we made a couple little custom families to understand dimensions, kind of establish a zero-zero system, and then all the planes are made in Digital Project to construct the geometry off that. So that family exports its parameters to an Excel spreadsheet, and then a bunch of planes are made off of that. So if we change the levels or change the grids, we just re-export it, because Revit can't do that on its own."

For another project where the coursing of a brick façade was designed to create the appearance of irregular undulations, SHoP employed a similar approach:

"We modeled [the façade], *we figured out the logic in software like GC and Digital Project, or even AutoCAD and Rhino, just understanding what was going on, and it really was just a simple rule for how much one brick could jump over. Then we just kind of gave them* [fabricators] *those rules and they remodeled it."*

I asked why the fabricators would remodel the geometry if the design rules had already been encoded into a digital model:

"They were milling the form-liners, so it was kind of on them, they were liable, so they did it, they rebuilt it all."

The desire of the fabricators to rebuild the façade geometry as a result of their liability suggests that they did not feel comfortable creating the building elements they were responsible for without first re-creating the design concept. This indicates that the fabricator needed to understand how the design model was produced through hands-on experience before they could translate the concept into physical parts. Recalling the model Shannon and Weaver developed in communication theory, the fabricators should have been able to receive the design message without the need for additional work. Instead, the fabricators followed a process, very similar to the one modeled by Peirce, of constructing meaning within the context of the project.

However, collaboration with fabricators and other consultants during the design process is not always possible, and therefore SHoP often has to assume the means and methods of construction during the design phase. Government projects prohibit design-assists because of the unfair advantage it would give those consultants during the bidding phase. An example of how this affected another project was discussed:

"That was a huge project where we couldn't bring in fabricators early, and after the fact, after we designed it on a 2ft increment we found out about the actual means and methods… we just didn't know who they were going to hire or how they were going to do it, but had we known that we probably would have embedded it [the particular fabricator’s rules in the design parameters]. *But in the end I really don't think it's on us* [the architects] *to figure that stuff out. I think we have to hint towards it, and say that's what we plan to do, but then...maybe one guy’s got a connection with one form company, and another one with another, so it's tricky, especially on big projects where* [the contractor] *has to do an open bid."*

SOM.

The Computation Group at SOM provides an internal computational consultancy for the firm. The group is comprised a small number of people. Members of the Computation Group work either in a consulting role on discrete problems or get embedded with a project design team. A related group at SOM, the Digital Design Group, focuses on the development and application of Building Information Modeling (BIM), which they define as virtual design and construction. The Computation Group and Digital Design Group use several CAD programs for design and analysis. Similar to the other case studies, a lot of the work done by the Computation Group relied on processes of making and re-making:

"Even within SOM, within the design team, sometimes we need to make different models for different applications. For example, for design models for renderings, I want to have a lot of detail in the model, and all the correct thicknesses, but if I'm creating a 3d print, I want to use the same design, but I need to make some adjustments. I can't use the same amount of detail, there needs to be less detail. Maybe I need to exaggerate some of the members because otherwise they won't print in the 3d printer. So I can either rebuild my model, or maybe adjust of the parameters in my application."

The fact that these processes of repetition were an important aspect in developing a particular design concept was clearly understood. For this interviewee, a predilection for this way of working has had a direct influence on their preference for design software:

"One reason why I say I like to use AutoCAD – it’s not a very smart or sophisticated program, it's very simple and dumb - but you could say that's the good thing about it, I have to do everything myself, but then I could use that [understanding] *anywhere else."*

In practice, the Computation Group manages interoperability through relatively typical means. They rely on widely available data transfer formats to transfer information between software. It was noted that this is not ideal since many of the most common exchange formats, such as DXF[36], can sometimes alter the design models in undesirable ways.

"A lot of the analysis tools we're using require their own model formats, and translating, using DXF for example, is not always the best way… sometimes it adds information that’s not necessary like, for example, if I have a model that’s not triangulated, sometimes the program will triangulate it because it doesn't want to make an assumption that a four-sided plane is going to be flat...so you end up with twice as much data as you really need."

Another option the Computation Group will regularly employ is to recreate the geometry in each software environment as needed.

The Computation Group also uses on scripted algorithms for the derivation of geometry. Many of these scripts are written in AutoLISP by Neil Katz, the head of the Computation Group who has more than 20 years experience at SOM. Katz is mainly self-taught in AutoLISP and relies on this method because of his comfort and facility with the scripting language. However, as with the majority of scripting languages, these scripts are software specific. Even though the script is based on a step-wise set of logical statements, it cannot be automatically converted to other scripting languages. The data structures created for, and used by, proprietary CAD software effectively prohibit the automatic regeneration

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[36] Data eXchange Format.

of geometry in the native file format of different platforms. Recently, the Computation Group began exploring alternative means communicating design information very similar to the Geometry Method Statements of Foster + Partners. During the design of the spire for the Freedom Tower in New York City the Computation Group created an annotated diagram which they sent to their steel fabricator in lieu of a digital model. The situation was similar to the SHoP example:

“[The engineer] *didn't want the geometry because he was going to be rebuilding it anyway and he needed the parameters to rebuild it in his analysis program…so I sent him the instructions as a PDF file so that he could look at it visually.”*

6. Computer Aids to Design

With respect to computer aids to design, it is important to make the distinction between the *act of design* and the *result of design*. To design - as a verb, is the act of creating, planning, or calculating in service of some desired outcome. When designing certain discontinuous jumps in logic and intuitive decisions may occur (for instance when designing a house, the desired outcome is a design for a house, not a horse). These result from the unrestricted seeing and thinking and doing of the design process.[24][18] However, a design – as a noun, is the resultant of a design process. A design can, should, and typically must be analytically rationalized into a series of discrete procedures by which it will be made. There may or may not be a direct link between the design process and the making of a design product. Production systems capture the above as a series of states and transitions between those states. Many of the popular computational schemas used in architectural design today (such as L-systems, Cellular Automata, and Genetic Algorithms) are variations of classic production systems. I speculate that one of the main drivers behind the development of these systems was technology and not design. What this means is that these methods were developed to explore the range of computational possibilities that digital computer technology had to offer, rather than as a catalyst for a critical discourse on design and design aids. To better understand how these systems operate it is worth a general review of the various data structuring[37] methods employed in CAD systems.

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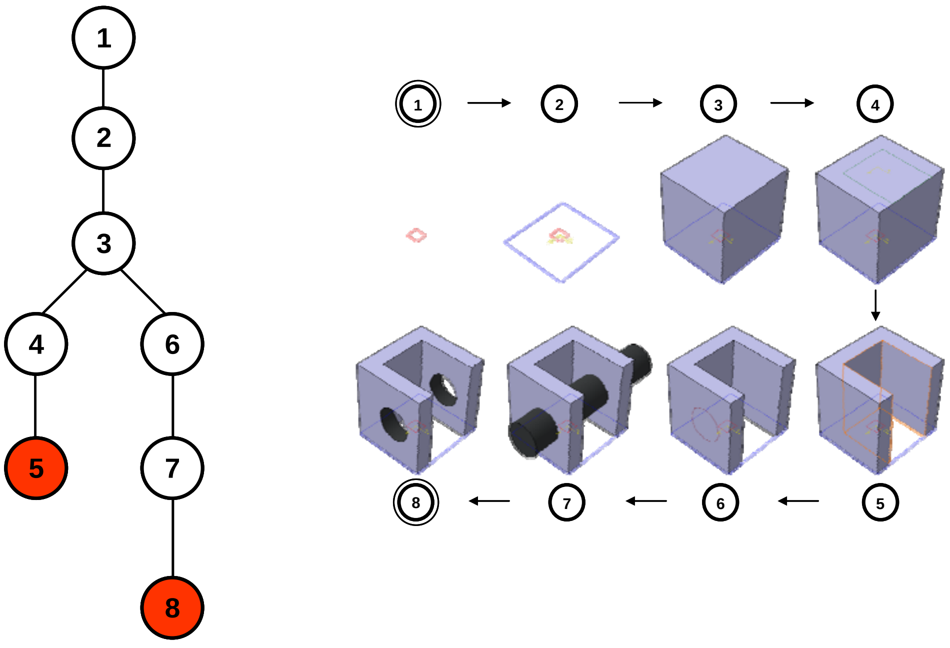
[37] A data structure is a way of organizing and storing digital information in a computer file. Typically, data structures are specific to the software to which they are in service. “The format of a digital object must be known in order to interpret the information content of that object properly. Without knowledge of its format, a digital object is merely a

Generally there are two types of computer modeling strategies used in CAD: history-based and history-free. History-based strategies record and create explicit hierarchies based on the order of operations the user employs in the derivation of geometry. This ordering is captured as a series of nodes in a directed graph referred to as the “history-tree”. The directed nature of this graph defines the topological hierarchy among all the elements of the model. This means that in a history-based system, the user is constructing a series of logical relations between a set of dependent and independent variables (from which a form is derived) rather than directly manipulating geometry.



history / specification tree

derivation sequence

Figure 5. Derivation of an arbitrary shape (right), and the topological hierarchy of the order of modeling operations (left).

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collection of undifferentiated bits.” Global Digital Format Registry, “About Global Digital Format Registry”, October 7, 2006, http://hul.harvard.edu/gdfr/ (last accessed May 21, 2008).

History-free systems do not maintain a record of modeling operations. Users of history-free systems work directly with geometry. The evaluation of a shape is instantaneous and not based on the prior elements or operations used in its derivation. In history-free models, the geometry remains persistent while geometric relationships are subject to change. Restated, in history-free modeling what you see is (more or less) what you can get.

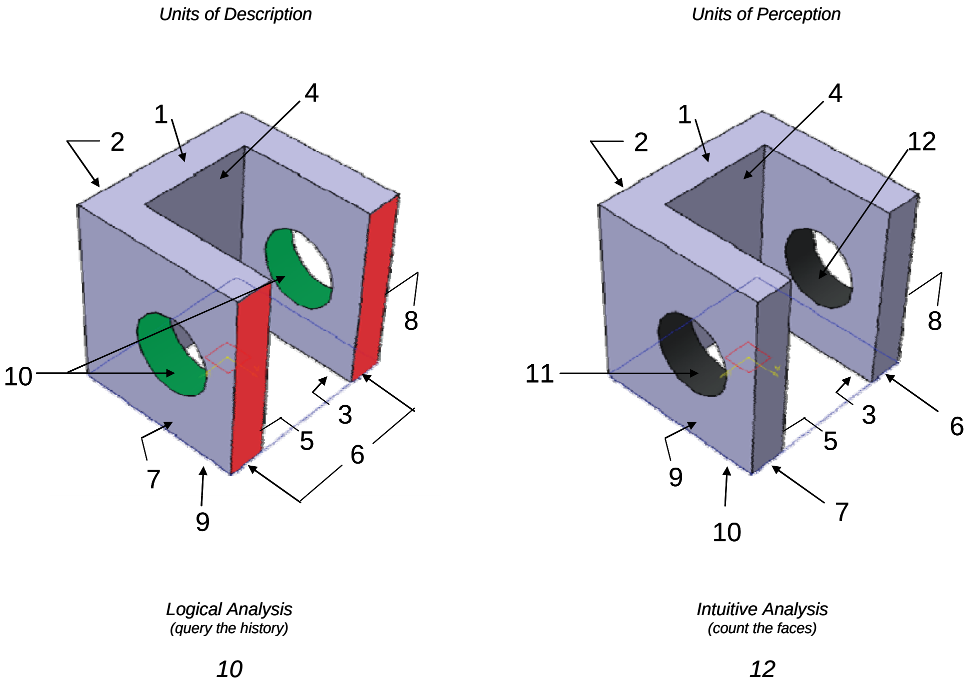

Figure 6. Topological comparison of the shape in Figure 5 as a history-based model (left), and a history-free model (right).

Changes made to history-free models are not dependent on the previous order of operations used in the derivation of the model. In a history-based model, the geometry is variable while the topology (explicit relationships between the elements, or graph nodes) remains fixed and constant. The focus on topology over content is a similar model to Shannon and

Weaver’s model of communication theory. In their model, the relationship between the source and the receiver by way of the transmitting medium was given greater consideration than the content of the message being transmitted. Figure 6 shows the topological difference of a single shape created in both history-based and history-free software. The process of derivation is shown in Figure 5. The history-based derivation is topologically defined as having only ten faces, while the history-free model is defined by twelve faces, which is the conclusion one would arrive at by simply counting the faces. The un-intuitive topology of the history-based model results from the order of operations used in its derivation. Because the shape was initially defined by a cube (Step 3, which was the extrusion of a square – Step 2) the faces of the two ‘arms’ of the shape are children of the parent feature, which was a single face of the cube. Therefore, this remains one single face, not two. In history-based modeling, what you see is *not* necessarily what you can get.

Modifications to a history-based model are made to the values assigned to the variables or to the logic of the system, but not to the geometry directly. Formal changes result from the re-evaluation of the system; however changes which violate the topology of the system are impossible. Figure 7 depicts the limitations to modifications that can be made to the history-based model from the previous example. Because the visually distinct faces of the two ‘arms’ of the shape are topologically one single face, it is not possible to modify just a single face. Those familiar with computer modeling might suggest the creation and Boolean union of another solid element to this arm as a way to work around the topological restriction. While this might solve the immediate problem, such approaches quickly generate a topological rat’s nest that becomes completely unmanageable.

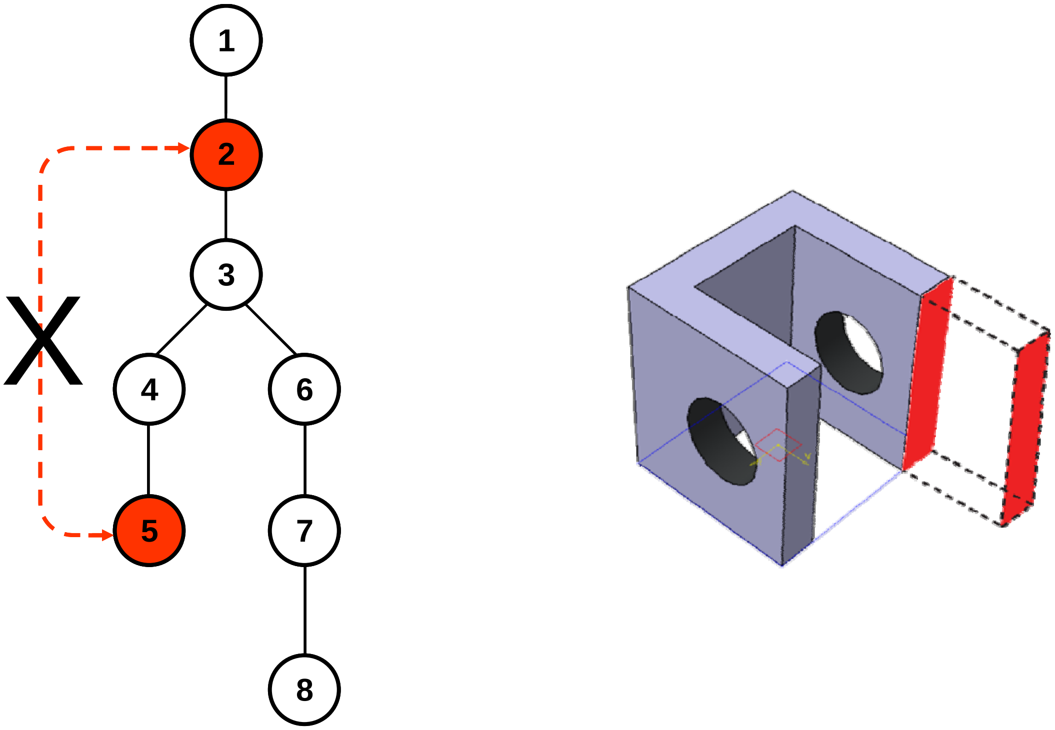

Figure 7. If a change needs to be made to an aspect of model not represented by some node or set of nodes in the tree, then the model would need to be rebuilt in a way that would accommodate that change.

Because of their explicit associative-dependency, history-based systems are often mistakenly considered a necessary precondition of a ‘parametric’ system. This is a misleading statement, and another example of the problems that can arise from the superficial integration of tools developed for and by other industries. A parametric system is any system which provides for the assignment of independent, arbitrary variables (either set values or functions) from which the instantaneous value of a particular entity or entities is derived. The ability to define parameters is not determined by the history-nature of CAD software.

The development and use of history-based systems in other industries is based on the fact that the processes employed to generate form may be more significant than the resulting form itself; this is not necessarily the case in architecture[38]. In architectural design, the rationale behind a model's structure may be the result of individuals' modeling habits, a lack of modeling ability, or based on very particular design intentions. Referring back again to the modeling example in Figure 5, the steps used in the process of derivation were arbitrary, and not carefully considered. It was just a quick and easy way to make the shape, which later proved to be very problematic. Theoretically there is no way I could have known in advance that I would later need to be able to modify the shape in a way that was topologically impossible based on that initial process. The history-tree captures and enforces the logic of the system, but the reasoning as to why that particular logic was used is not part of the system. This means that if I had employed the process of derivation shown in Figure 5 in order to intentionally constrain the model in this way, there would be no record of why. Therefore, even if the model and its topological definition were successfully shared with another designer or

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[38] Current initiatives towards process representation, such as the work on Building Model Repositories and Product Model Repositories being led by Chuck Eastman and others at the Georgia Institute of Technology, rely on the use of the carefully controlled use of a standardized, formal language to encode design methods. These methods are useful and effective for clearly understood and well-defined problems, the variability of which is constrained within predetermined limits, in much the same way that associative-dependency chains unambiguously bound the variability of "parametric" computer models. Malcolm McCullough nicely states the problem this way: "Parametrics work better in domains whose subject matter is engineered form itself – especially in mechanical components for complex assemblies such as vehicles. Parametric design works less well where physical configuration and performance are just the means, and a more emergent usage pattern is the end. Or, to put it the other way round, when the subject matter of design is more the social arrangements and less the mechanical assemblies used to house them. Parameterisation breaks down when the design problems are wickedly under- or overconstrained, or where the design variables are less obvious. Compared to an aeroplane part, even the aforementioned rote hotel room is less computable."[12 p14-15]

consultant, they would still have no way of knowing whether the topology was meaningful or arbitrary. Furthermore, the ability to exchange data structures between different CAD software is a non-trivial problem, and at the heart of the problem of technological interoperability. Most file formats do not provide for the exchange of explicit topological hierarchies or parameters. This will be discussed in greater depth later in this chapter.

The usefulness of associative-dependency based models is that they allow designers to explore the extent of a particular derivations topological variability, or logical bounds. Somewhat paradoxically, it is the fixed and unambiguous nature of the data structuring behind these systems that provides for a certain amount of design exploration. While often lauded for their 'flexibility', it is these same explicit data structuring requirements of contemporary CAD software that also distances the designer from the "indispensable immediacy"[39] of the design medium.

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[39] The term "indispensable immediacy" was used by Pegor Papazian in his 1991 Master's Thesis, *Principles, Opportunism and Seeing in Design: A Computational Approach*.[32 p45] Quoting at length: "Not all the intentions and constraints resulting in the creation of components (and their relationships) in a design document are made explicit in it. A computational system which compensates for this apparent shortcoming by extensive annotation and constraint management, runs the risk of losing the indispensable immediacy of the designer's interaction with the document. Due to the overwhelming ubiquity of constraints, the designer needs not only the ambiguity of a document (an intersection of lines can be a cross or two L shapes) but also the arbitrariness inherent in it (a line which could satisfy the relevant constraints by being anywhere within a range of locations, is actually placed in one particular location and the designer's subsequent interactions with it are a function of that particular location)." Bill Mitchell also addressed this topic in 1995 in his book *Digital Design Media*.[14 p376] Quoting at length again, "It makes little sense, then, to attempt organization of a design project around a comprehensive, fully integrated, three-dimensional assembly model from the very beginning – as many of the pioneering integrated computer-aided design systems attempted to do. The demands of this representation tend to force a designer's attention to issues that are irrelevant at a particular stage of consideration and deflect it from issues that are more crucial." And well before both of them, Vladimir Bazjanac came to exactly the same conclusion after working with computer aids to design in the 1970's: "The experiment [to test theories of the inability of CAD to make designing more efficient] confirmed that the use of computer-aided models in a design only distracts the designer from his original task of designing the building."[3 p23]

As indicated, the notion that design *intent* can be embodied in the geometric and mathematical parameters of a computer model is also incorrect. First, as shown in Chapter 3, architectural documentation does simply represents what the design concept is, not why it is the way it is. The difference is subtle but important. A design concept is an abstract or theoretical construct that embodies the essential attributes of the design ideas represented: the "what". Design intent is the meaning or purpose of a design: the "why". The correlation with the various models of communication presented in Chapter 2 should be fairly clear. To state that rule schema capture intent is to equate topology with meaning or as Shannon and Weaver and Saussure would assume signifier with signified. As shown in the shape derivation examples above, meaning cannot be encoded and topology cannot be assumed without explicit knowledge of the process of derivation.

An early proponent-turned-critic of CAD, Vladimir Bazjanac stated, "Information used in the design process always can be and usually is subjected to personal interpretation. That interpretation is more significant than the objectiveness of the reliability of the information itself."[3 p22] If something as simple as the dimension of a line could embody design intent, then the shape experiments in Chapter 4 should have been easy for people to do, and all the results should have been consistent. As the evidence shows, this was not the case.

Proponents of a technological solution to the problems of the individual interpretation (ambiguity) of information and interoperability in the AEC industry advocate a new model for communication known as Building Information Modeling (BIM). BIM is organized around the idea a single, unambiguous ‘master model’ which contains every piece of project information. The efficacy of BIM is based on the creation of an explicit framework through which a standard set of data structures can be shared. Built on a relational database model[40], project members (including architects and contractors) would be able to isolate and extract sub-sets of information for design, analysis, and coordination. All of this is predicated on creating and storing project information in a carefully controlled data structure. The current model of this data structure is called the Industry Foundation Class (IFC) model[41]. Given the amount of historical evidence that such a model is not useful in design or communication, it is surprising that such models continue to be favored by technologists. But faced with the problem of interoperability, what would a good solution be? It all depends on what the “problem” of interoperability really is.

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[40] Relational databases, including the IFC framework, often rely on ‘views’ as a method for isolating and co-locating subsets of information. Views do not resolve or create explicit relationships between the particular sets of information being displayed, rather “…the data that you access through a view isn’t dependent on the structure of the database. To illustrate, suppose a view refers to a table that you’ve decided to divide into two tables. To accommodate this change, you simply modify the view; you don’t have to modify any statements that refer to the view. That means that users who query the database using the view don’t have to be aware of the change in the database structure, and application programs that use the view don’t have to be modified.”[33, p352]

[41] IFC was developed by the International Alliance for Interoperability (IAI), an international consortium of commercial companies and research organizations founded in 1995. The actual development work is carried out by a six member group known as the Model Support Group. For a general explanation of the IFC model see, “The IFC Building Model: A Look Under the Hood”, online article; Khemlani, L. AECbytes Feature, March 30, 2004. http://www.aecbytes.com/feature/2004/IFCmodel_pr.html (last accessed May 19, 2008.)

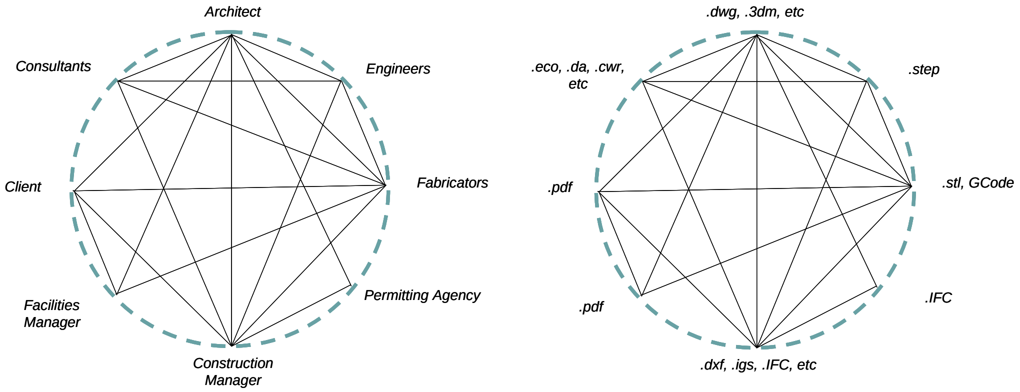

Figure 8. Interoperability is typically presented as a people issue (left), but in reality it is a file extension issue.

Interoperability. Commonly, the problem of interoperability is framed as a problem of communication among an ostensibly disorderly network of AEC roles and responsibilities. With respect to technology, the actual problem is one of exchanging information between a network of different file formats and data structures. As my interviewee at SOM indicated, the problem with data conversion is not simply one of information lost, but also one of unwanted information gained.

McGraw Hill Construction Research and Analytics reported in 2007 in *Interoperability in the Construction Industry, Smart Market Report - Design and Construction Industry* that an estimated 3.1% of total project costs are spent addressing issues associated with interoperability. Manual re-entry of data was ranked as the main driver of increased costs due to problems with software interoperability. “Less time drafting more time designing”[28] was rated as the most significant factor influencing the desire to use a BIM approach (later in this chapter I will present evidence that promises of the ability of computer aids to design to fulfill this goal have been made since CAD was invented). Ranking third on the list of factors influencing the adoption of BIM is “BIM’s Ability to Improve Communication with Clients/Others in Design and Construction Process”.[28] My research indicates that one of the most significant improvements to communication is not the conceptual framework behind BIM, but simply the 3D visualization of various building components concatenated in one model[42].

The degree to which digital information may be repurposed is directly related to the technological independence of the information. However, since the use of technology in the AEC industry is ubiquitous, the default solution is to try and impose standards. This is a generic problem in many technology-dependent industries. Quoting from The Irwin Handbook of

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[42] When asked about how work was being coordinated on a large project which involved several different contractors and sub-contractors, the person I interviewed at SHoP indicated, “They’re going to coordinate it all in BIM…it will be 3D coordinated. They'll do the construction BIM process, so, architects are…coordinating things to a certain extent, but they still can't tell them [fabricators] how to build it. We're [architects] just saying we're guaranteeing that we know it fits. We designed it in a way that its coordinated and we know that you can get all this stuff in here, but if the mechanical guy comes in and says ‘that's not the most efficient way for me to build this’, we can't force it. What we're doing is a diagram of how the systems work within a certain space, but then when it gets to means and methods, we can't tell them how to do that. So then there is a whole construction coordination process that goes on, and that's with the guys who sit over light tables with all that spaghetti stuff on a sheet and they say, ‘top of thing here and bottom of thing here’. But now its all happening in 3d. They model it based on shop drawings. We're doing that on a another project, we're offering a construction service where we're modeling all the shop drawings, but this is after our design contract is finished. We take all the shop drawings, and instead of just checking them [visually in 2d] now we're modeling them, that's our whole checking procedure. And then we're going to run collision detection on all the systems and see where there's clashes and interferences which will allow them to prefabricate more and put the systems up in pieces.”

Additional evidence was found in an article regarding the design and construction of a new US Courthouse in Rockford, IL. Kirk Stuaan of the design firm PSA-Dewbury stated “BIM is a great visualization tool, but it does not replace the dialog that needs to occur between team members within a given discipline. While the communication does not always happen as it should, there is no disputing the value of *seeing* the actual elements in the 3-D building space.” (my emphasis) [29].

Telecommunications: “The desire for standards and the desire for technical progress can often conflict because standards can not be set until technology has been proven through practice, and the only realistic way to validate that proof is through extensive and widespread use that has not yet been standardized.”[6 p17-18]

The majority of attempts to resolve this problem in design technology can be categorized as follows: committee-based, standards-based, market-based, and open-source. Committee-based solutions such as the Initial Graphics Exchange Specification (IGES), and the STandard for the Exchange of Product model data (STEP) have suffered from the retarding effects of bureaucratic decision-making, slowing their ability to keep pace with rapid changes in technology. Attempts to create industry standard data structures by commercial geometry kernel providers have failed due to the equalities of their readily available, high-quality products (ACIS, Parasolid, etc.). Market-based approaches by software vendors in the form of all-in-one CAD/CAM/CAE packages such as CATIA (and now the Autodesk suite of products) result in prohibitively expensive software and licensing costs, and the need for dedicated experts to operate the software with no guarantee of the software being the best choice for every job. Because no single obvious standard has emerged for digital modeling, affiliate programs through which software developers encourage third-parties to develop additional software functionality via plug-ins and APIs (Application Programming Interfaces) have not been widely effective. The most recent standards model is the aforementioned committee-based Industry Foundation Class (IFC) framework.

***BIM and The Toolmakers Paradigm*[43]. ***The Toolmakers Paradigm* is a story that functions as an analogy to draw out the implications of those models of communication which assume that symbols and their meanings are determinate and unambiguous (i.e. Shannon and Weaver, Saussure). In the beginning of *The Toolmakers Paradigm,* Michael Reddy suggests that when communicating, we are like people isolated in slightly different environments.[34 p171] In the story, he envisions a circular compound which is broken up into discrete pie-shaped sections. The environment in each section is slightly different, and there is only one inhabitant in each section. The only means of communication between sections is through an abstract piece of machinery at the center of the overall compound which can only deliver small sheets of paper from one environment to another. In my research, this is the exchange of architectural documentation. Reddy tells us that the inhabitants use this machinery to exchange “crude sets of instructions” for making things useful to their survival. Reddy stresses that the inhabitants do not have knowledge about the environments of the other sections or their inhabitants. In the AEC industry, although the various domains are closely related, as are Reddy’s toolmakers, they do not necessarily have a clear understanding of each others’ roles and responsibilities.

Over the course of the story, the inhabitants attempt to send blueprints for the making of tools they have created and which they find very beneficial in their environment. Implicit in the blueprints are certain assumptions about the other environments, such as the availability of common materials with which to construct the tools. This is not the case. Confusion ensues and further assumptions are made about the lack of each neighbors’

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[43] See [34].

intelligence. However, after much frustration the inhabitants begin to think that perhaps all is not the same elsewhere in the compound and, taking this into account, adjust the way they communicate. Rather than assuming the meanings of their messages are unambiguous the toolmakers begin to annotate their diagrams to indicate the type of materials they have used in making their tools. Additionally, those in receipt of the instructions also begin to annotate and return the instructions where they find the instructions unclear. This process of design and constructing meaning, of making and re-making, is a clear example of the effort necessary in any successful exchange of information. This is the model Peirce was describing and Papert was observing in how people learn. The toolmakers' method of validation is directly analogous to the professional obligations of architects and contractors described in Chapter 3. All parties involved in design and construction projects not only interpret the conceptual information they receive but must also prove, or validate, their interpretation. They do so by re-presenting information as a series of fabrication and construction procedures.

But the story doesn't end there; Reddy later introduces an evil wizard who casts a spell of forgetfulness on the toolmakers. Under the wizard's spell, after completing the construction of a tool, the toolmaker to instantly forgets that it was they who built the tool. Instead, the toolmaker believes that the completed tool was received intact from another toolmaker through some new trickery of the compound's communication machinery. Because the toolmakers could no longer recall whom it was that constructed the tools, they lost any sense of responsibility for its craftsmanship. As a result they began to blame their neighbors for defects in construction. Furthermore, without the ability to develop a sense of pride or achievement in the results of their toil (since they could not recall that it was their seeing and thinking and doing that created the tool to begin with), they spent less time and effort constructing the tools. This led to greater defects, more blame, and even less effort. Reddy concludes the story by stating that “Human communication will almost always go astray unless real energy is expended.”[34 p174]

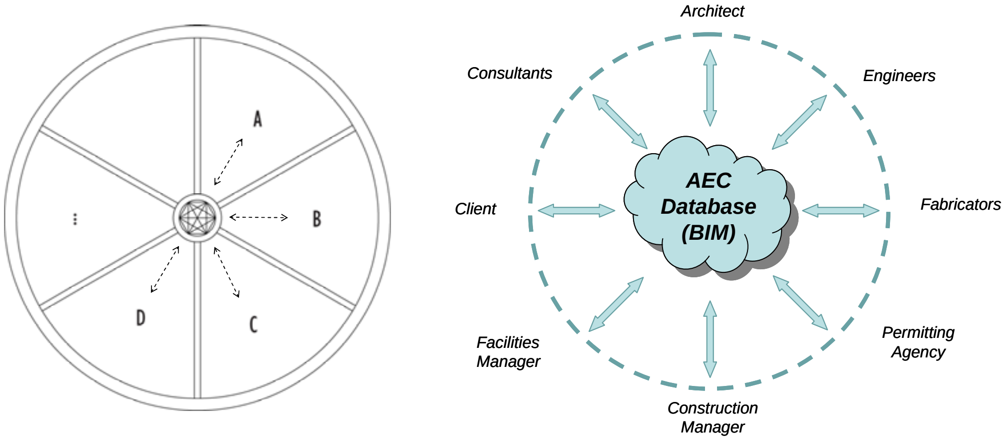

Figure 9. Diagram of the compound from The Toolmakers Paradigm (left). Diagram of the database (BIM) solution to interoperability for the AEC industry.

Reddy explicit notes the failure of Shannon and Weavers model to account for ‘radical subjectivity’ by assuming the indivisibility of signifier-signified relationship. As Reddy points out, “Signals *do something*. They cannot *contain* anything.”[34 p172, 184] It is interesting to note then, that the diagrams most often used to extol the benefits of BIM) in design and construction communication are almost identical to Reddy’s diagram of the Toolmakers’ compound (Figure 9). Based on the case studies and shape experiments conducted for this thesis, such an approach is antithetical to the effective communication of design and construction information. It is not surprising then that most of the BIM “tools” being developed for architects are directed towards the product of design documentation, rather than the production of design information. The developers of such software believe that the process of making is implicit and unambiguously described by the product made. The developers of Revit Architecture 2008, a so-called BIM tool, authored an instructional textbook in which they encourage the following approach to using the software:

“Begin with the end in your mind.” [44]

Productive and Unproductive Acts. Acts of making and re-making are fundamental to the way that architects and contractors relate to design information. Architects produce a design description, or state description, of a desired object. Through communication with the contractor the design description is interpreted and translated into a construction description. The contractor’s documentation dictates the means and methods of the work to be performed, and the acceptable tolerance range of the outcome of that work. Goodman compared these various descriptions to musical scores, and their performance.[5 p218-219] While Goodman points out the positive aspects of the repetition of such performances, others see them as wasteful. For example, in the book *Architecture in the Digital Age,* Branko Kolarevic points to the automation of “highly redundant and utterly inefficient” acts of making and re-making as the promise of contemporary CAD/CAM/CAE technology.[9 p60] These promises are nothing new.

In 1975 Vladimir Bazjanac noted that one of the reasons that practitioners were (then) still enamored with computer aids to design was the general belief that, “Computer applications will ‘free’ the designer from distracting and unproductive activities and allow him to devote more time

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[44] From *Introducing Revit Architecture 2008: BIM for Beginners* [8] p15.

to design."[3 p18] These activities included the "noncreative tasks that are considered wasteful of [their] time (like drafting, manipulation of information, maintenance of an extensive information system, etc.)."[3 p18] Bazjanac had initially shared this early enthusiasm. After ten years of working with CAD technology in professional practice, his enthusiasm turned to doubt. He noted that the flexible interpretations and intuitive models of human designers were difficult to capture within the rigid framework of fixed data constructs. The importance of information to those involved in design and construction "…was not its content but *how* he used it."[3 p21] Bazjanac concluded that in practice, the importance of technology was that it provided architects with what they considered to be an objective mechanism for substantiating their design solutions. With respect to a project for which Bazjanac was tasked with creating a simulation for pedestrian circulation in a multistory educational building he noted, "What they [the designers] expected from a computer model was *credibility*, not precision."[3 p21] This suggests that by itself the presence of information and its structure do not inherently benefit design. Rather, it is how the information is used that is most significant. This is a further condemnation of those models of communication which do not address ambiguity. This conclusion is also supported by the case studies I conducted along with the results from the shape experiments.

Given that Bazjanac was writing about these issues only ten years after the introduction of CAD into the professional practice of architecture, it is surprising that the same promises are being made with respect to contemporary technology. In 2007, the developers of Revit Architecture 2008 stated that their software would allow the computer to "…take responsibility for redundant interactions and calculations, providing you, the designer, with more time to design and evaluate your decisions."[8 p7]

I believe that the nature of these assertions is indicative of a failure to understand the actual problem to which its proponents are attempting to apply technology. Implicit in all of these discussions is the assumption that any and all repeated acts in design and communication are “highly redundant and utterly inefficient”.[9 p60] My research counters this assertion, indicating that acts of making and re-making are fundamental to the way that architects and contractors relate to design information.

Within everyday practice the contractual obligations of the architect, contractor, and sub-contractors are often blurred and/or misunderstood. The requirement of contractors to produce their own set of construction documents based on the architectural construction documents is an act of seeing, thinking, and doing. This is an act or repetition which demonstrates the contractor’s ability to comprehend and comply with the design concept. I submit that any determination of the usefulness of a computer aid to design must ask the following questions: What is wasteful repetition in design and construction? And, what is productive repetition in design and construction?

Both Chuck Eastman of the Georgia Institute of Technology and Richard Sennett of MIT, the London School of Economics, and NYU have recently published on the subject of repetition in processes of design and making[45]. Eastman’s notion of making is based on pre-determined parts and systems of production, similar to the process described in Christopher Alexander’s *Notes on the Synthesis of Form*.[2] Eastman takes his examples from manufacturing assembly lines. He implies that acts of

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[45] See Eastman, Chuck... [et al.]. (2008) *BIM handbook : a guide to building information modeling for owners, managers, designers, engineers, and contractors.* (Hoboken, N.J. : Wiley) and Sennett, Richard. (2008) *The Craftsman*. (Yale University Press).

repetition are blind, mindless procedures meant to produce exactly the same result every time. For Eastman, seeing and thinking have no impact on doing, other than to screw it up. Eastman’s acts of repetition present an ideal opportunity for automation because the feedback from every discrete act can be captured in a system based on the Boolean logic of 0s and 1s; the result of the act is either right or wrong.

Sennett’s definition of the craftsman also highlights the notion of repetition; however, he draws examples from music. Sennett asserts that the repeating of actions (the playing of musical scales for instance) is a fundamental part of learning for musicians. Musicians initially use repetition to develop *tacit* knowledge by training their hands, mind, and eyes to work in concert. The goal is to gain control of the process. This is similar to the anecdote given by SHoP on their use of multiple software to develop an understanding of the rules guiding the design of a brick façade. Once tacit knowledge has been developed the goal of repetition is no longer conformity, but variation. Repetition at this point becomes iteration - a method of exploration and continued learning through subtle and controlled variations. Likewise, designers rely on iteration to study the variability of their designs, as well as to validate their proposed solution. In Sennett’s world, deviations from the expected results become opportunities for new insight, rather than problems which require de-bugging.

Repetition for Eastman wastefully consumes time and resources. Eastman’s model works because the elements on which it operates are pre-selected for their ability to make the model work. In Sennett’s example, repetition is also time and resource intensive, but it is the source of learning and knowledge, and therefore indispensable. Eastman’s assembler has its roots in Minsky’s production systems.[13] Sennett’s craftsman is rooted in the seeing and doing of Shape Grammars.[24]

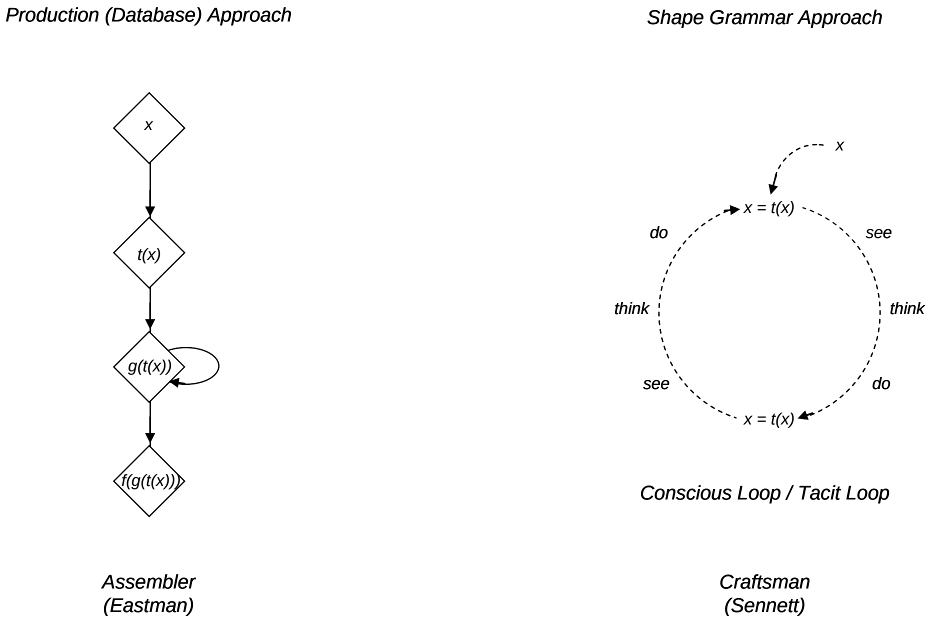

Figure 10. Productive and unproductive acts of repetition.

By determining those acts of repetition caused by particular data structures, and those acts of repetition which challenge tacit knowledge, we can assess the criteria with which to develop computer aids to design and construction. I conclude that productive repetition is generally defined as those acts which contribute to a deeper understanding of design and construction communication. In contrast, unproductive acts of repetition are those necessitated solely by technological limitations.

7. Conclusion

> “Sometimes a line is just a line. But the same line can represent the edge of a pyramid, the boundary of a field, or the path a crow flies. Knowledge about one transfers to the other.”
>
> - Leonard Mlodinow, *Euclid's Window,* p.17

The ability of a design concept to persist across representational media is fundamental to the communication of design and construction information. By moving away from material-dependent design manifestations Computer Aided Design (CAD) established a means for capturing, storing, and processing the information necessary to re-present a design object as explicit relationships between abstract-symbolic entities. However, the persistence of design information relies also on a shared culture of design and construction, not just good technology.

The introduction of CAD representations placed a new set of requirements on the producers of design information “quite independent” of the design object being described[46].[26 p75] Twenty years later, in *The Vitality of Digital Creation*, Timothy Binkley states that our ability to communicate orally with respect to digital technology lags behind our ability to use it in new and creative ways, and until “our language catches up with our

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[46] “To a large extent it has turned out that the usefulness of computer drawings is precisely their structured nature and that this structured nature is precisely the difficulty in making them. I believe that the computer-aided design community has been slow to recognize and accept this truth. An ordinary draftsman is unconcerned with the structure of his drawing material. Pen and ink or pencil and paper have no inherent structure. They only make dirty marks on paper. The draftsman is concerned principally with the drawings as a representation of the evolving design. The behavior of a computer-produced drawing, on the other hand, is critically dependent upon the topological and geometric structure built up in the computer memory as a result of drawing operations. The drawing itself has properties quite independent of the properties of the object it is describing.”[26 p75]

creativity” we will be left to “speaking about computers in paradoxes”.[4 p108] Binkley’s claim about our inability to speak of technology with the same facility with which we operate it can be construed as either a positive or negative state of affairs based on your opinion of paradoxes in design. I believe the paradoxes Binkley considers problematic are in fact fundamental to design communication. By creating representations, we externalize the division between what we see and what we (think) we know. Representational media provide us with the means and methods to explore new ideas and introduce new metaphors that suggest new ways of seeing and thinking and doing.

The exclusionary nature of any representational medium is a key aspect of it usefulness in seeing and doing[47]. Isolating, or framing, discrete subsets of design information reveal implicit or subtle aspects of the design, and design logic, that may not obvious in another context. This is both the power and danger of representation. By blocking out some information, it allows to see things we otherwise might miss. At the same time, if we do not remain cognizant of all that is being blocked out, we may lose the overall context, and thereby distort the meaning, of that which we are looking at.

What often saves us is the effort involved in the integration of mind, hand, and eye. Through the repetition of creative acts, we introduce the opportunity for reinterpretation and feedback. A mistake of the hand may open the eye to see differently and in turn trigger the mind to think of new

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[47] “A representation is a formal system for making explicit certain entities of types of information, together with a specification of how the system does this…Thus, there is a trade-off; any particular representation makes certain information explicit at the expense of information that is pushed into the background and may be quite hard to recover.[11 p21]

design possibilities. Design aids should provide the means for such decoupling of symbol and concept, enabling what Ackerman refers to as "creative symbol-use".[1] Unaided, it is unlikely that we would be capable of conceiving or recognizing uniquely new relationships that may be implicit in a design. All too often we recognize only what we have seen before, and we find only what we expect to find[48]. This is both the good and the bad of most digital design technology. Regardless of how many things you may see, the computer doesn't see anything at all[49].

Current standards-based approaches rely on this blindness by suggesting the possibility of disambiguating information through a strict data model. The problem is expert knowledge which does not fit the standardized model, or is not accounted for in the model, stands to be lost. Furthermore, a rigid and inflexible vocabulary may actually lead to the dis-integration of meaningful communication between design and construction information. There are several reasons for why these approaches are likely to fail. First, they all have in the past. Second, they are built on the assumption that meaning can unambiguously be connected with symbolic information. Third, these models assume and that individual interpretation is not necessary in the communication of design and construction. And lastly, these approaches assume that the solution must come from the formulation of a new model, rather than a new mindset.

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[48] Wittgenstein referred to this as the limitation of expectation, "Expectation is connected with looking for. My looking for something presupposes that I know what I am looking for, without what I am looking for having to exist." [Wittgenstein, L. *Philosophische*]

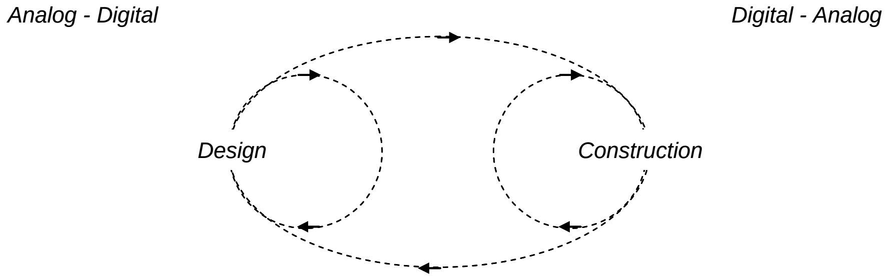
[49] "In a digital medium…the two functions of storing and displaying information are relatively independent. The fundamental purpose of a digital medium is to keep track of sometimes enormous collections of organized numbers. The numbers need to be exhibited somehow to have meaning, but since they are abstractions, they are not endemic to any particular medium of expression."[4 p110]

Architects are trained and practiced in the means and methods of design and design is an act of seeing, thinking, and making. This is the design mindset. It is an ephemeral process involving the use of the eye, the mind, and the hand. Whether it is a pencil or a mouse or a touch-screen, the design aids we employ must facilitate the work of our hands in coordination with our eyes and mind in a process of learning-by-seeing-by-doing. The role of the users of design technology must be in the productive exploitation of the unique characteristics of digital media to enhance communication.

> "In each period of our history, design and communication have evolved synchronously with the technology of the time. Each new medium has extended our sense of reality and each has looked to its predecessor for language and conventions, referencing and adapting its characteristics until its unique capabilities can be explored and codified." Muriel Cooper, 1989.

But the work doesn't end there. Once the unique capabilities of each new medium are explored and codified, it is the responsibility of practitioners (users) of that medium to reflect on its usefulness (productivity) in design and communication. The ways in which individuals to draw and model using CAD software do not necessarily contain or convey any information regarding their design intent. If digital technology is truly to be an aid to design, then it must act as a digital facilitator between the analog processes of designing and constructing. It must not arbitrarily compel designers to work within the strictures of its pre-defined data constructs if they result in unproductive repetition. It must instead facilitate productive acts of making and re-making. A complete understanding of what constitutes productive and unproductive acts is not to be inferred from this research. However, these notions are meant to be used as criteria with which to judge the usefulness of computer aids to design. The adoption of CAD software developed by and for other industries has shown benefits in the realization of complex form. However, in addition to computational robustness and formal dexterity, architects have also inherited the processes, assumptions, and metaphors of other industrial cultures embodied in the software. Like The Toolmakers Paradigm, my research suggests that the cultural assumptions embedded in such technology play a significant role in the way we understand, and employ computer aids to design and construction. And the conception we develop around our roles and responsibilities as designers and contractors has a dramatic impact on the mental models we use to interpret information.

By re-centralizing the link between seeing and thinking and doing, architects will re-join the ranks of process creators, rather than stagnating in their current role of process consumers. The implications are the development of actual computer aids to design, rather than simply digital design tools.



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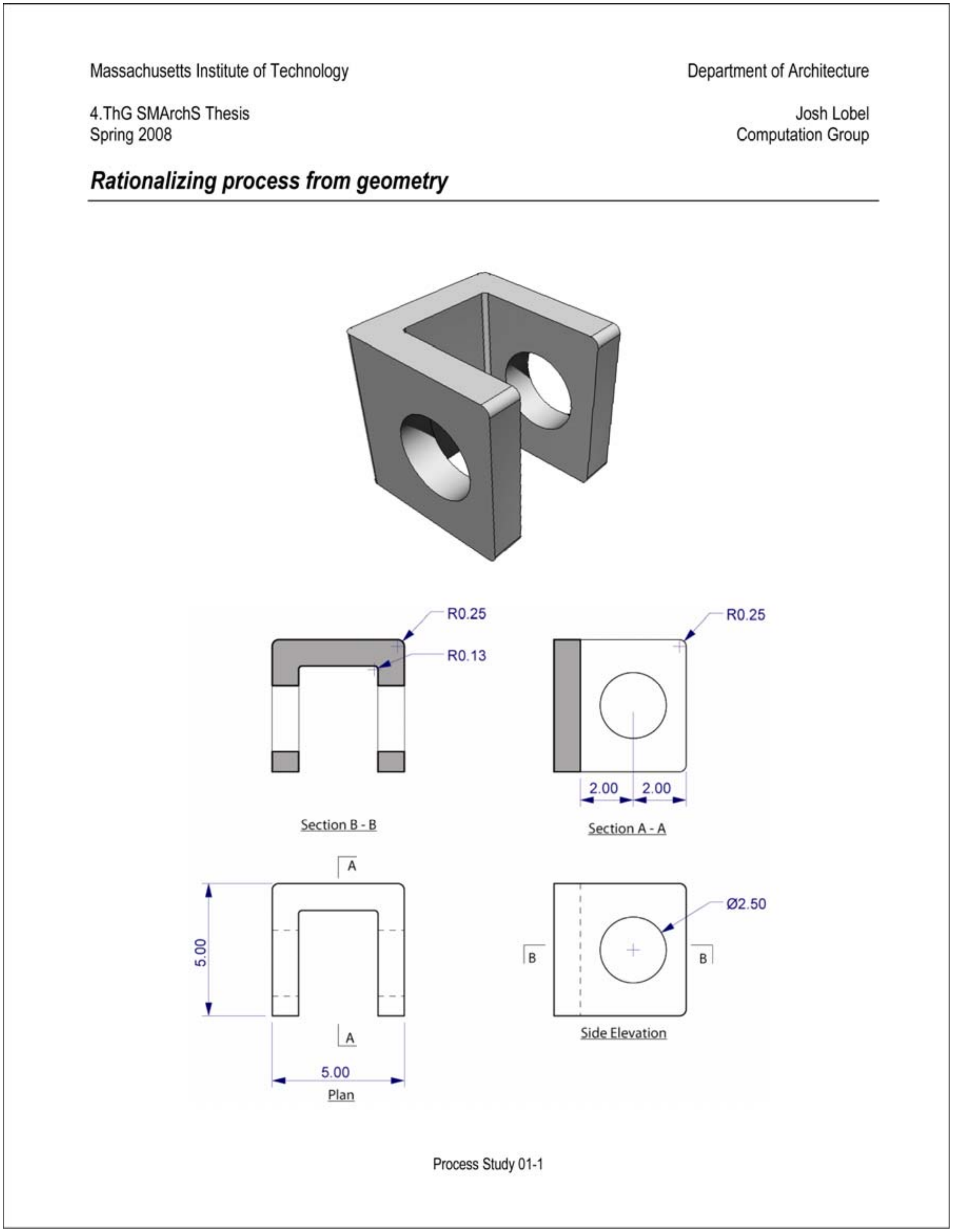
Appendix



Massachusetts Institute of Technology

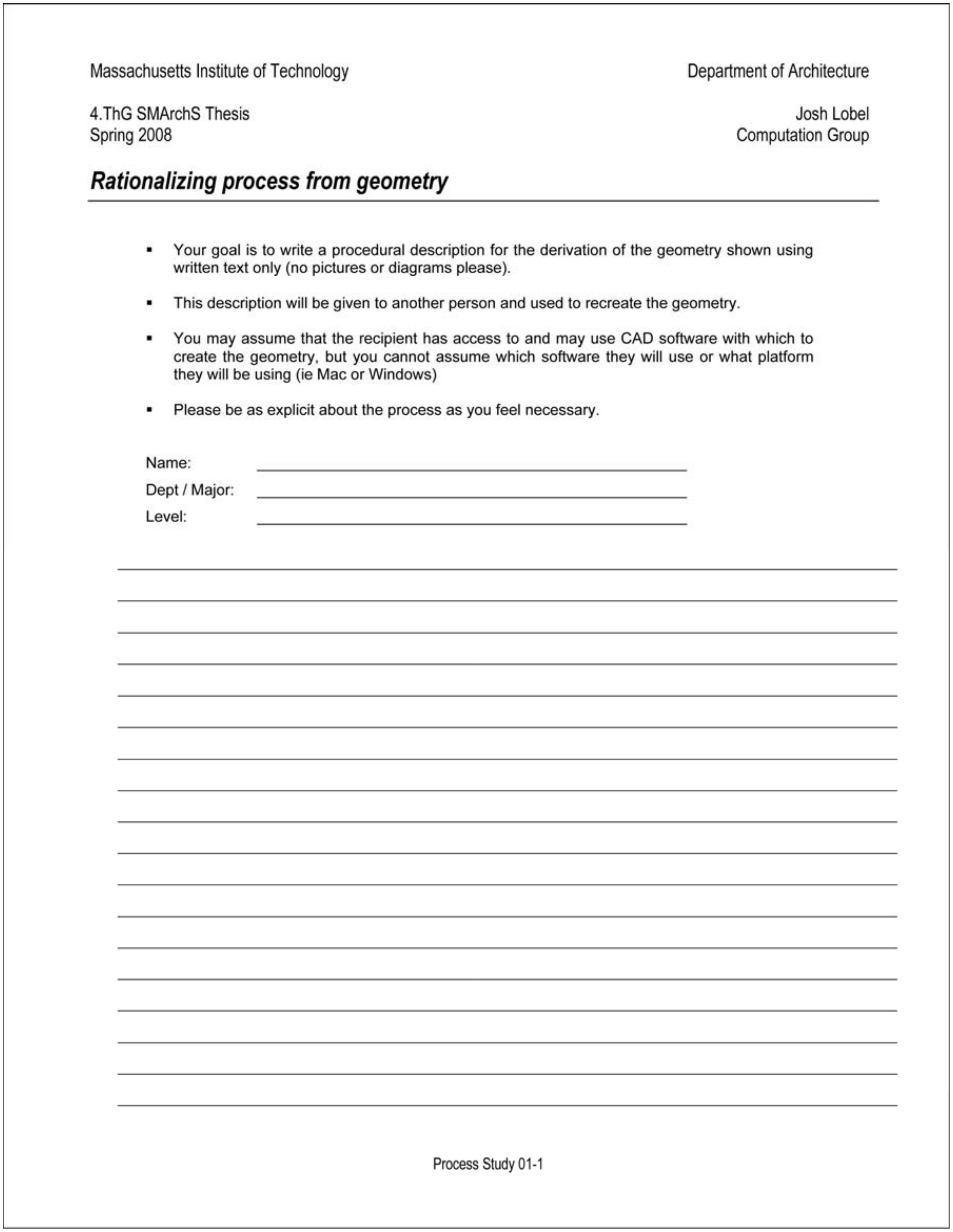
Department of Architecture

4.ThG SMArchS Thesis
Spring 2008

Josh Lobel
Computation Group

Rationalizing process from geometry

Process Study 01-1



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Rationalizing process from geometry

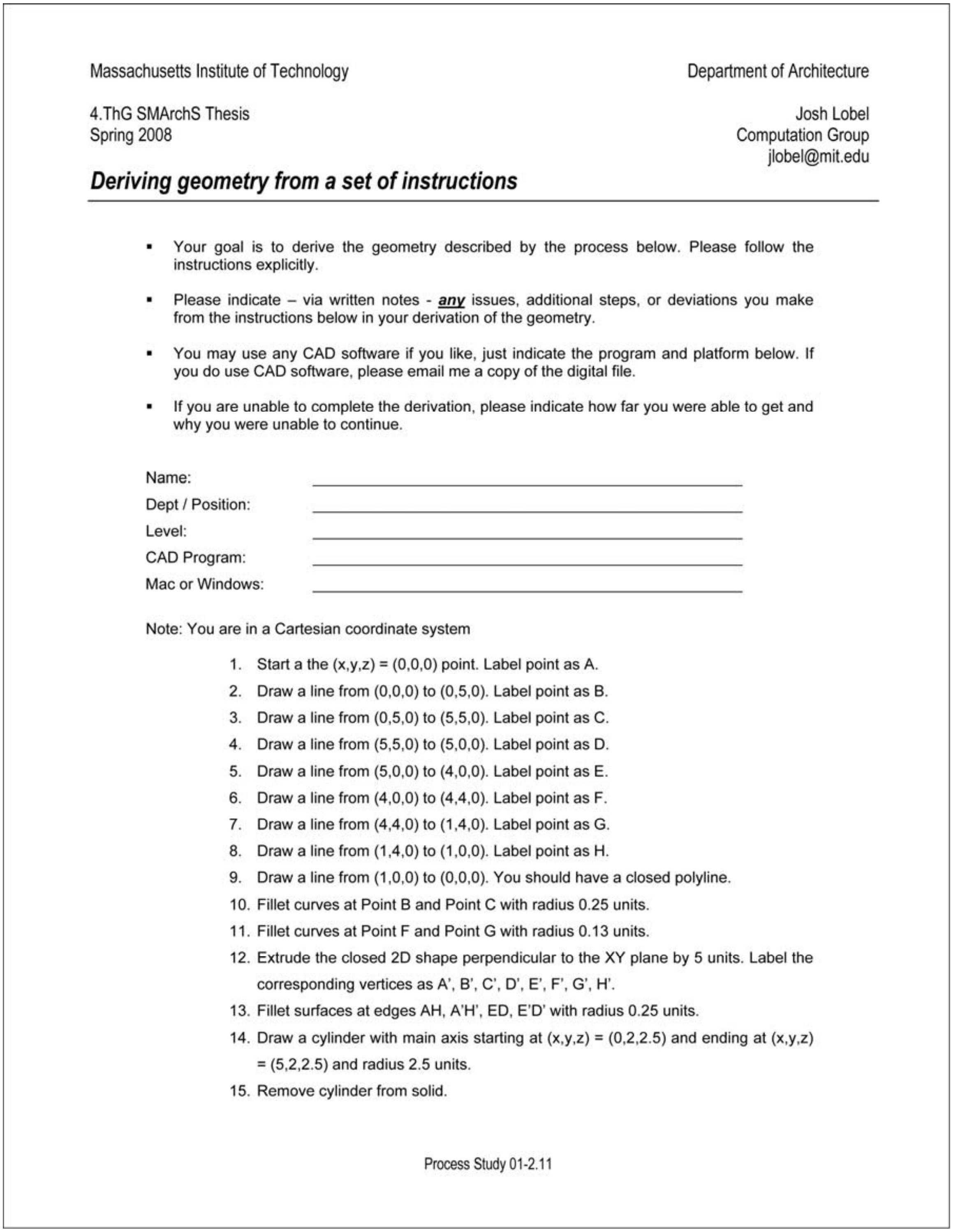
- Your goal is to write a procedural description for the derivation of the geometry shown using written text only (no pictures or diagrams please).
- This description will be given to another person and used to recreate the geometry.
- You may assume that the recipient has access to and may use CAD software with which to create the geometry, but you cannot assume which software they will use or what platform they will be using (ie Mac or Windows)
- Please be as explicit about the process as you feel necessary.

Name: ____________________

Dept / Major: ____________________

Level: ____________________

Process Study 01-1



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Deriving geometry from a set of instructions

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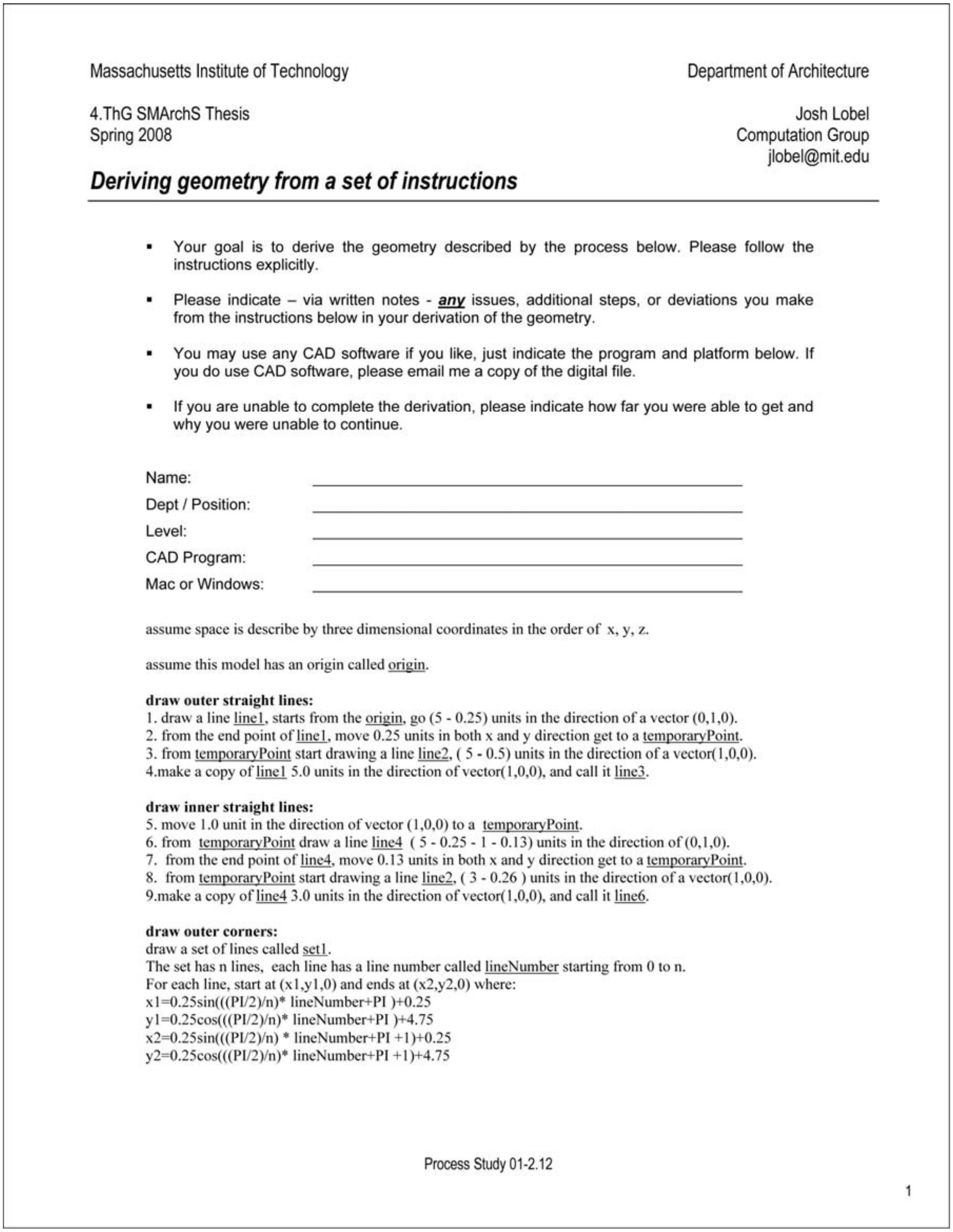
- If you are unable to complete the derivation, please indicate how far you were able to get and why you were unable to continue.

Name: ______________________________
Dept / Position: ______________________________
Level: ______________________________
CAD Program: ______________________________
Mac or Windows: ______________________________

Note: You are in a Cartesian coordinate system

1. Start a the (x,y,z) = (0,0,0) point. Label point as A.
2. Draw a line from (0,0,0) to (0,5,0). Label point as B.
3. Draw a line from (0,5,0) to (5,5,0). Label point as C.
4. Draw a line from (5,5,0) to (5,0,0). Label point as D.
5. Draw a line from (5,0,0) to (4,0,0). Label point as E.
6. Draw a line from (4,0,0) to (4,4,0). Label point as F.
7. Draw a line from (4,4,0) to (1,4,0). Label point as G.
8. Draw a line from (1,4,0) to (1,0,0). Label point as H.
9. Draw a line from (1,0,0) to (0,0,0). You should have a closed polyline.
10. Fillet curves at Point B and Point C with radius 0.25 units.
11. Fillet curves at Point F and Point G with radius 0.13 units.
12. Extrude the closed 2D shape perpendicular to the XY plane by 5 units. Label the corresponding vertices as A', B', C', D', E', F', G', H'.
13. Fillet surfaces at edges AH, A'H', ED, E'D' with radius 0.25 units.
14. Draw a cylinder with main axis starting at (x,y,z) = (0,2,2.5) and ending at (x,y,z) = (5,2,2.5) and radius 2.5 units.
15. Remove cylinder from solid.

Process Study 01-2.11



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- If you are unable to complete the derivation, please indicate how far you were able to get and why you were unable to continue.

Name: ______________________________
Dept / Position: ______________________________
Level: ______________________________
CAD Program: ______________________________
Mac or Windows: ______________________________

assume space is describe by three dimensional coordinates in the order of x, y, z.

assume this model has an origin called origin.

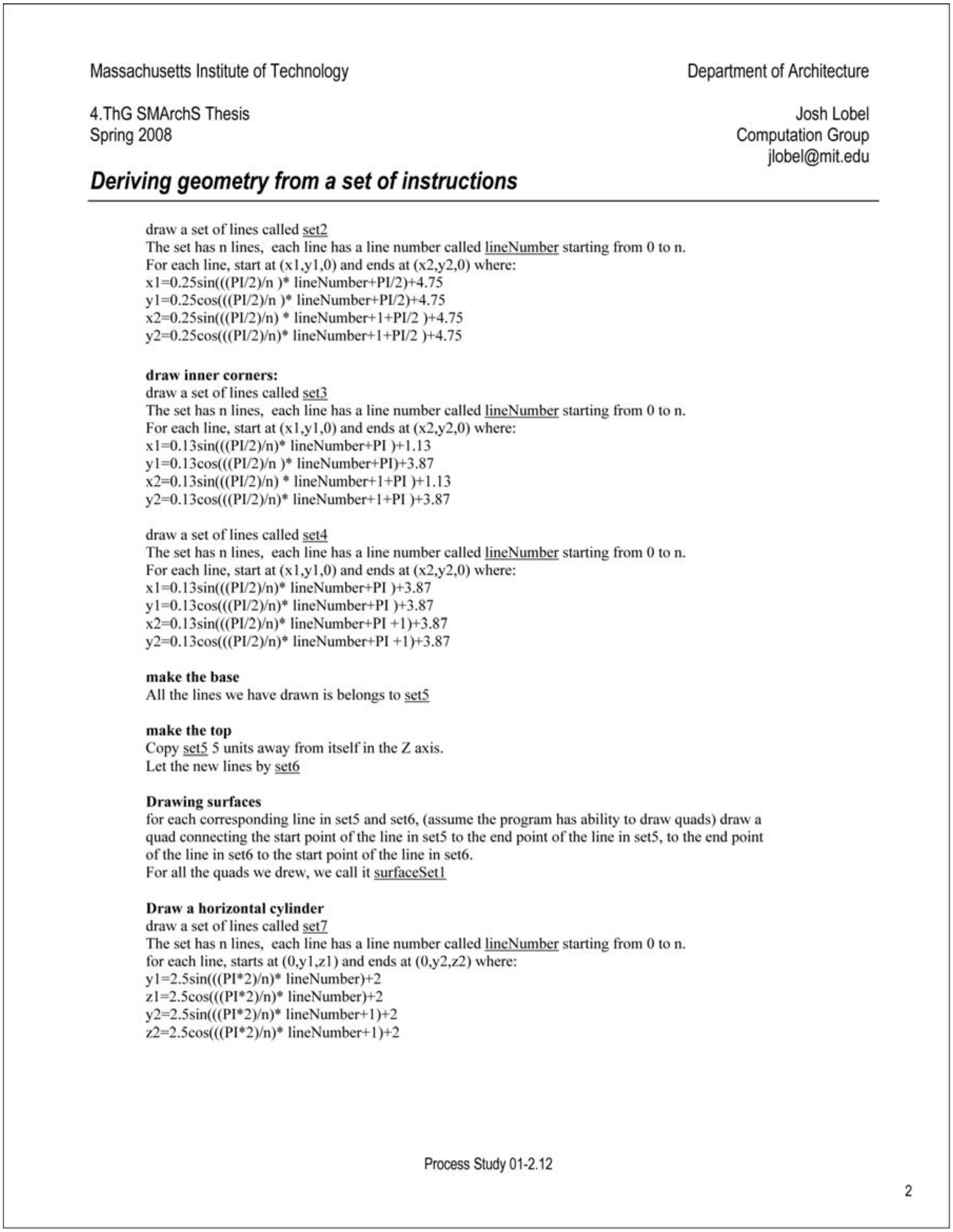
draw outer straight lines:
1. draw a line line1, starts from the origin, go (5 - 0.25) units in the direction of a vector (0,1,0).
2. from the end point of line1, move 0.25 units in both x and y direction get to a temporaryPoint.
3. from temporaryPoint start drawing a line line2, (5 - 0.5) units in the direction of a vector(1,0,0).
4.make a copy of line1 5.0 units in the direction of vector(1,0,0), and call it line3.

draw inner straight lines:
5. move 1.0 unit in the direction of vector (1,0,0) to a temporaryPoint.
6. from temporaryPoint draw a line line4 (5 - 0.25 - 1 - 0.13) units in the direction of (0,1,0).
7. from the end point of line4, move 0.13 units in both x and y direction get to a temporaryPoint.
8. from temporaryPoint start drawing a line line2, (3 - 0.26) units in the direction of a vector(1,0,0).
9.make a copy of line4 3.0 units in the direction of vector(1,0,0), and call it line6.

draw outer corners:
draw a set of lines called set1.
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
For each line, start at (x1,y1,0) and ends at (x2,y2,0) where:
$x1=0.25sin(((PI/2)/n)* lineNumber+PI)+0.25$
$y1=0.25cos(((PI/2)/n)* lineNumber+PI)+4.75$
$x2=0.25sin(((PI/2)/n) * lineNumber+PI +1)+0.25$
$y2=0.25cos(((PI/2)/n)* lineNumber+PI +1)+4.75$

Process Study 01-2.12

1



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Deriving geometry from a set of instructions

draw a set of lines called set2
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
For each line, start at (x1,y1,0) and ends at (x2,y2,0) where:
x1=0.25sin(((PI/2)/n)* lineNumber+PI/2)+4.75
y1=0.25cos(((PI/2)/n)* lineNumber+PI/2)+4.75
x2=0.25sin(((PI/2)/n) * lineNumber+1+PI/2)+4.75
y2=0.25cos(((PI/2)/n)* lineNumber+1+PI/2)+4.75

draw inner corners:
draw a set of lines called set3
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
For each line, start at (x1,y1,0) and ends at (x2,y2,0) where:
x1=0.13sin(((PI/2)/n)* lineNumber+PI)+1.13
y1=0.13cos(((PI/2)/n)* lineNumber+PI)+3.87
x2=0.13sin(((PI/2)/n) * lineNumber+1+PI)+1.13
y2=0.13cos(((PI/2)/n)* lineNumber+1+PI)+3.87

draw a set of lines called set4
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
For each line, start at (x1,y1,0) and ends at (x2,y2,0) where:
x1=0.13sin(((PI/2)/n)* lineNumber+PI)+3.87
y1=0.13cos(((PI/2)/n)* lineNumber+PI)+3.87
x2=0.13sin(((PI/2)/n)* lineNumber+PI +1)+3.87
y2=0.13cos(((PI/2)/n)* lineNumber+PI +1)+3.87

make the base
All the lines we have drawn is belongs to set5

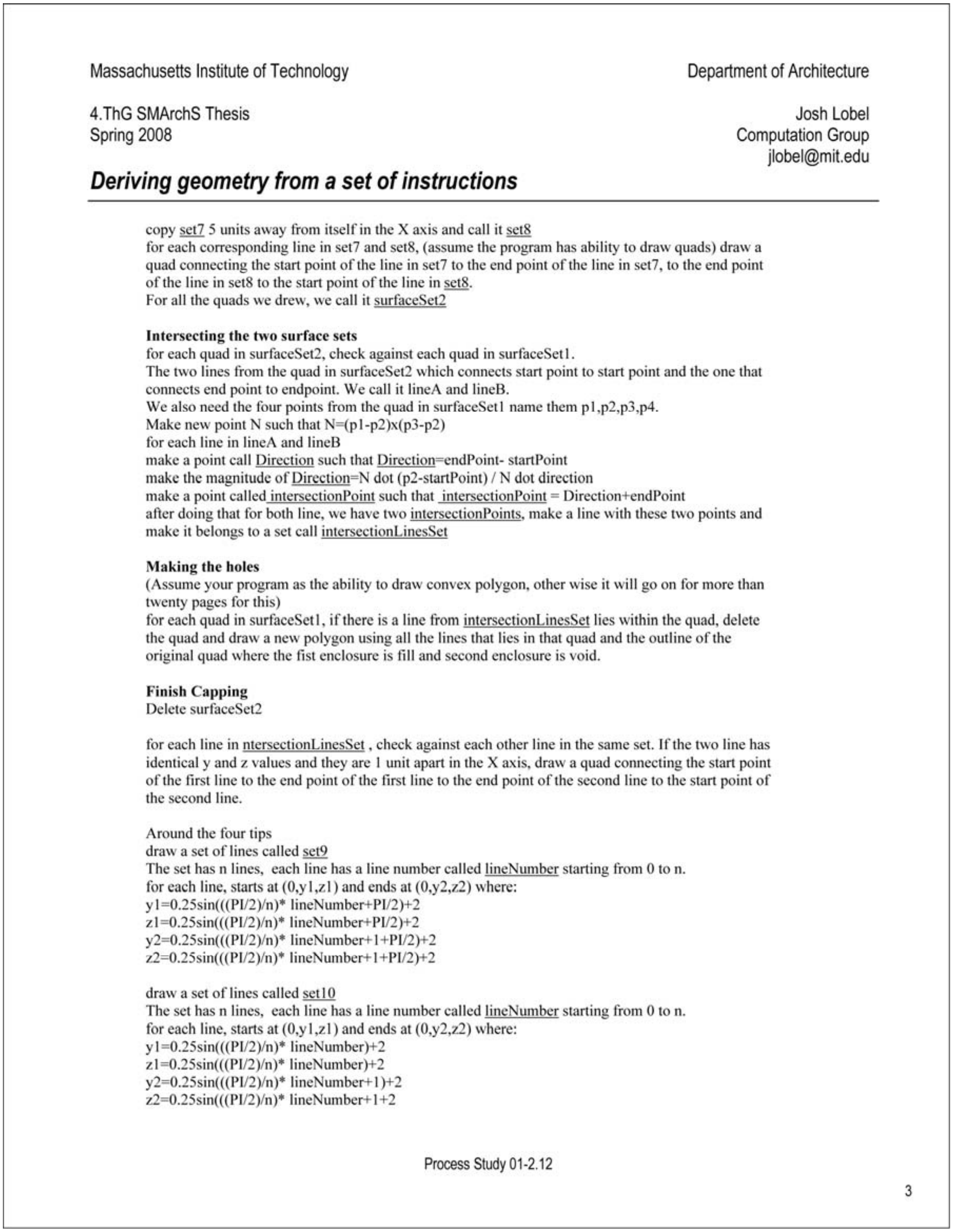
make the top
Copy set5 5 units away from itself in the Z axis.
Let the new lines by set6

Drawing surfaces
for each corresponding line in set5 and set6, (assume the program has ability to draw quads) draw a quad connecting the start point of the line in set5 to the end point of the line in set5, to the end point of the line in set6 to the start point of the line in set6.
For all the quads we drew, we call it surfaceSet1

Draw a horizontal cylinder
draw a set of lines called set7
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
for each line, starts at (0,y1,z1) and ends at (0,y2,z2) where:
y1=2.5sin(((PI*2)/n)* lineNumber)+2
z1=2.5cos(((PI*2)/n)* lineNumber)+2
y2=2.5sin(((PI*2)/n)* lineNumber+1)+2
z2=2.5cos(((PI*2)/n)* lineNumber+1)+2

Process Study 01-2.12

2



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Deriving geometry from a set of instructions

copy set7 5 units away from itself in the X axis and call it set8
for each corresponding line in set7 and set8, (assume the program has ability to draw quads) draw a quad connecting the start point of the line in set7 to the end point of the line in set7, to the end point of the line in set8 to the start point of the line in set8.
For all the quads we drew, we call it surfaceSet2

Intersecting the two surface sets
for each quad in surfaceSet2, check against each quad in surfaceSet1.
The two lines from the quad in surfaceSet2 which connects start point to start point and the one that connects end point to endpoint. We call it lineA and lineB.
We also need the four points from the quad in surfaceSet1 name them p1,p2,p3,p4.
Make new point N such that N=(p1-p2)x(p3-p2)
for each line in lineA and lineB
make a point call Direction such that Direction=endPoint- startPoint
make the magnitude of Direction=N dot (p2-startPoint) / N dot direction
make a point called intersectionPoint such that intersectionPoint = Direction+endPoint
after doing that for both line, we have two intersectionPoints, make a line with these two points and make it belongs to a set call intersectionLinesSet

Making the holes
(Assume your program as the ability to draw convex polygon, other wise it will go on for more than twenty pages for this)
for each quad in surfaceSet1, if there is a line from intersectionLinesSet lies within the quad, delete the quad and draw a new polygon using all the lines that lies in that quad and the outline of the original quad where the fist enclosure is fill and second enclosure is void.

Finish Capping
Delete surfaceSet2

for each line in ntersectionLinesSet , check against each other line in the same set. If the two line has identical y and z values and they are 1 unit apart in the X axis, draw a quad connecting the start point of the first line to the end point of the first line to the end point of the second line to the start point of the second line.

Around the four tips
draw a set of lines called set9
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
for each line, starts at (0,y1,z1) and ends at (0,y2,z2) where:
y1=0.25sin(((PI/2)/n)* lineNumber+PI/2)+2
z1=0.25sin(((PI/2)/n)* lineNumber+PI/2)+2
y2=0.25sin(((PI/2)/n)* lineNumber+1+PI/2)+2
z2=0.25sin(((PI/2)/n)* lineNumber+1+PI/2)+2

draw a set of lines called set10
The set has n lines, each line has a line number called lineNumber starting from 0 to n.
for each line, starts at (0,y1,z1) and ends at (0,y2,z2) where:
y1=0.25sin(((PI/2)/n)* lineNumber)+2
z1=0.25sin(((PI/2)/n)* lineNumber)+2
y2=0.25sin(((PI/2)/n)* lineNumber+1)+2
z2=0.25sin(((PI/2)/n)* lineNumber+1+2

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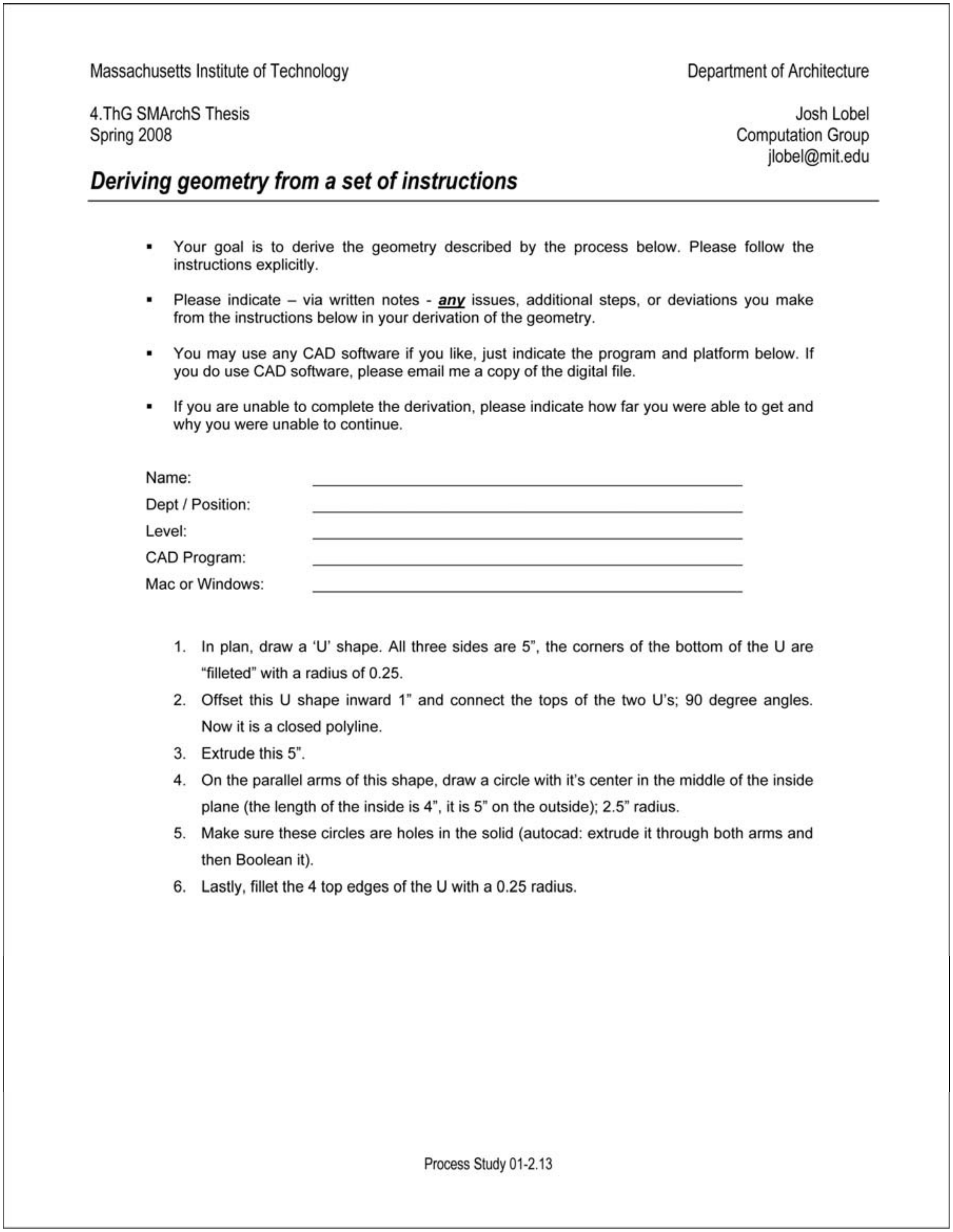
Deriving geometry from a set of instructions

merge set10 with set9 into set9.
Copy set9 5 units away from itself in the X axis and call it set10

using the same technique in **Intersecting the two surface sets** to produce intersectionLinesSet2, use the same technique **Making the holes** and **Finish Capping** to finish the task



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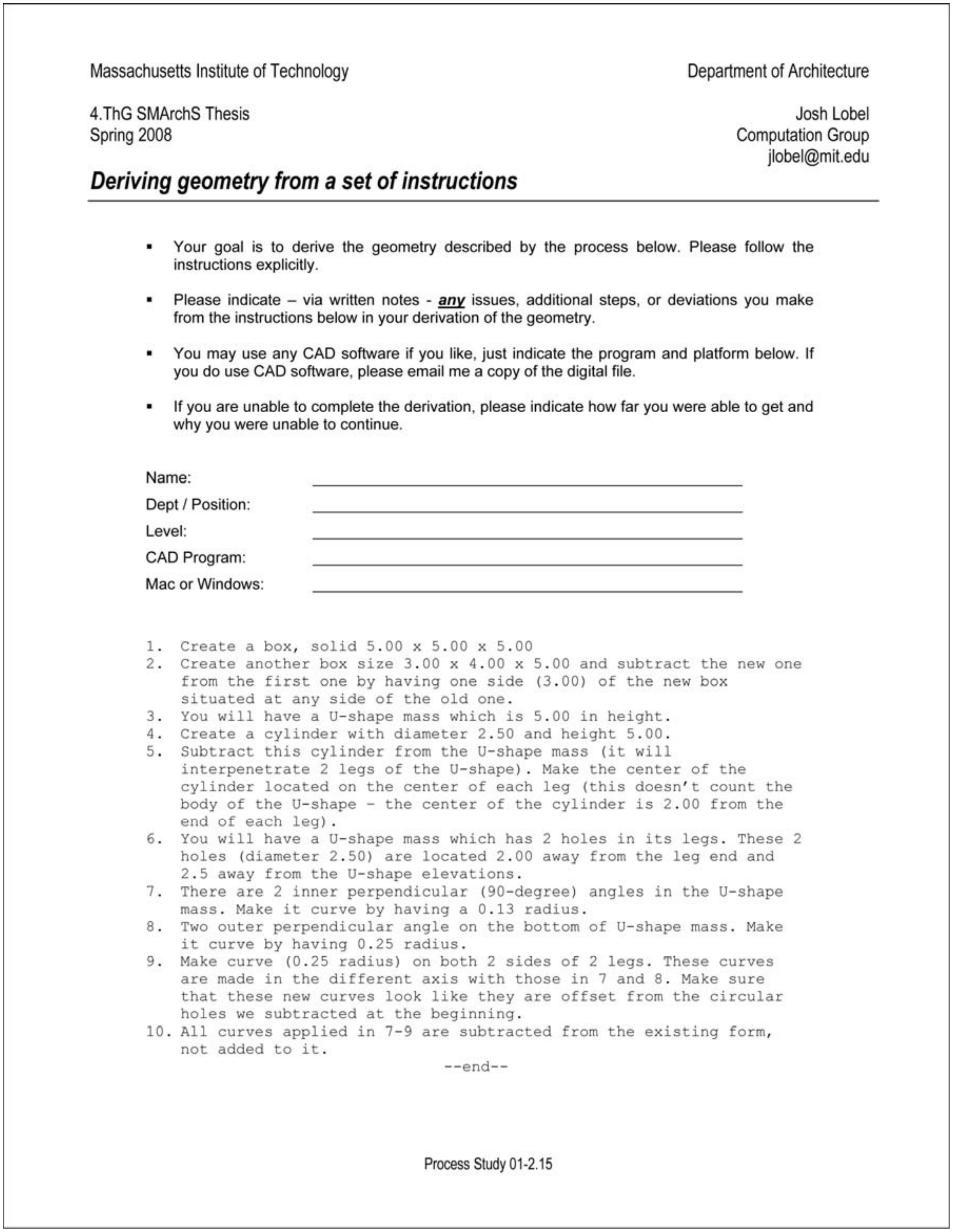
Name: ________________________________
Dept / Position: ________________________________
Level: ________________________________
CAD Program: ________________________________
Mac or Windows: ________________________________

1. In plan, draw a 'U' shape. All three sides are 5", the corners of the bottom of the U are "filleted" with a radius of 0.25.
2. Offset this U shape inward 1" and connect the tops of the two U's; 90 degree angles. Now it is a closed polyline.
3. Extrude this 5".
4. On the parallel arms of this shape, draw a circle with it's center in the middle of the inside plane (the length of the inside is 4", it is 5" on the outside); 2.5" radius.
5. Make sure these circles are holes in the solid (autocad: extrude it through both arms and then Boolean it).
6. Lastly, fillet the 4 top edges of the U with a 0.25 radius.

Process Study 01-2.13



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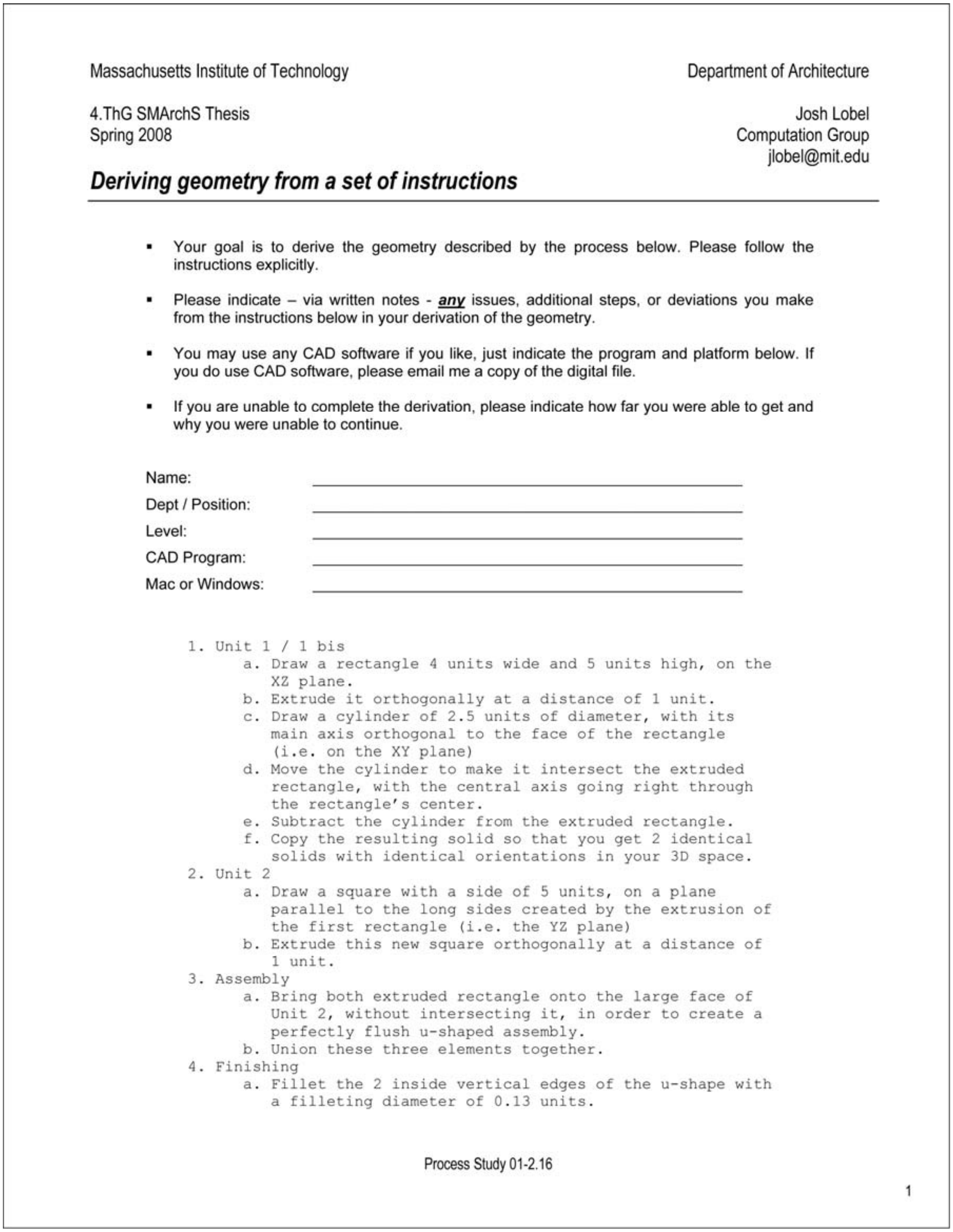
- If you are unable to complete the derivation, please indicate how far you were able to get and why you were unable to continue.

Name: ______________________
Dept / Position: ______________________
Level: ______________________
CAD Program: ______________________
Mac or Windows: ______________________

1. Create a box, solid 5.00 x 5.00 x 5.00
2. Create another box size 3.00 x 4.00 x 5.00 and subtract the new one from the first one by having one side (3.00) of the new box situated at any side of the old one.
3. You will have a U-shape mass which is 5.00 in height.
4. Create a cylinder with diameter 2.50 and height 5.00.
5. Subtract this cylinder from the U-shape mass (it will interpenetrate 2 legs of the U-shape). Make the center of the cylinder located on the center of each leg (this doesn't count the body of the U-shape - the center of the cylinder is 2.00 from the end of each leg).
6. You will have a U-shape mass which has 2 holes in its legs. These 2 holes (diameter 2.50) are located 2.00 away from the leg end and 2.5 away from the U-shape elevations.
7. There are 2 inner perpendicular (90-degree) angles in the U-shape mass. Make it curve by having a 0.13 radius.
8. Two outer perpendicular angle on the bottom of U-shape mass. Make it curve by having 0.25 radius.
9. Make curve (0.25 radius) on both 2 sides of 2 legs. These curves are made in the different axis with those in 7 and 8. Make sure that these new curves look like they are offset from the circular holes we subtracted at the beginning.
10. All curves applied in 7-9 are subtracted from the existing form, not added to it.

--end--

Process Study 01-2.15



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Name: ____________________
Dept / Position: ____________________
Level: ____________________
CAD Program: ____________________
Mac or Windows: ____________________

1. Unit 1 / 1 bis
    a. Draw a rectangle 4 units wide and 5 units high, on the XZ plane.
    b. Extrude it orthogonally at a distance of 1 unit.
    c. Draw a cylinder of 2.5 units of diameter, with its main axis orthogonal to the face of the rectangle (i.e. on the XY plane)
    d. Move the cylinder to make it intersect the extruded rectangle, with the central axis going right through the rectangle's center.
    e. Subtract the cylinder from the extruded rectangle.
    f. Copy the resulting solid so that you get 2 identical solids with identical orientations in your 3D space.
2. Unit 2
    a. Draw a square with a side of 5 units, on a plane parallel to the long sides created by the extrusion of the first rectangle (i.e. the YZ plane)
    b. Extrude this new square orthogonally at a distance of 1 unit.
3. Assembly
    a. Bring both extruded rectangle onto the large face of Unit 2, without intersecting it, in order to create a perfectly flush u-shaped assembly.
    b. Union these three elements together.
4. Finishing
    a. Fillet the 2 inside vertical edges of the u-shape with a filleting diameter of 0.13 units.

Process Study 01-2.16

1

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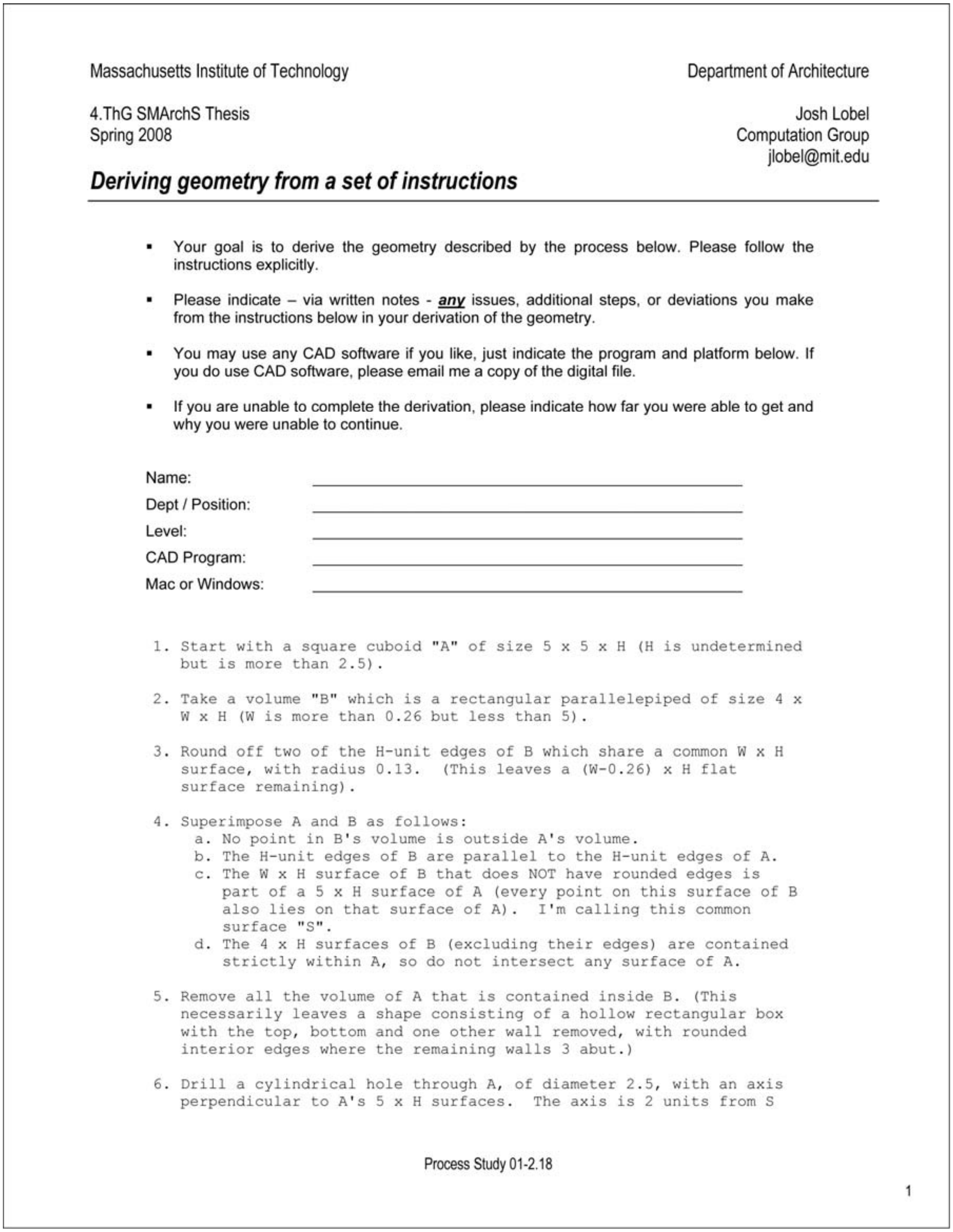
b. Fillet the 2 outside vertical edges of the u-shape (closed side of the U) with a filleting diameter of 0.25 units.
c. Fillet the 2 outside horizontal edges of the u-shape (open side of the U) with a filleting diameter of 0.25 units.

Process Study 01-2.16

2



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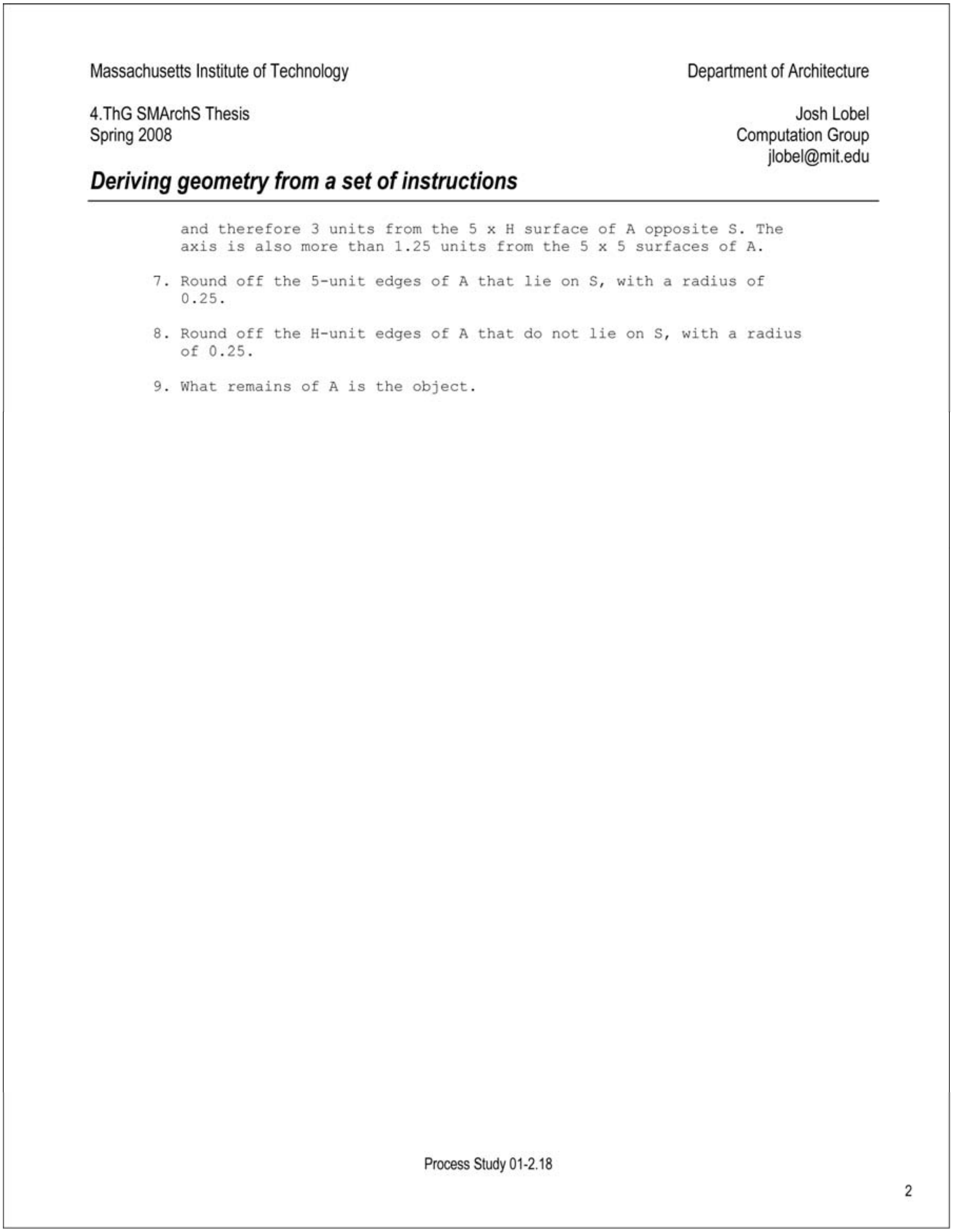
- If you are unable to complete the derivation, please indicate how far you were able to get and why you were unable to continue.

Name: ______________________________
Dept / Position: ______________________________
Level: ______________________________
CAD Program: ______________________________
Mac or Windows: ______________________________

1. Start with a square cuboid "A" of size 5 x 5 x H (H is undetermined but is more than 2.5).
2. Take a volume "B" which is a rectangular parallelepiped of size 4 x W x H (W is more than 0.26 but less than 5).
3. Round off two of the H-unit edges of B which share a common W x H surface, with radius 0.13. (This leaves a (W-0.26) x H flat surface remaining).
4. Superimpose A and B as follows:
    a. No point in B's volume is outside A's volume.
    b. The H-unit edges of B are parallel to the H-unit edges of A.
    c. The W x H surface of B that does NOT have rounded edges is part of a 5 x H surface of A (every point on this surface of B also lies on that surface of A). I'm calling this common surface "S".
    d. The 4 x H surfaces of B (excluding their edges) are contained strictly within A, so do not intersect any surface of A.
5. Remove all the volume of A that is contained inside B. (This necessarily leaves a shape consisting of a hollow rectangular box with the top, bottom and one other wall removed, with rounded interior edges where the remaining walls 3 abut.)
6. Drill a cylindrical hole through A, of diameter 2.5, with an axis perpendicular to A's 5 x H surfaces. The axis is 2 units from S

Process Study 01-2.18

1



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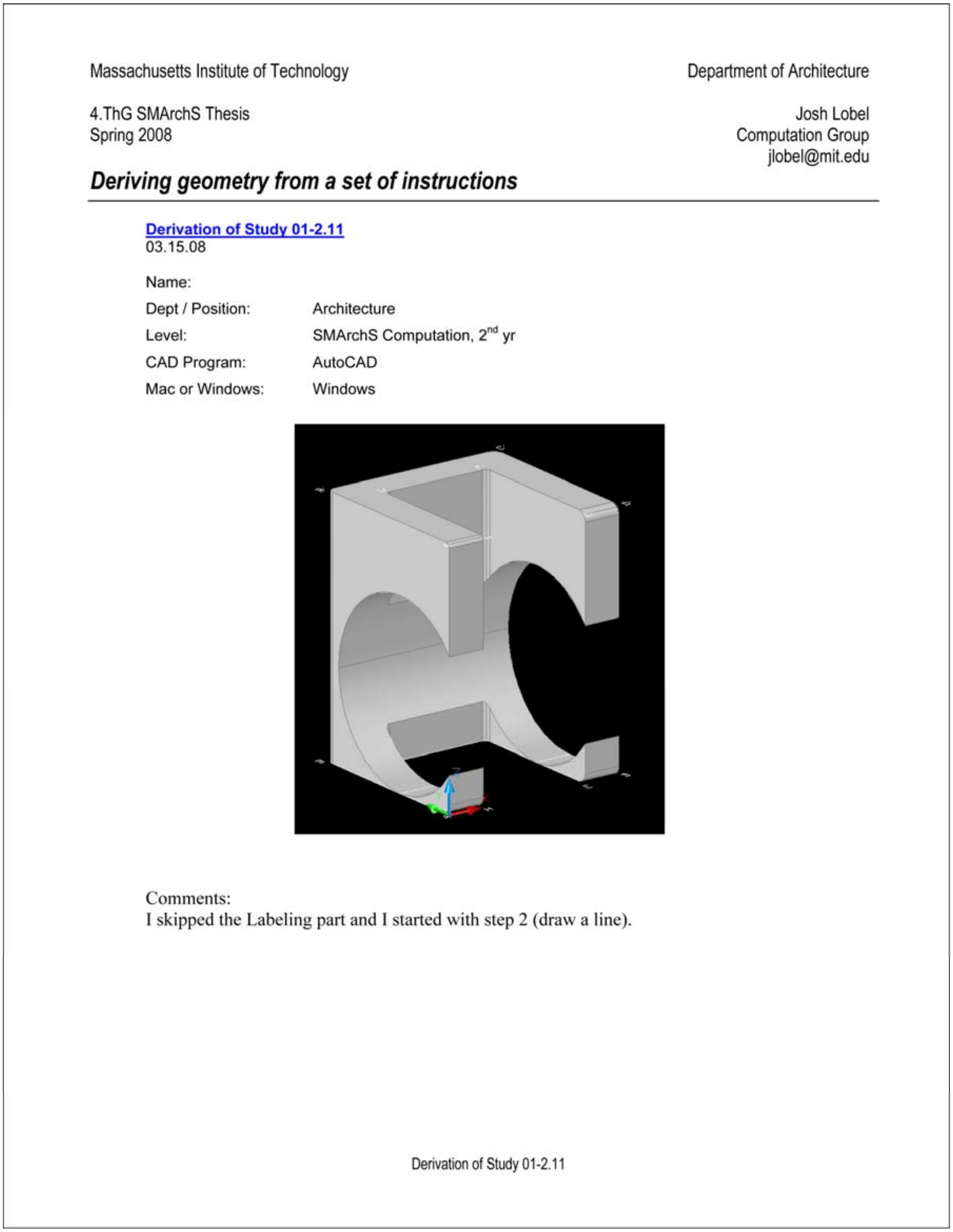
and therefore 3 units from the 5 x H surface of A opposite S. The axis is also more than 1.25 units from the 5 x 5 surfaces of A.

7. Round off the 5-unit edges of A that lie on S, with a radius of 0.25.
8. Round off the H-unit edges of A that do not lie on S, with a radius of 0.25.
9. What remains of A is the object.

Process Study 01-2.18

2



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Deriving geometry from a set of instructions

Derivation of Study 01-2.11
03.15.08

Name:	
Dept / Position:	Architecture
Level:	SMArchS Computation, 2nd yr
CAD Program:	AutoCAD
Mac or Windows:	Windows

Comments:
I skipped the Labeling part and I started with step 2 (draw a line).

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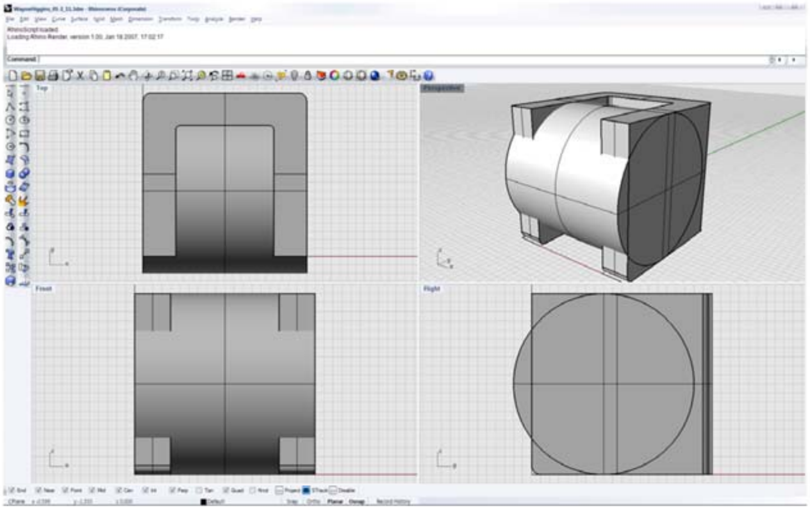
Deriving geometry from a set of instructions

Derivation of Study 01-2.11
03.14.08

Name:	
Dept / Position:	Architecture
Level:	MArch, Level II
CAD Program:	Rhino
Mac or Windows:	Windows

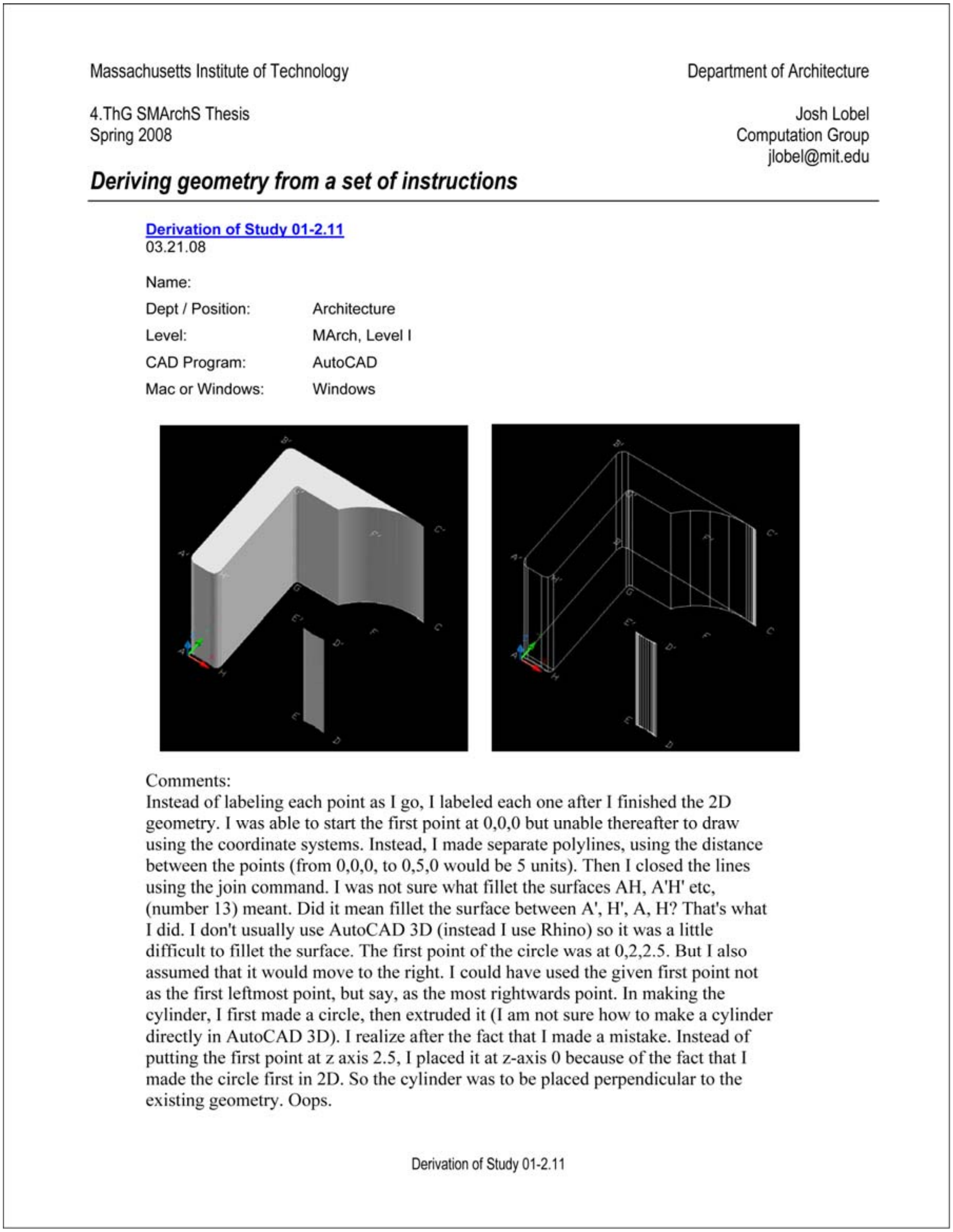


Comments:

In Rhino (software specific) you should specify which window to begin the sketch in. When you begin in a window which is not the horizontal x,y plane the sketch accepts your co-ordinates relative to the plane you're sketching in. Does that make sense? This creates orientation issues when you extrude the sketch in z.

I couldn't label or annotate the nodes in Rhino. I don't know how to easily apart from using the 3D letter tool.

The Cylinder wouldn't cut (remove) from my solid. I guess its because it couldn't calculate the cut due to two of the surfaces being planer.



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Derivation of Study 01-2.11
03.21.08

Name:	
Dept / Position:	Architecture
Level:	MArch, Level I
CAD Program:	AutoCAD
Mac or Windows:	Windows

Comments:
Instead of labeling each point as I go, I labeled each one after I finished the 2D geometry. I was able to start the first point at 0,0,0 but unable thereafter to draw using the coordinate systems. Instead, I made separate polylines, using the distance between the points (from 0,0,0, to 0,5,0 would be 5 units). Then I closed the lines using the join command. I was not sure what fillet the surfaces AH, A'H' etc, (number 13) meant. Did it mean fillet the surface between A', H', A, H? That's what I did. I don't usually use AutoCAD 3D (instead I use Rhino) so it was a little difficult to fillet the surface. The first point of the circle was at 0,2,2.5. But I also assumed that it would move to the right. I could have used the given first point not as the first leftmost point, but say, as the most rightwards point. In making the cylinder, I first made a circle, then extruded it (I am not sure how to make a cylinder directly in AutoCAD 3D). I realize after the fact that I made a mistake. Instead of putting the first point at z axis 2.5, I placed it at z-axis 0 because of the fact that I made the circle first in 2D. So the cylinder was to be placed perpendicular to the existing geometry. Oops.

Derivation of Study 01-2.11

Massachusetts Institute of Technology
Department of Architecture

4.ThG SMArchS Thesis
Spring 2008

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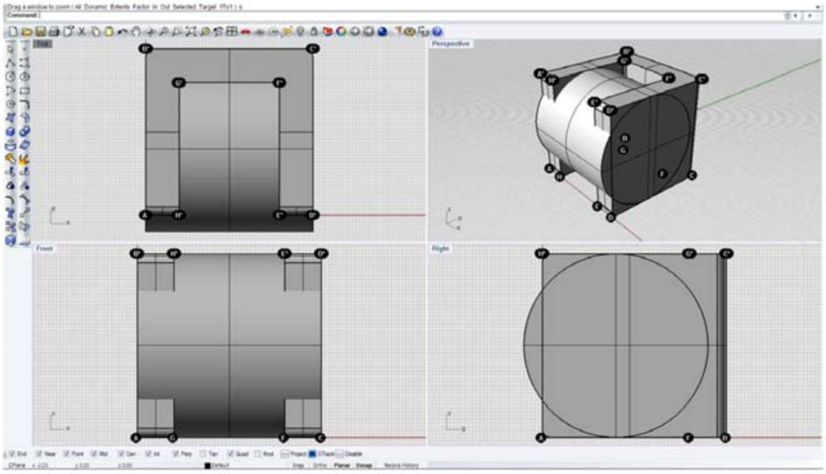
Deriving geometry from a set of instructions

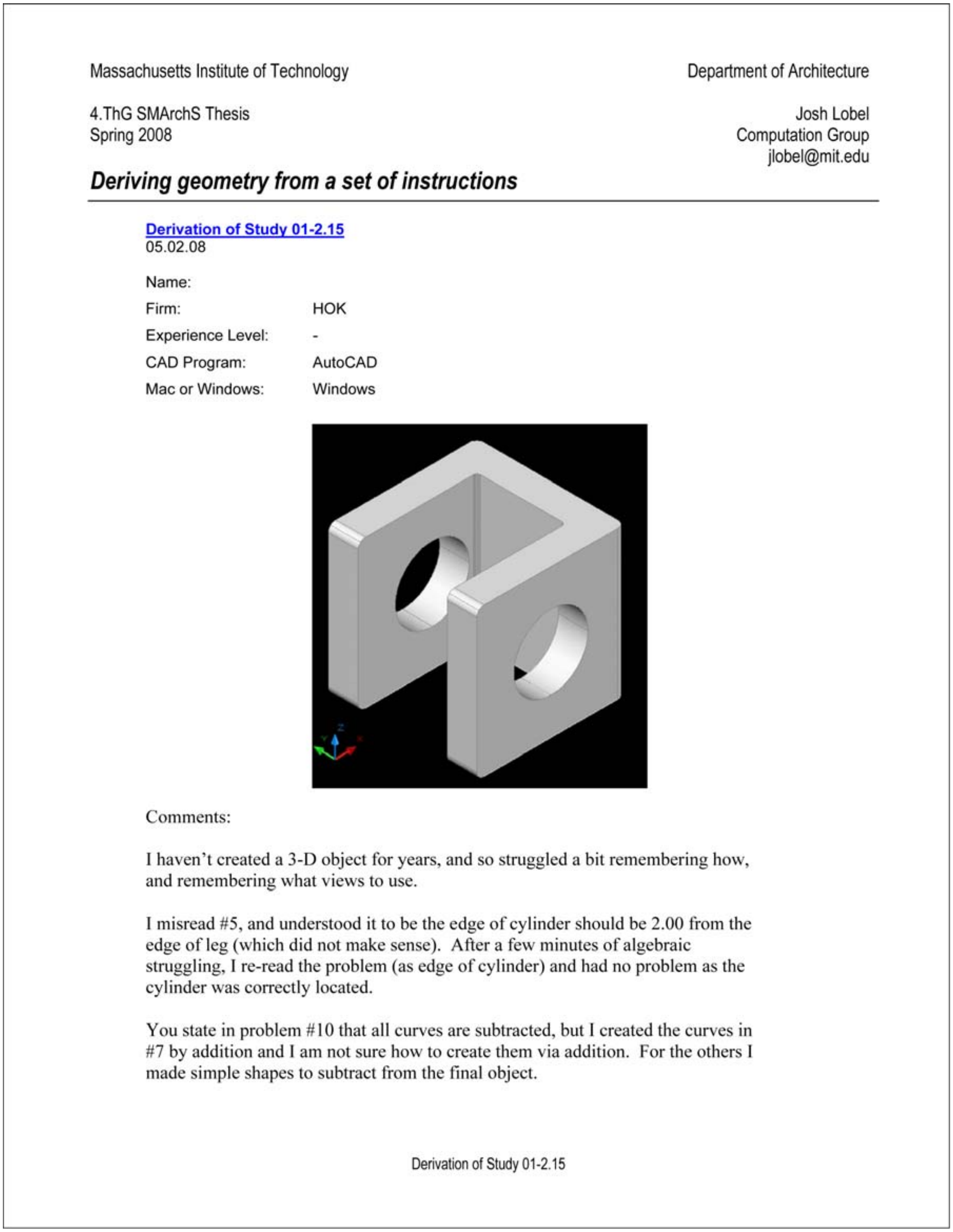
Derivation of Study 01-2.11
03.26.08

Name:	
Dept / Position:	Architecture
Level:	MArch, Level I
CAD Program:	Rhino
Mac or Windows:	Windows



Comments:

I made it through step 14. I was not able to complete step 15. Through step 14, I had no problems. For step 15, I tried the following: BooleanDifference, BooleanSplit, Trim, Split. Went back to step 13 and noticed the while Rhino filleted the 2 surfaces but not the lines perpendicular to the surfaces. Thought that might make a difference so I filleted those lines as well. I was still unsuccessful. I noticed that when I filleted the surfaces, the fillets were separate from the rest of the object, so I connected everything into one solid. Still didn't work. I tried to extend the cylinder beyond the sides of the other object, to make sure the cylinder overlapped the sides of the other object. Still didn't work. In the end, no matter what I did, I couldn't figure out how to remove the cylinder from the solid.



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Deriving geometry from a set of instructions

Derivation of Study 01-2.15
05.02.08

Name:	
Firm:	HOK
Experience Level:	-
CAD Program:	AutoCAD
Mac or Windows:	Windows

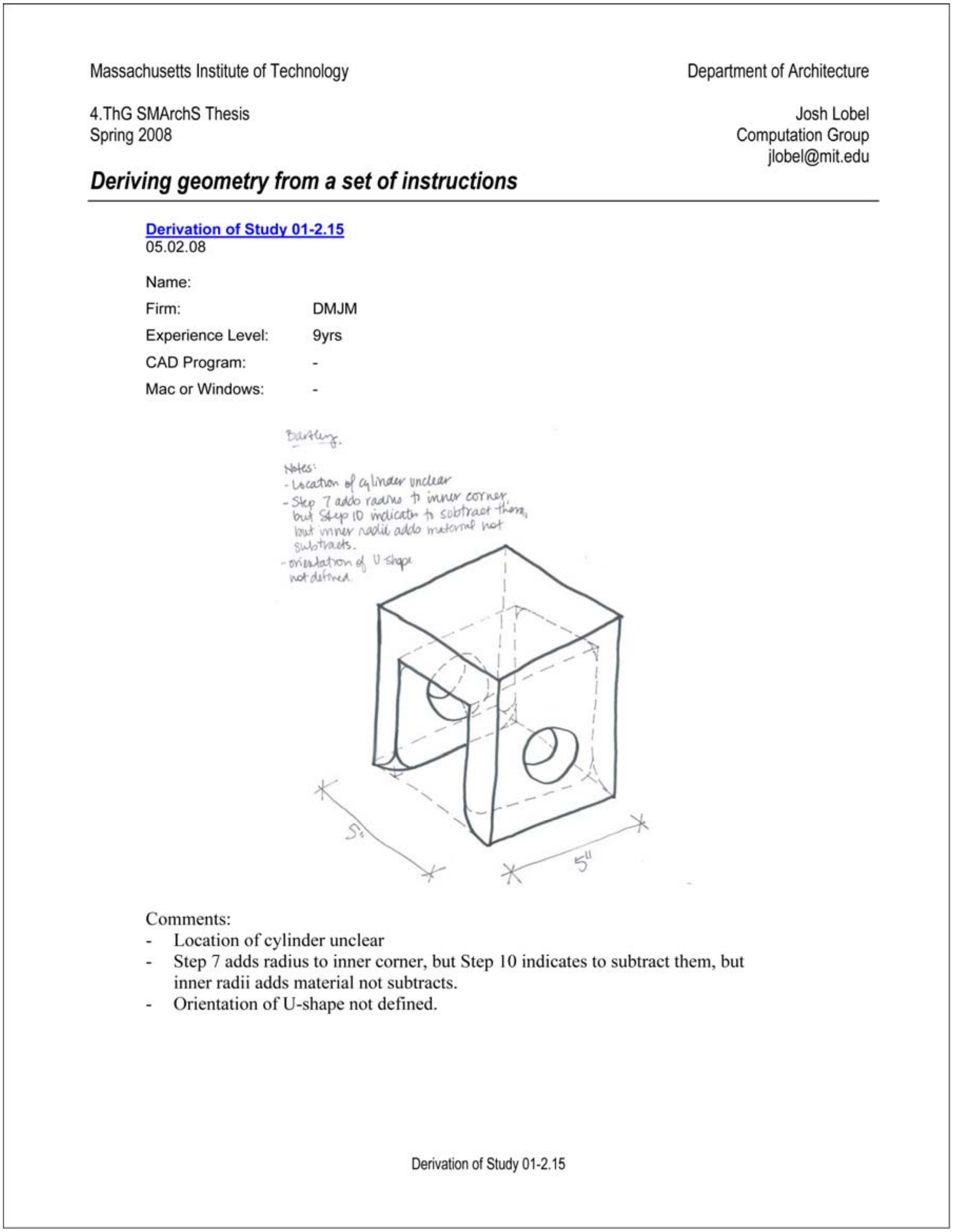
Comments:

I haven't created a 3-D object for years, and so struggled a bit remembering how, and remembering what views to use.

I misread #5, and understood it to be the edge of cylinder should be 2.00 from the edge of leg (which did not make sense). After a few minutes of algebraic struggling, I re-read the problem (as edge of cylinder) and had no problem as the cylinder was correctly located.

You state in problem #10 that all curves are subtracted, but I created the curves in #7 by addition and I am not sure how to create them via addition. For the others I made simple shapes to subtract from the final object.

Derivation of Study 01-2.15



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Deriving geometry from a set of instructions

Derivation of Study 01-2.15
05.02.08

Name:	
Firm:	DMJM
Experience Level:	9yrs
CAD Program:	-
Mac or Windows:	-

Bartley.

Notes:
- Location of cylinder unclear
- Step 7 adds radius to inner corner, but Step 10 indicates to subtract them, but inner radii adds material not subtracts.
- orientation of U shape not defined.

Comments:
- Location of cylinder unclear
- Step 7 adds radius to inner corner, but Step 10 indicates to subtract them, but inner radii adds material not subtracts.
- Orientation of U-shape not defined.

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Spring 2008

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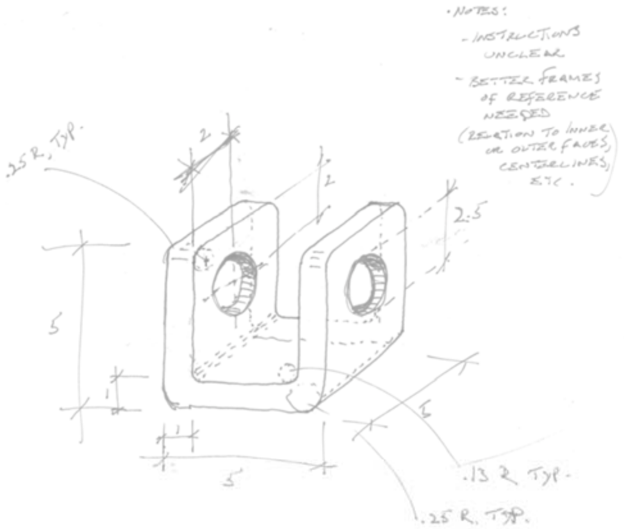
Deriving geometry from a set of instructions

Derivation of Study 01-2.15
05.02.08

Name:	
Firm:	Clive Wilkinson Architects
Experience Level:	6 yrs
CAD Program:	-
Mac or Windows:	-



· NOTES:
- INSTRUCTIONS UNCLEAR
- BETTER FRAMES OF REFERENCE NEEDED (RELATION TO INNER OR OUTER FACES, CENTERLINES, ETC.)

Comments:
- Instructions unclear
- Better frames of reference needed (relation to inner or outer faces, centerlines, etc.)

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Spring 2008

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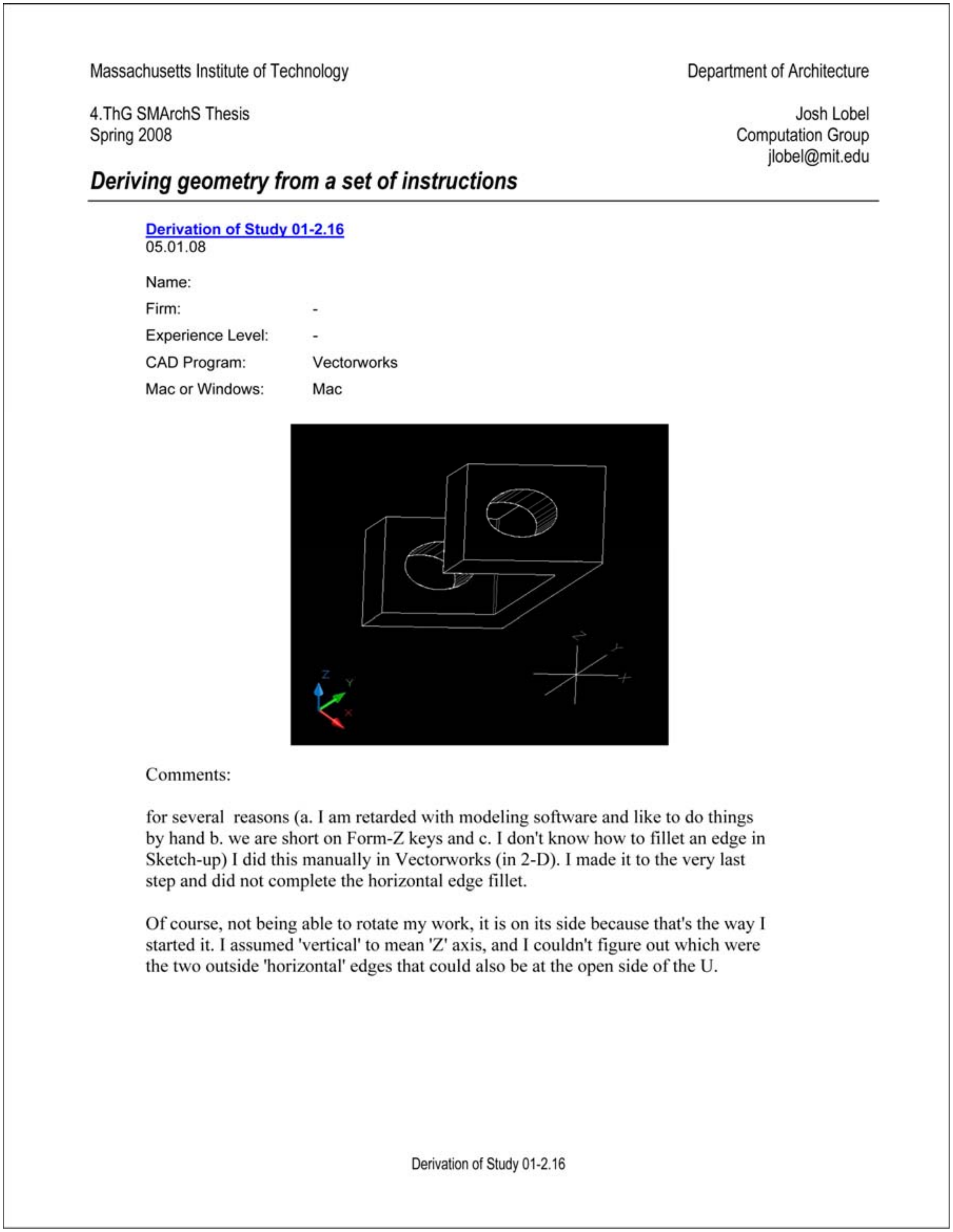
Deriving geometry from a set of instructions

Derivation of Study 01-2.16
03.19.08

Name:	
Dept / Position:	Architecture
Level:	SMArchS Urbanism, 2nd yr
CAD Program:	AutoCAD
Mac or Windows:	Windows

Comments:

I did not finish the exercise because When I was asked to do the "U shape" I needed to have two different UCS at the same time, something impossible to do in Auto CAD. I tried to do it in different ways, but I couldn't do it unless I started again, and I decided it interfered with the rules.



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Spring 2008

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Deriving geometry from a set of instructions

Derivation of Study 01-2.16
05.01.08

Name:	
Firm:	-
Experience Level:	-
CAD Program:	Vectorworks
Mac or Windows:	Mac

Comments:

for several reasons (a. I am retarded with modeling software and like to do things by hand b. we are short on Form-Z keys and c. I don't know how to fillet an edge in Sketch-up) I did this manually in Vectorworks (in 2-D). I made it to the very last step and did not complete the horizontal edge fillet.

Of course, not being able to rotate my work, it is on its side because that's the way I started it. I assumed 'vertical' to mean 'Z' axis, and I couldn't figure out which were the two outside 'horizontal' edges that could also be at the open side of the U.

Derivation of Study 01-2.16