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Imitation, Iteration and Improvisation:
Embodied Interaction in Computational Making and Learning

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Abstract

Despite advances in digital design and fabrication technologies, creative design practices still follow Alberti’s separation of the design phase from the construction phase. This separation causes a reliance on digital fabrication machines that pushes human agency to the periphery of the making process. The interfaces of these technologies and their linear process of production create cognitive and perceptual obstacles, making it difficult for non-experts to create and improvise independently. Design and the ability to make are often thought to be intuitive, yet significant research has suggested that intuition is developed through skilled practice, interaction with materials, tools, and machines. Existing pedagogical approaches to design focus on outcomes and instructors’ feedback to the students, neglecting the importance of the tools and the process itself.

How, then, do we learn to make something? What are the potential roles of computational tools, theories, and practices in understanding, describing, and enriching the making and learning process? What can we learn from machines, and what can machines learn from us? Finally, what do we learn from making?

Here, I introduce I³, a computational making methodology that enables emerging designers and makers to improvise and create on their own. I call this method I³ for its three-layer operation of Imitation, Iteration and Improvisation. Drawing upon research from other fields, this methodology for human-machine making and learning is based on a recursive process of embodied, situated interaction between learners, machines, materials, and the things-in-the-making. I describe the continuous process of developing and testing I³ through experiments I conducted during the teaching of three courses for graduate and undergraduate students. The qualitative research I conducted shows that through using the I³ methodology, students develop their spatial reasoning and decision-making skills while at the same time learning to use digital technologies as design companions.

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In-the-Making
1 In-the-Making

“Making, then, is a process of correspondence: not the imposition of preconceived form on raw material substance, but the drawing out or bringing forth of potentials immanent in a world of becoming. In the phenomenal world, every material is such a becoming, one path or trajectory through a maze of trajectories.” Tim Ingold, MAKING: Anthropology, archaeology, art and architecture, 2013.

I would like to begin this dissertation with three personal stories about seeing, sensing and doing. The first story is about learning to paint at a very young age. My late father always advised me to copy from an already existing photo or painting, and to do this until I was able to learn to create something original on my own. This was how he had taught himself when he was my age. However, I saw copying at that time as contradictory to the notion of being a creative artist. Eventually, however, I listened to him.

The second story took place during my undergraduate years in architecture. We were asked to look at precedents of assigned design projects and analyze them in presentations to our classmates. My late aunt, who was also an architect, showed me that I could put tracing paper on images of buildings and plans, and when I saw a line or curve that I liked, copy it by tracing it. I could trace as many lines as I wanted, compose them in any composition I wanted, draw, transform or add parts to them, and then put another tracing paper over that and a fused design of the entire thing would emerge.

The third story began during my last years in college and early years of architecture practice. At that time, I depended heavily on digital design tools and software to create representations of my designs and manual sketches. I opposed the idea of making a physical model manually, as 3D modeling did the job for me. Five years later at MIT, my advisor Professor Terry Knight “strongly” suggested in our early meetings that I take digital fabrication classes. I did not see the importance of this because, at that time, I was set on learning about computation and Shape Grammars. However, after suffering through encounters with some digital fabrication machines, breaking tools, and melting materials, I saw the wisdom of Knight’s advice. Making things became my obsession, especially after taking the How to Make (Almost) Anything course with MIT Professor Neil Gershenfeld. In my first year in my PhD at MIT, I co-founded Fab Lab Egypt, a community-based space in central Cairo whose aim was (and is) to build a large community of makers in Africa and the Middle East. My goal was to bring digital design and fabrication machines to a population that had not previously had access to them. I thought that once new users learned how to use these tools, they would be able to create and improvise on their own. However, I saw that only experienced makers were able to interact with the machines and create independently.

The assumption has long been held that that learning to design and make is an intuitive process and that new methodologies for teaching design are not needed. Existing pedagogical approaches focus heavily on instructors and outcomes, neglecting the importance of the learning process itself.

My motivation for this dissertation is to introduce a methodology that will enable emerging
designers and makers to improvise and create things on their own. The assumption has long been held that that learning to design and make is a very intuitive process, and that new methodologies for teaching design are not needed. But how, then, do we learn to make something? What are the potential roles of computational tools, theories, and practices for understanding, describing, and enriching making and learning? What do we learn from machines, and what do machines learn from us? Finally, what do we learn from making?

1.1 Making++

In combination with Herbert Simon’s (1996) definition of design as the “intellectual activity that produces material artifacts and activities,” and George Stiny’s (2008) approach to design as a form of computation, I view making as an embodied, “situated action” (Suchman, 2006) that responds to circumstances and surprises, uniting both mental actions such as design with physical actions such as construction (El-Zanfaly, 2015). You make something, you feel and sense it, and then you react to it. Along the same lines, Knight and Stiny (2015) define making as “doing and sensing with stuff to make things” (p. 12). This undertaking involves more than making physical models. It is an embodied activity that creates both material objects such as spaces and artifacts and immaterial phenomena such as light and experience.

1.2 Making + Design

Historically, theories of creative design practices in art, architecture and craft have reiterated a separation between mind and body. From antiquity to the present, writings about these activities persistently suggest that things must be designed and planned entirely before they are constructed. Mental and visual activities have been seen as the most creative part of the process, leaving the hand as the slave with which to implement what the mind has dictated.

The introduction of digital design and manufacturing machines in the mid-twentieth century has had an enormous impact on design. Digital design and fabrication technologies have evolved from being merely tools for representation and materialization to acting as key players in shaping design practice itself (Cardoso Llach, 2012). These technologies have brought many positive changes to architecture and industry: precision, the speed of construction, and the facilitation of communication among all parties involved in a project. However, even with the advancement of these technologies, design practices still follow Alberti’s adaption of Aristotle’s hylomorphic\(^1\) model of separating the design phase from the construction phase. In this linear process, the design phase stops when representations and execution of drawings begin. Yet despite the meticulous advanced planning allowed by digital tools, surprises may still arise on site during construction. One of the reasons for these surprises is that the effectiveness of digital technologies depends on the designer’s experience: designers who lack experience with a certain material, for example, may find that it simply will not work in the way s/he has foreseen on a 3D screen. These technologies also depend on one human sense: vision. It is expected that the

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\(^1\) According to Aristotle, putting Form (morph) and material (hyle) together is essential for creating anything needed, and this hylomorphic model has been in the western thought for centuries now. In other words, Hylomorphism is imposing a mental thought or idea on material; it is the separation between mind and body or designing and building. (Ingold, 2011a)
designer will be aware of the physical aspects and implications of their design: materiality and structure, and phenomenological aspects such as experience, delight, and gravitational force. Even simulation software depends on representation and the designer’s sight.

1.3 Making + Learning

“Tools... How [do they] affect our understanding of what it means to make things? And how might this understanding be changed if we were to regard the use of tools not as the operation of a technology but as an instance of skilled practice?” Tim Ingold, The Perception of the Environment, 2000.

Design pedagogy has suffered for two reasons; first, Alberti’s separation of design and construction has been applied to the design studio. Students are trained to represent their designs using 2D drawings and physical and digital models without understanding how their designs will be constructed or whether they are even buildable. While institutions offer courses on digital fabrication, students are encouraged to build prototypes in design studios without fully understanding how they might actually be constructed. This separation between design and construction hinders creativity and limits the students’ capabilities for predicting the feasibility of their designs. Second, pedagogical methods in the design studio have not yet adapted to integrating these technologies so that they engage all the students’ modalities in learning. The conversation for the past two decades has been about integrating computer aided design in the studio. Digital fabrication has been treated as a way to analyze and represent rather than as a tool for thinking through making and designing.

In order to learn about materiality, structure, tectonics, and spatial aspects, students need to do more than view their digital representation on a screen; they need to interact physically with the things being designed. This direct interaction is essential for improvisation and learning in making.

Contrary to common belief, improvisation and learning to design and make something is not a black box process that comes from acquiring tacit knowledge or creative intuition. As with any craft, it is an embodied process: the learner must get his/her hands dirty by directly interacting with the object-in-the-making. This direct interaction builds the learner’s sensory experience and spatial reasoning – i.e., the ability to imagine things in three dimensions with minimal information. It is essential to touch the material, make judgments, react to changes in the object, and to think about how parts come together. Although digital fabrication machines are used to serve as a creative means of making and learning, they are often no more than cookie-cutters, executing planned designs while sidestepping the human, embodied interaction that can lead to surprises. Furthermore, these surprises are important, as they present opportunities for learning, experimenting, and improvising.

1.4 Making + Machines

In 1966, MIT Professor Steven Coons heralded CAD/CAM machines as “the perfect slaves” that would “free man from the myriad, tedious mechanical tasks that sap his energies, and allow him to concentrate fully on the creative act” (p. 11). However, I agree with other theorists (Ingold,
2011a; Oxman, 2012) that this proposition reinforced a disunity between design and construction, engendering the late twentieth century reliance on digital fabrication machines to banish human agency to the periphery of the making process. Nonetheless, there is no doubt that machines save time and effort and allow iteration. Moreover, theorists and practitioners consider that these machines help in the feedback process of designing and making (Carpo, 2011; Marble, 2010; McCullough, 1998; Özkär, 2007; Phelan, 1981).

Current digital fabrication machines and robots have a few weaknesses. They have not changed since they were invented in the mid-twentieth century. They were built for automation and repetitive autonomous tasks, not a creative design companion or a learning tool. They promote interaction with virtual user interfaces without allowing physical interaction with the objects being made. These interfaces and their linear process of production create cognitive and perceptual obstacles, making it difficult for non-experts to create and improvise. My work eliminates these obstacles by helping users collaborate with fabrication machines, utilizing their computational power and precision in concert with hands-on engagement with materials.

1.4.1 The cookie-cutters

When digital fabrication machines are used as cookie-cutters, everything is predetermined and fixed and design becomes, as the late furniture design professor and theorist David Pye (1978) has described it, a “workmanship of certainty.” In this approach, precise design takes place first in modeling software, and is executed afterwards by the machine. As MIT computer scientist Douglas Ross (1960) stated, the machine builds the design “without human intervention.”

Acknowledging this gap between design and construction in digital fabrication machines, some scholars have suggested solutions, such as interactive digital fabrication (Willis, Xu, Wu, Levin, & Gross, 2011; Zoran & Paradiso, 2012). These attempts promise some modulation and direct interaction or, as Pye (1978) called it, “workmanship of risk.” However, these machines are still in too early a stage to achieve the advantages of functioning as digital fabrication machines and, at the same time, promoting direct engagement in learning.

Of course, not all machines in digital fabrication labs in educational settings are used as cookie-cutters. Fifteen years ago, Professor Neil Gershenfeld opened the first fabrication lab at MIT (Gershenfeld, 2008). At first, he observed that digital fabrication labs and community maker spaces were attracting mainly designers and makers who already had a background in making, or had a clear artifact in mind.

I propose that it is not enough for novice makers to learn the skill of operating a machine and know its capabilities. Having observed and taught different making workshops, I have realized that instruction-based learning does not allow the learner to transfer what he or she has learned in another problem or project to the current one. A novice maker might learn to make a curved surface on a 3D printer, but s/he may not realize that s/he can also make this surface with a laser cutter. Clearly, it is important to introduce techniques and interactions in making and learning that can help overcome this kind of cookie-cutter mind-set.
In order to solve this cookie-cutter problem, we need to develop a novel learning process that builds the novice’s sensory experience and spatial reasoning in making so that s/he can bring all her/his faculties to bear and see beyond the possibilities enabled by the machine.

1.5 Making + People

Digital fabrication technology and fabrication labs have both social and technological implications for individuals and communities, and they are expected to affect many more people in the future. In their recent book, Gershenfeld and his brothers describe personal fabrication as the third of three digital revolutions after computation and communication (Gershenfeld, Gershenfeld, & Cutcher-Gershenfeld, 2017). By providing both technological and social road maps of fabrication, they explain how fabrication and fab labs empower individuals and communities “to produce and share products on demand” (p. ). The book introduces “Lass’s Law,” which states that the number of fabrication labs in communities and universities in the world is doubling every year and a half. This means that by year 2030 there will be approximately one million fab labs across the globe; ten years later this number will reach one billion. Dale Dougherty, the CEO and founder of Maker Media, which issues Make magazine and organizes the global Maker Faires, sees making as a less formal maker movement. In his view, this movement does not need a strong technical background in digital fabrication (Dougherty, O’Reilly, & Conrad, 2016).

1.6 I: Imitation, Iteration and Improvisation

To challenge the disembodied interaction so often reinforced by the use of digital fabrication technologies in learning settings, I introduce in this thesis a new learning and making methodology inspired by craft learning and observations from experiments I have conducted. I call this methodology for its three-layered operation of Imitation, Iteration and Improvisation. While the acts of imitation, iteration and improvisation are utilized in many other learning environments, combing the three together in a formalized, cyclic manner using digital fabrication tools in design pedagogy represents a new approach. Tested in a variety of educational settings from middle school to university, I fosters a new ability to make things through the body’s direct and iterative engagement with materials, tools, machines and things. It brings learners back to the lost embodied interaction, and allows them to develop their sensory experiences to improvise and create on their own. It also teaches students how to use different mediums of creative production simultaneously, rather than going through the typical linear and sequential process of traditional design studio. In this thesis, I introduce and analyze case studies from
courses I taught at the Massachusetts Institute of Technology (MIT) and at the Istanbul Technical University to test the $I^3$ process.

In the following chapter – Chapter 2, Making to Learn and Learning to Make: Computational Making – I discuss the relationship between making, design, computation and learning. I discuss the importance of the morphogenetic model versus Aristotle’s hylomorphic model. Next, I argue the importance of the role of computation in generating and describing the process of making. I posit that both making and learning depend heavily on embodied, situated experience, which comes from both action and perception. I highlight the difference between tacit knowledge and skilled practice, the role of shaping the human experience, and the current pedagogical methods in design studio and making courses.

In Chapter 3, $I^3$: Imitation, Iteration, Improvisation, I introduce the $I^3$ process in detail. I explain how I created this process and discuss its stages of Imitation, Iteration and Improvisation. In explaining $I^3$, I use several examples from three courses I taught during the last three years: Computational Making: Light and Motion, given at MIT in Spring 2015; the Enormous Smallness Architectural Studio, taught in Istanbul Technical University in Fall 2015; and Making Spaces: Lightweight Structures for Social Interactions, given at MIT in January 2017. I introduce the concept of making fast and slow, a means for reflecting while making that helps students learn from their actions and decisions as they make. I also discuss the role of the instructor in the process.

In Chapter 4, Development and Testing with Case studies, I tell the story of the continuous process of developing and testing $I^3$ during the teaching of the three courses referred to above. In each course, the scale of the thing-in-the-making becomes larger. In Computational Making: Light and Motion, I began with small things – interactive lighting units. In the second course, Enormous Smallness Architectural Studio, the thing-in-the-making became a scaled play space for children. In the third course, Making Spaces: Lightweight Structures for Social Interactions, the thing-in-the-making became a 1:1 scale lightweight structure occupying a space of around thirty cubic feet. I present a summary and analysis of the case studies after each stage. At the end of this chapter, I present provisional results and an analysis of the $I^3$ case studies along with a summary of the data gathered from the questionnaires.

I present my concluding thoughts in the last chapter – Chapter 5, Conclusions and Future Work.
Computational Making: Making to Learn and Learning to Make
2 Computational Making: Making to Learn and Learning to Make

“The Bauhaus believes the machine to be our modern medium of design and seeks to come to terms with it.”

In this chapter, I examine the relationship between making, design, computation, and learning. I discuss the importance of the morphogenetic model as a remedy to Aristotle’s hylomorphic model. Next, I argue the importance of the role of computation in generating and describing the process of making. I posit that both making and learning depend heavily on embodied, situated experience, which comes from both action and perception. I highlight the difference between tacit knowledge and skilled practice, and investigate the role of embodied human-machine interaction in shaping the human experience. I also review current pedagogical methods in design studios, making courses, and online instruction projects in several educational settings.

2.1 Thinking through making

Aristotle introduced the hylomorphic model of imposing form (morph) on matter (hyle) to create something. This model has been prevalent in Western thought ever since, reinforcing the separation between mental and physical actions, and, according to some scholars, constituting a reductionist theory of life (Ingold, 2011a; Pallasmaa, 2009). Affected by the assumptions of the hylomorphic model, Renaissance architect Leon Battista Alberti introduced the concepts of Lineamenta and Structura, essentially separating the design stage as a higher mental activity from that of construction itself (Alberti, 1992; Carpo, 2011; Oxman, 2012). However, this separation is sometimes ineffective. For example, the architect Antoni Gaudi had to supervise and build some parts of the Sagrada Familia on site because he was unable to draw it for the workers. He had to explain it viva voce, to shape what was in his mind with his hands.

I propose that the making of any object provides an examples of the importance of what philosophers Gilles Deleuze and David Félix Guattari (1987) call “matter flow.” Using this idea of flow, the social anthropologist Tim Ingold (2013) introduces the morphogenetic model as an alternative to the hylomorphic model. In this model, making is a situated action between forces and materials rather than an exchange of action between mental image and object. In the computational theory of Shape Grammars, George Stiny (1971) proposes a computational design model based on rules, in which you see something, you apply any rule of your choice, and then you see something new. He calls this process “recursion and embedding” (Stiny, 2008). Similarly, Ingold (2013) explains that making is an intertwining process of the flow of material and consciousness together, a process which depends on action and perception (Figure 2.1).

These views of making are in contrast to the idea of the hylomorphic model. In the hylomorphic model, there is a separated longitudinal relationship between the flow of consciousness and the flow of material, in which the object is separated from the mental image.
Stiny (1977) introduced visual rules for the generation of the Chinese ice-ray lattice designs, claiming that the maker sees a shape as it emerges, applies a visual rule, and produces a new shape. I claim that the final shapes and geometry of these window screens emerged not only by the application of visual rules, but through the embodied interaction among the maker, the context, the material, the tools, and the ice-ray. As demonstrated in Figure 2.2, the maker actually sees new, emerged shapes while cutting the wooden rods and fixing them. Making the lattice on-site allows the maker to see the change of shadows as the entire shape emerges. S/he then reacts to these unplanned surprises and makes decisions accordingly. As a result of these contextual and embodied conditions, this process leads to different shapes of ice-ray windows every time. The maker applies the same rules, but different shapes emerge. This is thinking through making, in which the maker sees and senses something new with his/her whole body every time s/he adds a piece of wood. Here, discovery, as John Dewey states “is never made; it is always making” (1929, p. 76).
Figure 2.2
2.2 Computational Making

Building on the Shape Grammars theory proposed by Stiny, we can more easily formalize the process and actions of making by using rules and schemas. Some researchers have used Shape Grammars and schemas as a tool for students in design and architecture studios to reflect and describe their design projects (Arpak, 2016). A few years ago, I introduced a formalism, *Active Shapes*, for designing and making motion in kinetic structures (El-Zanfaly, 2011) (Figure 2.4). The idea behind this research was to describe and generate an intangible aspect in the design process: motion. Building on this research, I was curious to see if we could compute our sensory experience and become aware of our making actions through rules, a process I called “sensorial computing” (El-Zanfaly, 2013). By following explicit steps, students were able to perceive and describe kinetic motion (El-Zanfaly & Abdelmohsen, 2017). In later research, *Schemas for Material Computing*, I linked intangible forces such as magnetic fields with the shapes of the material shaped by them (Figure 2.5).
However, each one of us perceives and senses differently. While each of us can describe his or her own experiences, what he or she sees and senses, others will receive it according to their perceptions. My research interests grew to finding ways to introduce the making processes of both tangible and intangible things and describing them. In 2014, along with Professor Terry Knight and a colleague of mine in the Computation Group in the Department of Architecture, I introduced Computational Making, an interdisciplinary research group that examines the relationship between the theories, mathematical models and formalisms of abstract computation and the active making of artifacts, human experiences and spaces (Computational Making Group, 2014). Knight and Stiny (2015) introduced making grammars as a way to describe the action of making as computation. As a next step, Knight (2017) used making grammars to represent the temporality of craft performance. In Visualizing making: Shapes, materials, and actions, Gürsoy and Özkar (2015) used visual rules to describe material behavior and characteristics. In the next chapter, I introduce the notion of Making Fast and Slow, and discuss how we can teach students to use schemas to generate and describe their design and making processes.

2.3 Action and perception

As in the making of Chinese ice-rays, learning emerges from action and perception, which in turn is affected by contextual experience. As Dewey explained, learning emerges from experience, which is the interaction between the learner and the environment. Similarly, Ingold (2001) highlighted the importance of the maker’s engagement in perception and action with the environment. According to James and Eleanor Gibson (1955), learning is partially or completely “a matter of perception”; knowledge acquisition is affected by changes in perception, and experience plays an important role in this perception and our reaction to it. Additionally, feedback is important for perceptual development and learning (E. J. Gibson, 1963).

We perceive and learn with our whole body and all our senses while interacting with objects and the environment. It is important for the learner to be physically situated and engaged within the making process. According to the phenomenological philosopher Maurice Merleau-Ponty, we
perceive in a “total way” with our “whole being” (1964, p. 50). In the same line of thought, the anthropologist Mark Paterson claims that in this “inter-modal perception,” in which we perceive an object through some or all our senses, there are no “equivalences between sensory data” (2007, p. 41). Rather than being a process that occurs solely in an individual’s mind, learning is a situated process, which occurs in “a participation framework.” (Lave & Wenger, 1991).

Similarly, making results from situated actions undertaken to reach a certain goal; pre-planning is only a part of the process (Suchman, 2006).

2.4 Tacit knowledge versus skilled practice

Making and craft skills have been referred to as tacit knowledge, a black box knowledge that cannot be described or taught (Collins, 2012). Schön describes this craft knowledge as a process that is “artistic, intuitive” (1983, p. 49). He explains that our craft knowledge lies in actions that we are unable to explain. However, the sociologist of science Harry Collins (2012) claims that all aspects of skill knowledge can be described and learned except the social aspect, which is tacit. On the other hand, Ingold (2011b) challenges the notion of tacit knowledge and the dichotomy between innate and acquired abilities, cultural and biological skills. He introduces skilled practice, in which skill is the product of the field of relations between the mind, the body and the environment. This skill is both biological and cultural, developed by the possibilities offered by the context or environment. Skilled practice is learned by skilled coordination between perception and action and not by the transmission of rules or instructions.

2.5 Embodied interaction: Making to learn and learning to make

Learning comes from experience and direct engagement with the environment. The constructivist approach of learning from experience or learning by doing introduced by Dewey (1938) has been implemented in educational settings from elementary schools to universities. Educators and theorists have endorsed methods in different learning environments that require ways of direct engagement, including Froebel’s kindergarten system (Brosterman, 1997), the Sloyd education system (Sjoberg, 2009), Seymour Pappert’s LEGO/Lego (Resnick & Ocko, 1991), and the approach of the Bauhaus (Moholy-Nagy, 2005).

Thinkers in different fields throughout history have endorsed the role of direct engagement in building the learner’s experience. The geographer Yi-Fu Tuan (2001) defined experience as the ability to learn, not just to perceive and feel. Dewey (1938) considered experience the core of the education process. He emphasized that this experience should have a continuity leading to future experiences. By depending on their own sensations and perceptions gained by experience, learners begin to make their own judgments about the quality and process of their work instead of waiting for feedback from others (Dormer, 1994; Eisner, 2002).

If learning comes from experience, experience is then gained through the process of making an artifact and not by focusing on delivering the final product. While making, the maker learns by interacting with the materials, machines, and tools (Dewey, 1938; Moholy-Nagy, 2005). The material shapes what the maker knows about the material, and the maker shapes the material (Bamberger & Schön, 1983).
While the Beaux Arts depended heavily on the master-apprentice model of craft in studio education (Ockman, 2012), the Bauhaus adopted a hands-on materials-based approach, which advanced through the years from industrial design objects to more experiential objects (Phelan, 1981). Walter Gropius placed “building” -- Bau -- and “design” -- Entwurf -- at the center of the school’s curriculum, which also included material analysis, technical construction, and representation, among others.

2.5.1 Design studios
Current traditional design studios, modeled on the Beaux Arts and Bauhaus models, depend heavily on the feedback students receive from instructors, which influences the students’ next steps and feelings about their work (Ciravoglu, 2014). From the beginning, students depend on external assurances and judgments of their work in order to move forward (A. M. A. Salama & Wilkinson, 2007). Usually, the studio methodology assumes that the students’ design thinking will be linear as in design practice (Ockman 2012).

The role of computer aided design technologies as both tools and design companions in design practice and pedagogy has been discussed widely (Llach, 2015; Mitchell, 1977; Mitchell & McCullough, 1995; Snoonian & Cuff, 2001). However, there is less research on how to integrate computer aided manufacturing technologies and digital fabrication machines into the design studio, and on how this integration affects cognition and perception. Some researchers (Snoonian & Cuff, 2001) have argued that both technologies emphasize the separation between design and construction, and that this separation might negatively affect students’ learning. In the same line of thought, Nicholai Steino and Mine Özkar (2012) highlight the fact that the modernist pedagogical approach in the design studio focuses early on form and space, leaving materials as a second consideration that might be handled by someone else such as a structural engineer. The authors take issue with this approach, emphasizing the importance of the students’ interactions with physical materials as essential to design education.

It is important, then, to introduce a new pedagogical methodology that is based on embodied action and perception, a methodology which shapes the learner’s experience in making using digital fabrication machines. Below, I discuss three learning approaches to formalizing and implementing digital fabrication in education within and outside academia: first, in architecture and design studios; second, in other academic and non-academic settings; and third, in DIY and K-12 education. I discuss a variety of examples in these three approaches. I want to show that there are many pedagogical approaches that focus on utilizing making with digital fabrication machines as a way of materializing planned designs, and that there are fewer approaches that focus on making with these machines as part of the design learning process. I do not include “tinkering” as an approach in my discussion, because it is completely unstructured, random, and with no guarantee of learning or productive results.

In this dissertation, I introduce a methodology that utilizes digital fabrication machines not only as tools with which to execute designs, but as tools that help the learner to enhance his or her design skills through making with them.
2.5.2 Design, art and architecture pedagogy

Currently, in contrast to studios that depend on representations and prototypes, some universities and colleges offer what are described as “design-build studios” in which students learn to design a project and then construct it. Sometimes these design-build programs have a social goal, such as building a shelter for the homeless. In other cases, these studios have been introduced to extend students’ skills in materials and construction techniques (Wallis, 2007). However, I believe that even naming a course as Design and Build highlights the separation I have been discussing in the previous sections.

Some attempts have been made to formalize the teaching of making by using machines in digital fabrication laboratories. Researchers such as Gabriela Celani (2012) apply explicit scientific methods to formalize teaching digital fabrication by structuring fabrication laboratory instruction, step by step, to impart technical skills that allow students to solve a practical problem. There has also been some research on integrating digital fabrication machines into the hands-on learning process. Instead of looking at CAD/CAM as an add-on to design education, some researchers have encouraged students to become accustomed to the machines’ capabilities and limitations as part of the design process (Özkar, 2007). Other researchers have tried to introduce new frameworks for a process of design to construction and applying the frameworks in the design studio (Raspall, 2015).

Some schools, such as the School of Architecture in the Swiss Federal Institute of Technology in Zürich (ETH), see digital fabrication as a core course and area of research in architecture. The ETH actually offers a Masters program that focuses on architecture and digital fabrication. A few years ago, I visited the main digital fabrication facility there. During an interview I conducted with one of the research groups, a researcher explained that they focus primarily on the technical and material aspects of the design process, even in the courses they teach. Other design schools also acknowledge separation between design and fabrication and try to introduce pedagogical approaches to unify them. For example, Professors Jason Kelly Johnson and Andrew Kudless founded the California College of the Arts Digital Craft Lab in 2013. The lab acts as both a studio space and a place for digital fabrication. In an interview last year in an online magazine, *Metropolis*, the founders described the lab’s pedagogical process as an iterative and continuous process, like the process of making furniture in a shop. Johnson described their teaching philosophy as one that attempts to shift “the perception that working with digital tools is a hands-off approach, that software and fabrication tools are autonomous and don’t require a physical craft” (Kwun, 2017). The Taubman College of Architecture and Urban Planning at the University of Michigan is another school with a large fabrication lab facility. Its digital fabrication machines include six industrial robots that work on a wide variety of materials. According to the school’s website, “Research through Making” is a research program that started in 2009 to engage both faculty and students “in architecture research or creative projects that are predicated on making” (“Research Through Making,” 2018).

2.5.3 Other academic and non-academic settings

As I explained in the first chapter, Professor Neil Gershenfeld founded the first Fab Lab at MIT. He teaches the highly regarded course, *How to Make (Almost) Anything*, which focuses on learning the technical skills of digital fabrication. The course is open to students from all majors, including architecture, humanities and computer science majors. The course consists of weekly
exercises designed to teach how to use one of the digital fabrication machines to make a weekly project. The students are expected to bring all their learned skills together in a final project. The weekly assignments include learning computer-aided design, electronics production and design, 3D scanning and printing, computer-controlled machining, embedded programming, molding and casting, output and input devices, interface and application programming, composites and networking and communications (Gershenfeld, 2018) (Figure 2.6). The same version of the course is offered to a wider community of students across the globe through the Fab Academy directed by the Fab Foundation and taught by Gershenfeld. Another important element in both versions of the course is the stress on documentation of the making process in each assignment. Each student is asked to document the process verbally and visually step by step on their course website.

The separation of design and digital fabrication makes some sense if the students have some experience in design and need to enhance their skills by learning digital fabrication techniques. For example, the course How to Make (Almost) Anything focuses on teaching both basic and advanced digital fabrication skills, and starts by asking students about their end-of-term project. Because most of the students join the course with an idea already in mind about what to make, the course does not teach design concepts. In fact, the course was designed for MIT Media Lab students who had joined the lab with many skills already.

![Figure 2.6 How to Make Almost Anything Open House, December 2014.](image)

Other approaches focus on learning making by learning the technical skills of using digital fabrication machines as cookie-cutters. In both the School of Engineering and the School of Architecture and Planning at MIT, students are given a one-hour training session, after which they can use digital fabrication labs to make whatever they want. This suggests to me that there is an assumption that students will arrive with creative ideas, indicating the belief that they are already equipped with a tacit knowledge of design. Just to highlight the disembodiment and separation between Mens et Manus, Mind and Hand, in the MIT slogan, “Project Manus” was introduced at MIT in 2015 with a long-term plan to equip MIT with 45 major makerspaces that would occupy more than 150,000 ft². The project is led by MIT professor Marty Culpepper, who is called “Maker Czar” at MIT (“MIT Project Manus,” 2018). The project offers a program that teaches digital fabrication skills to MIT freshmen called MakerLodge (“MakerLodge,” 2018). Basically, the students are taught to use digital fabrication machines but are not given instruction
in design. A special course for all majors and years has been recently introduced at the Martin Trust Center for MIT Entrepreneurship called, *Intro to Making* (Figure 2.7). According to the class website, in addition to teaching how to use digital fabrication machines such as 3D printers and laser cutters, the class also “integrate[s] fun activities that require using knowledge and skill, i.e. *Mens et Manus*.” One of these activities is called the “Equipment Petting Zoo.” The approach of the course seems to be to expose students to a variety of fabrication machines, but it does not appear to integrate these into the design process per se. The capstone of the course is a task in which students apply the skills they have learned to building “a machine to complete a mission” (“Intro to Making - MIT 15.351,” 2018). Since this last task is done “in a race against time,” according to the website, the emphasis seems to be on “designing fast” and producing a final product. In the following chapter, I explain that focusing on the process of making and designing, and “slowing” it by reflecting on it while in action, is important for the student’s learning process.

Another non-academic pedagogical approach is the introduction of digital fabrication skills in a military setting. According to the DARPA Mentor2 Annual by the Fab Foundation report of July 2014-2015, the Fab Foundation’s MENTOR2 project was designed to address “workforce training for military field repair and maintenance, as well as in-theater equipment and part manufacture in ways that decrease dependence on remote supply chains and model-specific repair and maintenance approaches and increase technician ability to problem-solve and innovate in the field.” (The Fab Foundation, 2015, p. 1) The Fab Foundation installed two full fab labs
and conducted two customized Fab Academy courses for military technicians in two different military bases, MARM in Norfolk, VA and SOCOM in Tampa, FL. In both programs, the students went through four, one-week learning modules (Figure 2.9). Among the Fab Foundation’s findings was evidence that “iterating” on the same project in the SOCOM site was more effective in leading students to be able to create a final project than were the short, discontinuous exercises undertaken in the other program. This example supports my discussion of the importance of iteration in the next chapter.

![Figure 2.8 Machine building workshop from MENTOR project by the Fab Foundation. From the DARPA Mentor2 Annual Report by the Fab Foundation, 2015.](image)

### 2.5.4 DIY and K-12

Generally speaking, in the DIY and K-12 context, the use of digital fabrication machines as cookie cutters has been reinforced by their role in materializing what is already designed and prepared. I have observed in K-12 education workshops and meetings with teachers and fabrication lab managers that students are expected to first draw and model in the classroom, then go to the lab to execute their pre-planned design. Stanford Professor Paolo Bilkstein leads a project that he created in 2008 called Fablab@School, which focuses on fabrication labs in K-12 schools. Bilkstein has observed that the main users of fab labs in schools are children who are already makers (Bilkstein, 2014). In DIY websites such as Instructables.com (“Instructables,” 2015) and Makezine.com (“Make,” 2015), makers from the online community give detailed step-by-step instructions on building projects. Some projects in these websites even offer files ready for laser cutting and 3D printing. Some websites, such as Thingiverse.com (“Thingiverse,” 2015), provide the 3D files ready to be printed on any 3D printer. Students have only to download the file, press print, and a 3D printed object emerges, a perfect example of using the tools as “cookie-cutters.”

We need a new methodology that will bring embodied learning back to the classroom. In the design studio, we need methodologies that will take digital design and fabrication technologies and bring them into the design and making process as equal partners. In the next chapter, I introduce I³, a three layered embodied methodology for making and learning that unites design and construction. This methodology could be used in both academic and non-academic learning environments. In this dissertation, however, I focus on introducing I³ in academic settings at both the undergraduate and graduate.
Imitation, Iteration, Improvisation
3 I³: Imitation, Iteration, Improvisation

In this chapter, I introduce I³, a process for learning to make and making to learn that I developed to address the pedagogical problem of the separation between design and fabrication in the design studio. First, as background to I³, I discuss the notion of mindful copying. Then, I explain how I created the process of I³ and discuss its stages of Imitation, Iteration and Improvisation. To help explain I³, I use several examples from three courses I taught during the last three years: Computational Making: Light and Motion, given at MIT in Spring 2015; Enormous Smallness Istanbul Architecture Studio, given at the Istanbul Technical University in Fall 2015; and Making Spaces: Lightweight Structures for Interactions, given at MIT in January 2017. I then introduce the concept of making fast and slow, a means for reflecting while making that helps students learn from their actions and decisions as they make. Last, I discuss the role of the instructor in the I³ process.

3.1 Precedents of I³

"Immature poets imitate, mature poets steal, bad poets deface what they take, and good poets make it into something better, or at least something different." T.S. Eliot, 1920.

The actions of Imitation, Iteration and Improvisation exist separately in many learning settings. However, putting all of the three actions together in a formalized, cyclic manner using digital fabrication tools in design pedagogy is new. I discuss below the notions and precedents that inspired my I³ methodology. I show that copying is a creative action, and discuss precedents of each “I” in the arts, crafts, cognitive sciences, organizations design, performance and music.

Over the course of my graduate study and teaching, I realized, through my observations and experiments, that acquiring technical skills and following step-by-step instructions are not enough for learners to improvise and create on their own. This realization led me to study how we learn a craft. In Educating the Reflective Practitioner, Schön (1990) explains that in order to enable students to improvise, we need to adopt learning methods from art studios and craft apprenticeships. Craft is, after all, a human-centric making process that involves interacting with materials, tools, and the thing-in-the-making. As in painting or drawing, learning a craft relies heavily on copying and modulation. The learner first copies the making actions performed by the master craftsman in order to copy a thing in-the-making. Then, since making one copy is usually not sufficient to master a technique, learners must make several copies. Each copy is a varied iteration of the earlier copy.

3.1.1 Mindful copying

Take, for example, how a student learns to make ceramics. The master demonstrates how to center clay on the wheel, and the students follow the instructions, observe and copy the actions, and attempt to produce the demonstrated thing. Over several sessions, students repeat the actions to create small, even cylinders out of clay. However, once they start copying the cylinder, they often realize that what they are making is not even close to what the master demonstrated. Through this process, they learn how the clay behaves under their hands and understand what happens if they increase the pressure or add water (Figure 3.1). They will probably make several
iterations that are more like bowls than cylinders, although eventually they may produce an even cylinder. Throughout this process, they gain skills and experience, and as they progress, they are able to experiment with new tools and techniques to create new forms on their own.

Figure 3.1 Copying in the ceramics studio.

Contrary to common belief, copying is a creative act; it depends on the learner’s observation and judgment in choosing what and how to copy. I call this *mindful copying*, and it is essential for the learning process. We learn from imitation: reverse-engineering is a good example of learning by doing (Cross, 2011). Art education in many universities is based on copying masterpieces and learning the techniques used to create them (Fitch, 2010). In some cultures, copying an artwork is considered an artwork in itself and the foundation for learning to create other artworks. For example, in Japanese calligraphy, copying the master’s work is essential for learning (Nakamura, 2008). In China, the verb *shanzhai* is known as the act of innovative copying; it comes from Shenzhen city, where products such as electronics that are already on the market are copied.

Picasso’s series of paintings inspired by Diego Velázquez’s painting *Las Meninas* is one of the great examples of how creative mindful copying can be. Picasso painted forty-five variations of this painting, keeping the same figures and their roles (Sabartes, 1959). However, all the paintings in the series are different, varying in composition, color, and level of detail. Picasso explained that he wanted not to make a copy of *Las Meninas*, but to paint his own, unique version. Each one of us *senses* differently, in terms not only of what we see but also of what we touch or smell. Thus, whatever is being copied, whether an action or a thing, emerges as something different from the original copy and is thus unique.

### 3.1.2 Imitation precedents

As I discussed in the section above, Imitation is creative and has been implemented in the learning approaches of several fields. For example, art education in the eighteenth century was based on observation, imitation and emulation (Graciano, 2013). The Ecole des Beaux Arts
pedagogical approach to teaching architecture depended heavily on copying and replication exercises of previous artists’ work (Mix, 2015). In other words, imitation was considered a method of knowledge gaining and transmission (Jacob, 2016). Cognitive scientists have long studied and proven the importance of imitation in learning. For example, MIT professor and neuroscientist Michael Fee studies the brain circuits that are responsible for trial-and-error learning and producing complex sequential behavior in the human brain and in the brain of birds at different stages of life. His research shows that birds learn to sing through imitating their father’s songs several times (Andalman & Fee, 2009). Other cognitive scientists have shown that art students produce new artwork by copying another’s art work and/or the actions that produced that work. They also showed that students produce creative results when they copy unfamiliar art styles (Okada & Ishibashi, 2017). Imitation is also applied in teaching machines to perform complex tasks through observations and actions by both humans and machines (Hussein, Gaber, Elyan, & Jayne, 2017). Today, I consider that imitation is what users do by following instruction-based tutorials for DIY (Do It Yourself) projects such as Instructables, and that it is a key means of learning to make.

3.1.3 Iteration precedents
Iteration is a process that has long been applied in software and product development and in knowledge acquisition. Besides applying iteration in craft learning, iteration has been used as a means for students to develop their projects in the design studio (Zamberlan & Wilson, 2017). Some educators have even tried to plan iterations in the design studio to produce better outcomes (Shannon & Radford, 2010). Iteration is part of interdisciplinary research processes and approaches employed to encourage creativity (Darbellay, Moody, & Lubart, 2018). Some analysts consider that one of the main reasons for the success of companies in Silicon Valley is the iteration of products from older versions of the products or other precedents (Lauria, 2014). Part of the development in user interface design is the cyclic process of iteration through user testing and producing updated versions (Nielsen, 1993).

3.1.4 Improvisation precedents
Improvisation is the act of responding to surprises and/or acting on the fly. Jazz and other theatrical performances are known for their improvisational approaches. The teaching of jazz in music schools highlights the improvisational and embodied nature of skilled practice, which I discussed in Chapter Two; some studies also found that experiential learning enhances improvisation (Pereira Christopoulos, Wilner, & Trindade Bestetti, 2016). These improvisation approaches have already been adapted and applied to other fields. For example, some researchers have applied improvisational jazz approaches in product development in business environments to adapt to uncertainties that might arise (Kamoche & Pina e Cunha, 2001). Other researchers examined stimulating organizational creativity in companies using theatrical improvisation (Nisula & Kianto, 2018).

Scientist have studied improvisation in performance as a way for brains to become more creative, and they also showed that improvisation is better nurtured through formal training (Lopata, Nowicki, & Joanisse, 2017). In other words, we can teach improvisation in a formalized way. Like the steps in learning a craft, learning jazz can be seen to include the three stages of Imitation, Iteration and Improvisation in an indirect way. The students first learn to imitate and
play pieces by heart, then try to play them in a different way and, finally, they are encouraged to forget everything they have learned and improvise (Wilf, 2010).

Action shapes our perceptual apparatus (Noë, 2004). Learners need to make several iterations in order to see and feel new things each time, gaining skilled practice, and learning to respond to surprises as they arise. I consider creating and responding to surprises in making to be improvisation. Like many theorists, I claim that acquiring this craft knowledge allows makers to make whatever they can imagine (Dewey, 1934; Eisner, 2002; Gropius, 1919). I believe that new ways of making to learn and learning to make should thus allow modulation – i.e., iteration and improvisation. I discuss below I^3, the methodology I propose here to learn design through making.

3.2 [I^3] Imitation, Iteration and Improvisation

Design studios have not yet successfully integrated digital fabrication machines and tools into the pedagogical process. As in design practice, the studio follows a linear process of first designing and iterating, then fabricating. Additionally, digital fabrication machines in learning settings are most often used as cookie-cutters or wind-up toys; everything is planned in advance, leaving little space for surprises. Yet reacting to surprises is important in learning to make something. In order to learn to make and learn through making, we need a direct, embodied interaction between the learner, the tools, and the thing in-the-making. I introduce here a process for learning to make and making to learn inspired by the idea of mindful copying.

This new process aims to achieve what I described earlier as a morphogenetic approach to making, eliminating the separation between design and construction (Ingold, 2011a). I call this methodology I^3 for its three-layered operations of Imitation, Iteration and Improvisation. By highlighting making as a situated, embodied action, I introduce a human-machine making process in learning that achieves direct physical interaction among the maker, the thing-in-the-making, and the tools being used (Figure 3.2). Consequently, the thing-in-the-making emerges gradually (Sjoberg, 2009). This I^3 process fosters improvisation, empowers learners to create on their own, and allows the transfer of their learned knowledge to another project. As learners progress through the process, their need for external guidance decreases and their ability to judge for themselves increases. This pedagogical process can be used with both novice and experienced makers and designers but is most successful with novices.
Hands-ON Direct interaction with object and material.

Hands-OFF Using digital fabrication machines as wind-up toys or cookie cutters.

Hands-ON Machines become companions to the maker in making.

Figure 3.2 Learning to Make and Making to Learn. How \( I^3 \) brings back the hands-on interaction of traditional craft, which is in contrast to the current cookie-cutter role of digital fabrication machines in learning settings.

With Imitation, Iteration and Improvisation in making, learners build their sensory experience with judgment and dexterity. Imitation involves copying a thing while analyzing and processing many aspects of the thing; Iteration involves making copies and variations of the thing that include changes; and Improvisation involves creating something new or spontaneously, altering the thing. \( I^3 \) is sequential and layered (Figure 3.3). Improvisation includes both Iteration and Imitation, and Iteration includes Imitation.

Figure 3.3 The overlapping layers of \( I^3 \) Imitation, Iteration and Improvisation.

\( I^3 \) starts first with the Imitation stage, asking students to choose and analyze a precedent, then try to make it with the materials and tools at hand. The imitation could take the form of making an exact copy of a thing, copying a design concept, or copying from more than two things. Second,
in the Iteration stage, students are asked to make several guided iterations of the things. In each iteration, students are asked to change only one aspect of the thing, such as its material or geometry. Third, in the Improvisation stage, learners improvise and produce another final iteration or completely new thing (Figure 3.4). In general, once learners finish the iterations, they have enough experience to be able to improvise and make decisions about future steps.

Figure 3.4 The process of \([I^3]\) Imitation, Iteration and Improvisation by Jackie Liu in the Computational Making: Light and Motion class.

### 3.2.1 \(I^3\) development and testing

I have been developing \(I^3\) and computational design and making methods since 2013 (El-Zanfaly, 2013). To test the \(I^3\) process, I conducted experiments in educational settings in the United States and the Middle East. Through early experiments, I observed and tested the making processes of novices and their interactions with machines. Later experiments were conducted to further test and develop the \(I^3\) process. One of the early experiments was conducted in Summer 2014 at the Fab Lab Egypt, a community maker space. It consisted of six weekly workshops for middle and high school students with no prior background in design and physical making. The students gained experience by first imitating a project from the website Instructables with a laser cutter, and then making iterations of several selected projects with a laser cutter and electronics (Figure 3.5). By the end of the six weeks, the students were able to improvise and make what they had in mind for new projects using the laser cutter.
In the following sections, I define Imitation, Iteration and Improvisation more fully, using examples from experiments I conducted in a series of courses I taught both at MIT and Istanbul Technical University (ITU). I list the courses here:

(1) *Computational Making: Light and Motion*, Spring 2015, MIT.
(2) *Enormous Smallness Istanbul Architecture Studio*, Fall 2015, ITU.
(3) *Making Spaces: Lightweight Structures for Interactions*, January 2017, MIT.

In the first course, *Computational Making: Light and Motion*, which I taught in consultation with MIT Professor Terry Knight in Spring 2015, students were asked to make a small thing: an interactive lighting unit. The students designed the lighting units so as to react to external changes occurring around them by changing their physical shape or lighting state. Students were undergraduate and graduate students from diverse majors. Their design and technical backgrounds varied. We used I³ as the course structure, and we led the students through a process of first imitating an existing lighting unit, then making four guided iterations of it, and then improvising on their existing unit or creating an entirely new one. During the course, the students used visual rules to describe and document their processes of making. As this was the first course to implement and test I³, I wanted to observe where the method was most effective and where I might need to change it in future courses.

In the second course, *Enormous Smallness Istanbul Architecture Studio*, the thing-in-the-making became larger: a scaled play space for children. The course was offered as an architecture studio for second year architecture students at Istanbul Technical University in Turkey in Fall 2015. The studio was led by MIT PhD alumna Mine Özkar. This was the first architecture studio for the students; they had no background in 2D and 3D modeling software or digital fabrication and had spent their first year learning basic representation techniques and tools. I wanted to see how I³ could be implemented in an architecture studio to teach not only design, but also digital modeling and fabrication skills. My goal was to use I³ to weave these aspects together.
In the third course, *Making Spaces: Lightweight Structures for Interactions*, given in January 2017 at MIT, the thing-in-the-making became a full scale lightweight structure occupying a space of approximately thirty cubic feet. The course met nine times during the January Independent Activities Period at MIT. Students from a variety of backgrounds and levels attended the class, including visiting students from the Singapore University for Design and Technology. In this course, I wanted to examine and develop I^3 in the context of building larger structures. More specifically, I wanted to add scale as a major element in the process and observe how students would react to scaling up their prototypes.

I discuss and analyze case studies from these three courses in more detail in the next chapter. In the following subsections, I explain what I mean by the three stages of I^3 with some examples.

### 3.2.2 Imitation: (x → prt(x))

I define Imitation here as the act of mindful copying of a thing either fully or partially. Students can choose or be instructed either to copy the entire thing or only a part of it (x → prt(x)). If they choose to copy the entire thing, then they must use the same materials, geometry, structural elements, assembly, design concept and fabrication technique as the original, if these are available. As I explained before, the imitated thing will never be exactly the same as the original thing, but the intention of the maker should be to copy the thing as accurately as possible, in all its detail. Imitating a thing partially includes copying only some aspects of the original thing such structure, geometry, scale or even the fabrication technique. Through the process, students apply their own judgment in choosing what to copy and to make from what they are imitating.

In the I^3 process, Imitation is a first stage for jumping in and breaking the ice with the design and fabrication media. Instead of spending time deciding what to make and what details to include, students have something to begin making. Once they start, they learn the basic technical skills of using the digital and manual tools to realize what they are trying to make. Imitation includes observation, analysis and interaction, all of which involve the senses and movement.

As they make, students observe and analyze the details of how things come together, how to assemble the structure, and how to attach the parts. They decide on the exact location of each part, estimate approximate dimensions, test physical and material behaviors, and see how to first draw and then fabricate a specific geometry. While interacting with the tools, machines and materials to make the thing, students use their bodies to sense and learn.

For instance, in the *Enormous Smallness Architecture Studio* that I co-taught in Istanbul in 2015, one group of second year architecture students calling their project *Inside-Out* chose an already-built structure, analyzed it and recreated it (Figure 3.6). They even contacted the architect who built the original structure to learn about how it was built. They explained that it had been built from a steel structure, filled with foam and then wrapped in plastic sheets to create a smooth surface. They first used manual drawings and sketches to make a scaled copy of the original structure. The structure had some openings in it, and realizing that these openings were random, the students estimated their dimensions in relation to the structure of the whole. They bent some metal rods to create the main frame of the structure, then realized that they needed a way to connect all the structural pieces together. After testing the use of foam in the structure, they
realized that it failed to create the smooth surface they wanted. So, they used plastic wrap and carved the foam after it dried.

By having to consider all these aspects and fabrication techniques in order to imitate and attempt to remake something, students reframe their perceptual experience. At every stage of the making experience, there are more details to be seen and felt, more details to think about, more decisions to be made about the next steps. These details could include physical properties such as surface textures, specific material behaviors, or phenomenological aspects such as experience, light, and shadow. Students thus acquire the experience and feel of a “skilled practice” (Ingold, 2011b). Additionally, they learn to judge what is relevant to their project (Dormer, 1994).

In using 13 as a course structure, instructors first ask the students to choose some examples related to the theme of the course, then choose one example to imitate. Depending on the course theme and the background of the students, this imitation could be full or partial (Figure 3.7). Students can choose images from photos, from the Internet, or from books. The more detailed the image is, the better it is for learners, since they must otherwise assume fabrication techniques and hidden details. If learners are novices, it is better to ask them to choose one precedent and imitate it fully, instead doing of a partial imitation, so that they have fewer surprises along the way. Their energy and focus will be directed toward which material and tools to use, and how to put everything together. If the students have a background in design and fabrication, imitation can be partial. Imitation can also be accomplished by combining two or more precedents, such as imitating the geometry from one precedent and the fabrication technique or material from another.
3.2.3 Iteration: (x → t(prt(x)))

I define Iteration as the making of another copy of the thing already made in the Imitation stage, but adding something new to it or changing it in some way. Iteration here is guided; in every iteration made, everything must be kept the same except for one feature and whatever depends on that feature. The changed feature could have to do with material or geometry, or with the scale of one element and whatever depends on it. In I^3, students must make at least three iterations in order to have the opportunity to experiment with several design and making aspects and to interact with several tools.

Iteration in making is an embodied activity that allows “recursion and embedding” (Stiny, 2008) along with action and perception, the importance of which in learning and experience I discussed earlier. In every iteration, learners sense something new, whether through seeing or touching. Additionally, Iteration provides a means for breaking the fixation that novice designers often have on their early design, and helps improve their basic techniques (Cross, 2008). Limiting each iteration to a change in one feature only, prt(x), forces them to focus on developing and enhancing their thing in terms of one certain aspect x → t(prt(x)). This focus prevents learners from trying to change many aspects at once, which might lead to confusion. This focus also allows them to learn more about the changed feature and the consequences produced by changing it.
For example, changing one feature may lead to changing the material, which in turn can lead to learning about a new material behavior different from that of the original material used. The change in material might also lead to a change in the structure or geometry that was shaped by the original material. These changes might also lead to learning new fabrication techniques and technical skills. Making an iteration that enlarges the scale, for example, would lead to moving from laser-cutting a sheet of acrylic to milling wood on a CNC router. For example, in the course *Making Spaces: Lightweight Structures for Social Interactions*, a group of students calling themselves The Briar group moved from paper, which they used in the Imitation stage, to laser-cut clear polystyrene in the first iteration, to a one-eighth inch flexible wood sheet cut on the CNC router in their full-scale iteration (Figure 3.8).

![Figure 3.8 The Briar Group making a scaled iteration of their structure.](image)

3.2.4 **Improvisation: (x → y)**

Improvisation involves sensing new things and reacting to surprises as they emerge while designing and making. According to several theorists (Ingold & Hallam, 2007; Sawyer, 2000), improvisation is the creative process and the movements that produce results. As I³ is a process of making and learning, it focuses on the creative work-in-progress and actions that create the thing. We can introduce new methods in the making process that allow matter-flow, or the unity between the image and thing in making -- as Dewey called it, “doing and undergoing” (1934). Thus, Improvisation is open-ended.
Even in the Imitation and Iteration stages, improvisation exists, although its level increases with every stage. The learners’ making and sensing abilities increase during the I³ process until they can create something on their own. In the Imitation stage, fewer surprises occur; learners are copying a thing that they already see. Surprises occur in the fabrication process, when using the machines or tools or when dealing with unexpected structural or material behavior. Learners have to react to solve the emerging surprises to build their copy of the thing.

In the Iteration stage, learners face a new challenge in choosing what to change in each guided iteration, and how to modify it in reaction to the surprises arising from such a change. Thus, improvisation increases in every iteration made. Improvisation reaches its maximum at the final stage, where learners are not provided with any guidance. Improvisation also prepares learners to be able to create an iteration from a precedent in a new context or with a new project.

In *Making Spaces: Lightweight Structures for Interactions*, the Briar Group faced a new challenge. Although they had tested some parts of their structure at 1:1 scale (Figure 3.9), when they started building the final structure they realized that the wall pieces would not stay in their allocated slots in the base because the material weight was putting unexpected tensions and forces on the entire structure (Figure 3.10). Thus they had to improvise and add some wooden pieces to the base in order to hold the wall in place (Figure 3.11).

![Figure 3.9 The Briar group testing part of their structure at 1:1 scale.](image)
Figure 3.10 Realizing that the walls come out of the base and that they need to find a solution.

Figure 3.11 Adding small pieces to hold the wall pieces to the base.
3.3 Making fast and slow

In his book, *The Reflective Practitioner: How Professionals Think in Action*, Schön (1983) introduces the idea of “reflection-in-action” to describe how a practitioner reviews and thinks about what s/he has done in a creative process. Reflecting on decisions and actions is an important aspect of the learning process. Learners reflect on their making process by observing, documenting, and analyzing what they are doing. The method of describing and reflecting on making varies; it could be verbal or visual, using photos and/or visual rules. For example, Sophie Lehman (2012) explains that through what she calls “the hand of the brain,” we can imagine a familiar motion and process of making a thing by seeing visual stimuli. Thus, reflections on action in $I^3$ and the decision to take new actions should be externalized instead of being kept internally, through verbal descriptions and visual descriptions such as sketches, images and/or videos.

This externalization requires stopping to record at chosen intervals so as to document the process. I call this *making slow* in order to contrast it with the *making fast* of experienced makers, who often do not want to take the time to describe or reflect on their process.

Rule-based thinking is very important for describing and reflecting on the making process. It helps us record and describe the changes made in every stage of $I^3$, and also helps generate new designs. We often fail to keep track of what we are doing and how we are making a thing during the action and process of making itself. What I mean by “keeping track” is that we are often not mindful or aware of our making actions. Failing to keep track limits learners’ ability to learn from and reflect on what they are doing. We already segment our actions in parts automatically, depending on our movements and goals. These segmentations affect what we learn and remember later (Zacks & Swallow, 2012). For example, when I started learning ceramics, I was not able to create a centered clay cylinder on the wheel. Instead I created a form that was very close to a bowl, with the diameter of the rim larger than that of the diameter of the base. Only when I began to analyze my hand movements and adjust the pressure on the clay was I able to make the diameter of the rim match that of the base. I would not have made such progress if I had not segmented my actions and reflected on them.

In every stage of $I^3$, keeping track of the changes using visual description of physical rules slows down the process and prevents students from changing too much too fast. For example, in the classes I taught, I asked the students to describe all the transformations they made, whether they were physical transformations such as geometry, or intangible transformations such as experience, light, and shadow. Physical rules could be used to generate new designs by first putting the transformation rule in any $I^3$ stage and then applying it. For example, by introducing a rule to transform the flexible material used in the Imitation stage to a rigid material in the first iteration, a new design may emerge.

To achieve slow making, I introduce computational making and visual rules for students to use in describing their visual and physical making process and design generation. I used laser-cut cardboard pieces for hands-on exercises to demonstrate how to create physical rules, generate a

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2 See the discussion of rules in Chapter 2.
small thing with the rules, and describe the whole physical process visually. I used cardboard pieces because they allow the learners to go beyond symbolic one-dimensional pieces; learners can cut or fold the cardboard pieces if they want. For example, in the *Computational Making: Light and Motion* course, I asked the students to make a small lighting unit using these cardboard pieces, to describe the physical rules for making it, and then describe the light and shadow generated by this physical rule. I also asked them to describe the process verbally, if they wanted to (Figure 3.12).

"The trickiest part of learning how to assemble these cardboard shapes, in my opinion, was understanding the planarity of attaching these shapes at skewed planes. I think the addition of hands in an illustration of the cardboard shapes would help visualize the planes of the cardboard in 3-dimensions, as we can better understand the twists our hands must make when we have a point-of-view illustration." Jackie Liu, 2015.

Additionally, in the *Computational Making* class, I asked students to read Sophie Lehman’s paper on describing making; then I asked them to introduce new ways of showing and describing how to make an origami piece. Students introduced novel ways of showing how to do this. One of the students made a video with the sound of folding paper; another student used the opacity of the 2D step-by-step sketch to indicate folding paper (Figure 3.13 & 3.14). I then asked them to exchange instructions and try to make the origami piece with the instructions given to them. This exercise allowed them to see the importance of showing and describing the making process.
“Origami instructions usually include dotted lines and arrows to show the folds and each step of making any origami piece. Are there any new ways of showing origami making? Use what you learned from Lehmann’s paper, and show the making of an origami piece of your choice. This origami piece could be a crane, a wheel, or something else. More importantly, this exercise is about showing making, so ask yourself: if I give my making instructions of the origami piece to a friend, will it trigger his/her ‘hand in the brain’? How about the materiality of the visualizations of making?” Dina El-Zanfaly, from the first assignment in the Computational Making class, Spring 2015.

Figure 3.13 Showing how to make an origami crane per Xinyi Ma. 2015.

Figure 3.14 Showing how to make an origami crane per Bailey Zuniga. 2015.
In each assignment in the Computational Making course, I asked the students to describe the steps and changes they made using physical rules through sketches, images or in any other way. I asked them to highlight which rules they had kept and which rules they had changed. In addition to the visual description of the design and making process, I asked students to describe their decisions in each assignment verbally. In the Enormous Smallness Istanbul Architecture Studio, by the end of the third iteration, we asked them to make a video of their process including both Imitation and Iteration stages. In this way, they reflected on their reflection.

3.4 The role of the instructor

As in any course or workshop, there is a need for an instructor, facilitator, or coach. Researchers have tried to frame the role of coaching in design to support students’ learning experiences. For example, Adams et al. (2016) frame *integrated knowledge, situated practice* and a *shared repertoire* as comprising a theoretical concept of coaching to which more methods could be added. Instructors play an important role in the learning process of I3: they design the course outline and moderate each session. Their actions are also situated as they reflect-in-action (Schön, 1983): they have to improvise and respond to students’ work depending on each situation. As their experience increases, their creativity and improvisation in teaching increases (Sawyer, 2011). They plan the assignments, observe students’ actions, and guide them. With their technical skills, they also guide students on fabrication methods and encourage them to challenge the limitations of materials and tools. Most importantly, they enable the students to acquire autonomy in decision making and judging their own work (Goldschmidt, Casakin, Avidan, & Ronen, 2014). Education researchers encourage peer learning in the classroom as way for students to learn from each other. David Boud et al. (2001) define peer learning as “a two-way, reciprocal learning activity” which involves “sharing knowledge, ideas and experience between the participants” (p. 3). Instructors should also encourage students to learn from each other, whether they are working independently or in groups. Peer feedback could also be incorporated during session reviews, signaling to the students that their inputs are valuable and developing their ability to trust their own judgment.

In each session, instructors should ask the students to present their work-in-progress, provide feedback on next steps, and encourage students to give feedback to their classmates. At the end of each one or two sessions, instructors should hand out a detailed written assignment describing what is to be done in the next step. More specifically, at every stage of the I3 process instructors should give clear instructions regarding what to change and what to keep in the thing-in-the-making. Instructors should also suggest which material, machine or tool to use depending on the work-in-progress and with an eye to the student’s current skills. They can also invite a speaker whose work is related to the course theme or plan a field visit to see something related. For example, in the Computational Making course, we took the students to a demonstration in the ceramics studio at MIT so that they could observe and analyze the embodied process of making with clay. Most importantly, instructors advise the students on what is doable within the time frame of the course, using available materials and machines.

For example, in the first session of the Computational Making course, I handed the students the course plan for the twelve sessions. At the beginning of each session, I explained the session...
Knowing the session plan in advance helps students to be aware of what is going to happen and understanding the reasoning behind what they are doing. In every weekly session, I gave them an assignment for the following week. The assignments contained detailed instructions on what to change and what to have ready for the next session. I also encouraged them to give feedback to each other regarding what to change.

Figure 3.15 Jackie Liu showing her early lighting unit prototype to her peers and to Professor Terry Knight in the *Computational Making: Light and Motion* class, 2015.

Sometimes students fail to achieve an acceptable result or become stuck at a certain stage. In all my classes, I emphasize that the process is as important as the final product, and that we learn from our mistakes. I encourage my students to experiment and to expect that something they may try might not work. While I sometimes see that a student’s attempt with a certain material will fail, I let them try anyway, knowing they will learn from the attempt. Occasionally some students try to minimize the changes outlined in the required guided iterations in the hopes of avoiding failure. As an instructor, I encourage them to experiment. In the *Computational Making* course, one student kept her changes to a minimum in terms of material and geometry. However, in the last iteration, which required adding interaction, I showed her that her lighting unit might have to change in physical shape in order to accommodate the motion she wanted to add. The amount of work required to adapt her design at that point demonstrated to her the value of making more daring changes earlier in the process (Figure 3.16).
In this chapter I introduced $I^3$ as a computational design and making pedagogical method based on action and perception. In the next chapter, I discuss and analyze $I^4$ with case studies.
Development and Testing with Case Studies
4 Development and Testing with Case Studies

In this chapter, I tell the story of the continuous process of developing and testing I\(^3\) during the teaching of three main courses. In every course, the scale of the thing in-the-making became larger. In the Computational Making: Light and Motion course I taught in consultation with MIT Professor Terry Knight during Spring 2015 at MIT, I began with a small thing -- an interactive lighting unit. In the second course, the thing-in-the-making became a scaled play space for children. The course was given as an architecture studio for second year architecture students at Istanbul Technical University in Turkey in Fall 2015. This studio, which we called Enormous Smallness, was led by MIT PhD alumna Mine Özkar. In the third course, Making Spaces: Lightweight Structures for Interactions given in January 2017, the thing in-the-making became a 1:1 scale lightweight structure occupying a space of around thirty cubic feet.

In order to assess the effect of applying I\(^3\) as the course structure, the students in each of the three courses were given two questionnaires: one at the beginning of the course and one after the last session. The questionnaire asked students to order the steps they would take when approaching a new design project and to generally rate their technical skills. It asked them to define the terms “making” and “improvisation,” and to describe a making process. It also asked students to assess their design and making processes before and after the course; most importantly, it asked how they would use I\(^3\) after completion of the course. I present a summary and analysis of the case studies after each stage. At the end of this chapter, I present provisional results and an analysis of the I\(^3\) case studies along with a summary of the data gathered from the questionnaires.

4.1 Case studies

4.1.1 Computational Making: Light and Motion

In the Computational Making course, the students made physical lighting units and developed their prototypes by adding interactivity using motion and electronics. The course included undergraduate and graduate students from diverse backgrounds; all were from MIT, with the exception of one cross-registered student from the Graduate School of Design at Harvard University. The design and technical skills of the students varied. The course was divided into twelve weekly sessions.

The course consisted of four parts: Methods for showing a making process, Imitation, Iteration, and Improvisation. The first part consisted of an exercise on how to describe and reflect on any making process. In the second part, Imitation, students were asked to choose an example of lighting unit, analyze it, and imitate it by making a copy. In the third part, Iteration, students were asked to make four iterations in four weeks with some constraints, but without changing anything except the elements that depended on the changes made. In the first iteration, they were given the option to change anything in the lighting unit except the material. In the second iteration, they were asked to change the material. In the third iteration, they were asked to change the light source and pattern. In the fourth and last iteration, they were asked to add motion to the lighting unit, so that the lighting unit could change in shape or react to a surrounding motion (Figure 4.1). In the fourth part, Improvisation, the students were asked to make another lighting unit as a product line from the fourth iteration or make a new lighting unit completely from scratch. During the weekly sessions, invited speakers gave talks related to session themes such as
"materials" or "machines." Additionally, to begin a conversation about making and embodiment, the class visited a ceramics lab at MIT and observed a master potter throwing clay and instructing students. The students also attended some sessions on basic technical skills in the digital fabrication lab, and some optional sessions were offered for more technical skills involving Arduino and electronics.

Figure 4.1 A lighting unit made by Anne Schneider in the Computational Making: Light and Motion course. Photo by Diego Pinochet, 2015

4.1.2 Enormous Smallness: Istanbul Architecture Studio

In order to test the I³ process in another context and on a larger, architectural scale, I applied the process in an architecture studio for second-year architecture students in Fall 2015 in Turkey. In the studio, named Enormous Smallness Istanbul Architecture Studio, twenty students designed and built scaled spaces for children to play in (Figure 4.2). Some of the student groups added interactivity to the scaled spaces using micro-controllers and electronics, but this was not required in their assignments. Unlike in the Computational Making class, all twenty-one students in this studio were second-year undergraduate architecture students from Turkey, with the exception of one visiting student from Germany. English was the main language of communication, but students also used Turkish when needed to speak with Professor Özkar and the teaching assistants.
This was first architecture studio these students had participated in. They did not have any background in digital 2D and 3D modeling or in digital fabrication. During the studio, we used a fabrication lab in the Faculty of Architecture School at Istanbul Technical University. As we progressed through the sessions, the students used different media simultaneously, including both digital and manual representations and fabrication techniques and tools. Their technical skills grew as the studio progressed.

The studio met twice per week, but the groups presented their progress and weekly assignments only once per week. The studio was divided into fourteen weeks. I was present for just over half of the sessions; Professor Ozkar was present for all sessions. Since it was the students’ first architecture studio, we wanted them to learn how to design a small space. We thus decided to focus on the idea of “nooks and crannies.” We defined nooks and crannies as small spaces or corners that are inside something else. In the two assignments in the first three sessions, the students learned about design principles, especially in the urban environment.

In the third assignment, we asked the students to choose examples of existing nooks and crannies for children and to present them in studio. I joined the studio in the third week, after they had already done the three assignments. We asked the students to form groups and each group to then imitate one example from the examples presented from assignment three. We also introduced visual rules as methods for generative design and describing both processes of physical making and design. We discussed the basic design principles of repetition, similarity, difference, variance and unity. In the fourth week, we discussed types of materials and digital fabrication techniques, including knitting, CNC milling, paper cutting, and throwing clay. We then asked the
students to make three iterations of what they made in the Imitation stage with one change per iteration per week while keeping everything else the same: first, change one element except material; second, change an element that addresses children's senses, such as color and texture; third, change an element that addresses another sense, such as sight or sound. We then asked the groups to prepare a video in which they presented their entire design and making process. They then showed the video in front of invited critics in studio without any verbal explanation from them. However, after showing each video, the student groups answered questions by the reviewers. After I left Istanbul, the students designed and built individually-scaled models of kindergartens inspired by the nooks and crannies that they had made in the first part of the studio.

4.1.3 Making Spaces
The next step was to move from a scaled prototype of an architectural space, to applying and developing I³ by building an architectural space in 1:1 scale. In January 2017, I taught a two-week class at MIT during the Independent Activities Period (IAP). The built spaces, such as small lightweight structures and pavilions, included some scenarios for interactions using sensors and Arduino micro-controllers (Figure 4.3). The class was funded by a grant from the Singapore University of Technology and Design (SUTD), and had eight students from both MIT and SUTD. The students' backgrounds varied: there were two first-year Master of Architecture students, two undergraduate architecture students, a freshman with an undeclared major, and two undergraduate students in Mechanical Engineering.

Figure 4.3 Making Spaces course at MIT, January 2017

Some of the students had some background in programming and some of them had some digital modeling and fabrication experience, including using a laser cutter for architecture studio
models. During the course, we used the fully equipped digital fabrication lab in the International Design Center at MIT. Because of the time limitation of the course, I ordered most of the materials in advance, leaving other materials and electronics to be ordered depending on the projects’ needs.

The course lasted only two weeks; there were nine daily sessions from 10 am until 4 pm with a long weekend in the middle. I had two teaching assistants who were present the entire time. On the first day, I introduced the course objectives and goals, explained the 13 process, and showed some examples of lightweight structures and pavilions. As I mentioned earlier, I also handed students a questionnaire that asked them to order the steps they might take in approaching a new design project and to generally rate their technical skills. I also asked them to define the terms “making” and “improvisation” and to describe a making process. I also explained my expectations for the class. In the afternoon session, I introduced shape grammars and visual rules and gave a hands-on exercise with the press-fit kit to demonstrate how to apply and describe rules. At the end of the day, I handed students the first assignment; first, to build a scale enclosure using the press-fit kit pieces and define the rules used; second, to choose five examples of lightweight structures from which they would choose one to imitate and build with dimensions around 10x10x10 feet, and with a prototype scale of 1:8.

At the end of the second day, each student presented her project. We then voted on the top three projects and students formed three groups to work on these projects for the rest of the course. The students also attended an orientation session given by the shop manager on how to use the machines and tools in the space. In the second assignment, I asked the students to choose one element to change in their project. I explained that the change could be a change in geometry or in the dimensions of a structural element, for example. The only constraint was that they could not change the material. I also indicated in the assignment that they had to describe their process and what they kept and what they changed using visual rules and sketches. The students presented their first iteration at the end of the third day.

In the third assignment, I asked the students to make a second iteration of their project. This time, they were to keep everything the same except the material of one element and whatever depended on it. I explained that they could change the material of the structure of the skin from paper to wood or corrugated cardboard, for example. I added that this material should be the final material to build the space with, so any scale would work as long as it was larger than 1:8. The second part of the assignment was to draw a scenario or a storyboard to show how users would interact with their space. In the fourth assignment, I asked the three groups to build parts of their spaces at 1:1 scale with the final material. During the rest of the course, I advised each group separately as they progressed with their projects. On the final day, I handed them the review guidelines, and we had a final review with an invited panel.

In the sections below, I introduce five case studies of students going through the stages of Imitation, Iteration and Improvisation in the three courses described above: Computational Making: Light and Motion, the Enormous Smallness Istanbul Architecture Studio, and Making Spaces: Lightweight Structures for Social Interactions. Each stage is described separately below. Within each stage, I divide the case studies into three scales of small, medium and large to correspond to the increasing scale of the thing made in each course.
For the *Computational Making: Light and Motion* course, I chose the projects of two students with different levels of expertise. The first student, Jacquelyn Liu, was a freshman at MIT who had almost no background in design and digital fabrication prior to taking the course. Jacquelyn completed two projects called *Pulsepod* and *The Infinity Mirror*. The second student, Xinyi Ma, was a Master of Architecture student at MIT with an advanced background in design and digital fabrication. She called her project *Light in Between the Folds*.

For the *Enormous Smallness Istanbul Architecture* studio, I chose to examine the project of one group consisting of three students, because all students shared the same background and skills. The group consisted of Ilayda Memis, Begum Saral and Ekin Eryilmaz and they called their project *Inside-Out*. Besides this being their first architecture studio, the three students did not have any background in digital modelling or fabrication.

For the *Making Spaces: Lightweight Structures for Social Interactions* course, I chose two groups, each with three students. The two groups had different skills and backgrounds. The first group, who called their structure *The Briar*, consisted of three undergraduate students: Katherine Paseman, an undergraduate in Mechanical Engineering; Maxine Beeman, a freshman with an undeclared major, and Joei W., an undergraduate student in Architecture. The second group also consisted of three students: two first year Master of Architecture students, Hyerin Lee and Natalie Bellefleur, and an undergraduate architecture student, Joey T.. They called their structure *The Feeler*.

### 4.2 Imitation case studies

As I explained earlier, the Imitation stage is a way to start to design and to jump into making immediately. The students are usually asked to imitate some thing or concept. And during making, they start thinking about materiality, structure and assembly, and fabrication methods.

#### 4.2.1 Small scale: Computational Making

In the Imitation stage of the *Computational Making* course, students were assigned to choose five lighting units that they found interesting, then chose one and analyze how they would build it in terms of material, geometry, scale, light, and composition.

**Pulsepod**

Jacquelyn chose a Hydra Pendant lamp by the designer Roxy Russell to imitate. In order to imitate and build a lighting unit using only a photograph as a reference, she had to make decisions on materials, scale, dimensions, fabrication method and assembly. The making process in this stage allowed her to gain some technical skills in using a 2D drawing software and a laser cutter. She drew the petals digitally in 2D, laser-cut them in mylar, and then attached them to a copper frame that she had made manually (Figure 4.4). Besides gaining some technical skills, she started being able to judge her own work. She reflected on her making process in class, and concluded that her lighting unit was “chaotic.” She did not like that she could see the copper frame when the lights were on (Figure 4.5). By describing her making process through visual rules of physical making, she was able to decide what to change next to be able to eliminate the effect of the copper frame that she did not like. This description also helped her to draw a link between her making process and the resulting “chaotic” effect.
Light in Between the Folds

Xinyi chose Ron Resch’s triangular tessellations, which consist of two sizes of triangular cells (Schmidt & Stattmann, 2009), as her imitation case. In her Imitation, she experimented with creating the pattern (Figure 4.6) by printing on paper and folding it manually. Having the lighting unit in mind, she added laser-cut cardboard pieces to control the light’s intensity (Figure 4.7). She had to think about the relation between the materials she used and the lighting effect they created.
4.2.2 Medium scale: Istanbul Architecture Studio

In the Imitation stage of the Enormous Smallness course, student groups were asked to choose three precedents of play spaces for children. We then asked each group in the studio to choose one of the three precedents to imitate. They first had to analyze the precedent, its material and structure, and then build it in a scale of their choice. The Inside-Out group chose a precedent called “White Tube” by Hans Henrik Ohlers. It is a full-scale built play structure for children in Copenhagen. They analyzed how to build such a structure and contacted the architect asking him about the construction and building process of the “white tube.” He sent them a video about the
construction process of the structure. All the details they were able to get were through visual images and the video.

In the Imitation stage, the students naturally had to think about the fabrication methodology. However, they also had to think about the thing in-the-making as a space for people not just an artifact, and figure out the dimensions of their space and its scale. They had to choose materials, learn about material behaviors, and decide how to assemble the structure. First, they experimented with wire bending to build a metal frame. They described their building process using sketches and visual descriptions of bending the wires and connecting them using thinner wire (Figure 4.8). Second, in order to create a smooth surface, they made three trials with material. They first wrapped the metal frame with plastic sheets and then sprayed it with a thin layer of liquid polyurethane foam. However, they then realized that they were not getting as smooth a surface from the foam as they had expected (Figure 4.9). They then moved to experimenting with white silicon, which they realized did not give them a thick clean surface. So, they made a decision to go back to using liquid polyurethane foam to form a thicker layer, which could be carved afterwards to create a smoother finish (Figure 4.10).

Although we did not ask them in the assignment to add embedded electronics to create a potential interaction between the space and its users, the group added a simple electronic circuit of color-changing LEDs and an Arduino microcontroller. Because they had practiced using visual rules earlier to describe their making process, they were able to use the rules to describe how they had incorporated the electronics circuit.

![Diagram](image)

Figure 4.8 Imitation: Making process by the Inside-Out group in the Enormous Smallness architecture studio. On the left: The group is describing wire bending to form the frame of the structure. On the right: Describing adding electronics to their scaled structure. Figure by the Inside-Out group, Fall 2015.
4.2.3 Large scale: Making Spaces
The students worked individually for the first two sessions to build a small scale space for social interactions. They were asked to choose some precedents of pavilions, and choose one or more to imitate, then make one pavilion. They were asked to make a pavilion that would occupy a volume of maximum size 10 feet x 10 feet x 10 feet, with minimum scale of 1:8.
The Briar

In the Imitation stage, Katherine was inspired by the structure-like sculpture made of tree saplings “Whiplash” in Palo Alto by the artist Patrick Dougherty and the “Dragon Skin Pavilion” in Hong Kong by Emmi Keskiarja, Pekka Tynkkynen, Kristof Crolla and Sebastien Delagrange (Figure 4.11). She created modular units out of paper, which when assembled created an enclosure close to the precedents she chose (Figure 4.12). In this stage, she thought about scale, structure and geometry, putting less emphasis on material.

Figure 4.11 The “Dragon Skin Pavilion” in Hong Kong by Emmi Keskiarja, Pekka Tynkkynen, Kristof Crolla and Sebastien Delagrange. Photo by Forgemind Archimedia from Flickr under Creative Commons license.

Figure 4.12 Imitation stage by Katherine from The Briar group, 2017.

The Feeler

Natalie chose one of the structures made by Marc Fornes, “Vaulted Willow,” as her precedent in the Imitation stage. She analyzed the structure in terms of material, geometry and fabrication
By analyzing the precedent, Natalie was able to choose some elements to imitate. By describing \( x \rightarrow \text{prt}(x) \), as the elements she imitated from the precedent, she explained that she created a vaulted form with overlapping panels and void spaces to conserve material (Figure 4.13). Making the structure and analyzing it led her to think about what to develop further (Figure 4.14). For example, she explained that the folding connections needed more details, and described how she would panelize the form further. She also suggested that the folds might increase stability, so that maybe she could think about making the panels move.

Figure 4.13 Imitation stage by Natalie Bellefleur from The Feeler group, 2017.

Figure 4.14 Imitation stage by Natalie Bellefleur from The Feeler group, Marc Fornes's "Vaulted Willow," is shown in the back, 2017.
4.2.4 Summary and analysis of Imitation case studies

a. In summary, in each act of imitation, the students were free to decide what to copy and how to copy it. As I explained in the Imitation section in Chapter Three, Imitation could be full or partial; students could either copy the precedent using the same material, geometry and fabrication technique, or they could copy a part of the precedent. The decisions were made depending on what the students saw and felt. The copied item was never an exact replica of the precedent, however. For example, in the Pulsepod project, although the student tried to make an exact copy of precedent, the result was not as she expected. In other cases, students copied parts of precedents. For example, in the Computational Making course, Annie in her Revitalizer project copied the technique of melting wax and not the whole geometry. In her Light Between the Folds project, Xinyi imitated the material system of triangular tessellations. In the Briar project, one student imitated the geometry of a cyclical enclosure from two different precedents, using manually cut paper pieces.

b. In both the Pulsepod and the Inside-Out projects the students tried to imitate the precedent fully using the same materials and proportions. This full imitation enabled the students to understand the material behavior but sometimes made it difficult for them to duplicate the exact geometry. In contrast, students from both the Briar and Feeler projects focused on imitating the geometry by using paper rather than the original material. This enabled the students to immediately start imitating -- they even cut paper manually using scissors without using any machines.

c. In all the case studies, the Imitation process itself guided the students to think about the physical aspects of the things they were copying. Imitating a thing made them focus on which aspect of something appealed to them, which they felt would be easy or difficult to copy, and which fabrication techniques would be most useful. It also led them to consider whether they should use software and/or fabrication machines. In short, the Imitation step brought a number of considerations to the forefront, and got students thinking about concepts of geometry, scale, structure and fabrication techniques including modeling software and the scale of fabrication machines. The thing that the students imitated enabled the students to gain a sense of the scale and size of the thing they were making.

d. The actual imitated thing allowed the students to see and feel unexpected aspects. For example, in one of the large-scale case studies, the Feeler, the student felt that the folding connections needed more detail and described how she would panelize the form further. She observed that the folds might increase stability, and thought about the next step of making the panels move. Seeing the strengths and weaknesses of the imitated thing gave students insights into the materials and structure that would be carried over into the next step. For most of the students, it was their first experience making a functional thing and not just a physical model, helping them develop their tactile senses along with their ideas about design.

e. Students used visual rules to describe what they were copying and to record their making process step by step, as we saw in the small scale case studies, Pulsepod and Light in Between the Folds, in the medium scale case study, Inside Out, and in the large scale case study, the Briar. Students in the small scale case studies from the Computational Making course, who had more time to learn the rules, used them also to describe the intangible aspects produced by their
lighting units, such as lighting patterns and shadows. As I explained in Chapter Three, the students were given an exercise at the beginning of the Computational Making course to make small lighting units out of cardboard modular pieces following some visual rules they chose.

4.3 Iteration case studies

The Iterations in 13 are guided, which means that the students are asked to experiment with different aspects of the thing in the making, such as material and geometry. By now, most of the students have become more comfortable using software, digital tools, and machines to design and make. The Iteration process allows them to experiment more with materials, and push the limitations of what they are making and the tools they are using.

4.3.1 Small scale: Computational Making

As described previously, in the Iteration stage in the Computational Making course, the students were assigned four iterations: 1. to change anything except material, 2. to change material, 3. to change lighting source and pattern, and 4. to add motion.

Pulsepod

After her Imitation stage, Jacquelyn made some changes in geometry in both the inner frame and the outer body (Figure 4.15) for her first iteration. In her second iteration, she changed the material from something soft and flexible to a rigid material, acrylic. She laser-cut the body, and by using vacuum forming and a heat gun, shaped the acrylic shell (Figure 4.16). In her third iteration, she chose to use el wire, a special wire that lights up, instead of a regular light bulb. She wanted to create a hollow sphere with the light (Figure 4.17). In her fourth iteration, motion, she described the narrative of her lighting unit in a storyboard, saying that the blinking light should indicate her heart rate (Figure 4.18). She added a pulse sensor that controlled another layer of el wire when touched.

Figure 4.15 Iteration 1: Change anything except material by Jacquelyn Liu in the Computational Making: Light and Motion course. Photo by Jacquelyn Liu, 2015
Light in Between the Folds

In her first iteration, Xinyi made some changes in geometry by moving from a flat surface to a cylinder and a torus, using laser-cut mylar and cardboard pieces (Figures 4.19 & 4.20). Then in her second iteration, she wanted to control the opacity of light and create a folding pattern embedded in the material itself, so she experimented with making a glued, three-layer material to form the surface, with different paper thicknesses and textures (Figure 4.21). In her third iteration, she chose to use a circular light bulb instead of a regular light bulb, because she wanted to create a torus-shaped lighting unit (Figure 4.22). In her fourth iteration, motion, she added a small motor attached to the folded paper with wires to control the geometry of the shell around the torus light, and to give different light intensities (Figure 4.23).
Figure 4.19 Iteration 1: Change anything except material by Xinyi Ma in the *Computational Making: Light and Motion* course. Photo by Xinyi Ma, 2015

Figure 4.20 Iteration 1: light patterns by Xinyi Ma in the *Computational Making: Light and Motion* course. Photos by Xinyi Ma, 2015
Figure 4.21 Iteration 2: Experimenting with different textures by Xinyi Ma in the Computational Making: Light and Motion course. Photo by Xinyi Ma, 2015

Figure 4.22 Iteration 3: Changing light by Xinyi Ma in the Computational Making: Light and Motion course, 2015.
4.3.2 Medium scale: Istanbul Architecture Studio

As explained earlier, the students were assigned three iterations in the Iteration stage in the Istanbul Architecture Studio: 1. Change one element except material; 2. Change one element that addresses children’s senses, such as color and texture; 3. Change an element that addresses another sense, such as sight or sound.

The Inside-Out group changed the geometry of their structure in the first iteration. They kept the same material and fabrication technique of wire bending by connecting thick wires with thinner ones, but changed the geometry to more a closed loop. They wanted to create part of the structure above the ground and called it Module A; they decided to create a second part, Module B, as a tunnel passing through the ground (Figure 4.24). The Inside-Out group realized that their first iteration looked like a deformed version of a Klein bottle and decided to simplify the geometry in the second iteration. They removed the underground part, and tried to create a uniform Klein bottle. In the second iteration, we asked all the students to start using digital tools and fabrication machines in their design and making process. This led them to think about dimensions and proportions of the structure; they had also to think about scalability and the movement of children inside the structure. When they saw that the geometry created dark spaces inside the structure, they decided to keep the holes they made on the skin from the precedent they made for lighting and ventilation. It was their first attempt to use 3D software, Rhino, and they explained that they had gone through several attempts to draw it. These first attempts helped them gain the basic skills to use the software (Figure 4.25).
Figure 4.24 Iteration 1: The Inside-Out group kept the same fabrication method from the imitation stage and changed the geometry of the structure. Figures by the Inside-Out Group.

Figure 4.25 Iteration 2: The Inside-Out group realized that their first iteration looked like a deformed version of a klein bottle and decided to simplify the geometry in the second iteration. Figures by the Inside-Out Group.

They were then able to “slice” the model into a ribbed frame using other digital software. The process allowed them to move from using a wire structure to a cardboard structure, which would resemble a wooden one in reality (Figure 4.26). When they tried assembling the frame after laser-cutting the pieces, they realized that the structure was not connected. It was a good step for them to realize that the way that the software sliced their 3D model into a frame, was not the ideal way to construct it physically. This led them to understand that the design and making process is not limited to one medium, whether digital or manual.
In the third iteration, the Inside-Out group decided to simplify the geometry further. They described it as a "tunnel with a shell surrounding it" to keep the idea of inside-out. Instead of building the inner frame out of cardboard, they chose to build with laser-cut wood to give the frame more stability and strength. They developed the idea of holes further by creating some holes on the inner tunnel, and larger holes on the outer shell. Adding permeability to the structure allowed them to design the children's experience inside it. They added lights with different colors in several parts of the structure that would react to the children's motions. This system would encourage children to move through the structure to control the lighting in different parts (Figure 4.27). By this stage, the group had already learned about the material behavior of each element in the structure, and knew how to shape it to create the form they wanted. For example, they knew that they would need to use a thick layer of foam around the frame they built out of laser-cut pieces of wood (Figure 4.28). They then carved the foam to create the form and painted it with gesso to create a smooth surface (Figure 4.29). They also described the lighting system inside the structure - different groups of colored LEDs connected to an Arduino and triggered by an ultrasonic sensor (Figure 4.30 and 4.31).
Figure 4.28 Iteration 3: The Inside-Out group used a thick layer of foam around the frame they built out of laser-cut pieces of wood, first on the tunnel, then on the outer shell. Figures by the Inside-Out Group.

Figure 4.29 Iteration 3: The Inside-Out group used a thick layer of foam around the frame they built out of laser-cut pieces of wood, first on the tunnel, then on the outer shell. Figures by the Inside-Out Group.

Figure 4.30 Iteration 3: They then carved the foam to create the form, and they painted it with gesso to create a smooth surface. Figures by the Inside-Out Group.
The sensor sends an ultrasonic signal, which hits something and bounces back. Using this method, when the sensor is triggered, authorised LEDs light up.

4 different groups of coloured LEDs are welded to + and - wires, subsequently connected to the bread board.

Figure 4.31 Iteration 3: Description of the electronic circuit inside the Inside-Out structure. Figures by the Inside-Out Group.

Figure 4.32 Iteration 3: Inside-Out structure reacting to different motions inside it.

4.3.3 Large scale: Making Spaces

After working individually in the Imitation stage, the students then formed groups to work on one structure made by one of the students in each group. As a group, the students worked on making the first iteration. As instructed, they had the freedom to change the geometry of their structure while keeping the material and everything the same.

The Briar

The Briar group changed the geometry of the modular unit of the structure to create an enclosure inspired by nature. They described the iteration in terms of $x \rightarrow t(x)$ which they applied on the
modular pieces that formed the structure in the Imitation stage (Figure 4.33). The students then applied an additive rule to form the new iteration (Figure 4.34). Although students were asked to make only one guided iteration per session, the group made several (Figure 4.35). They first manually cut the units with scissors then they laser cut the modules in paper, which facilitated the iteration process.

**iteration: \( x \rightarrow t(x) \)**

for our iterative process we decided to alter the central unit \( x \) by joining the individual modules together into a more organic form. all modules were hand cut with scissors out of paper.

Figure 4.33 Iteration 1: The students saw the modular pieces as a large long piece. Figures by the Briar Group.

**rules: \( a \rightarrow a + b \)**

To create the overall shape, we notched each new unit into the previous in three joints and repeated until an entire sheet had been created. We then joined the final unit with the initial to form the ringed shape of the final structure.

Figure 4.34 Iteration 1: The students applied an additive rule to form the new iteration. Figures by the Briar Group.

Figure 4.35 Iteration 1: changing geometry. Figures by the Briar Group.
They then moved from using paper to using 1/8-inch-thick flexible polystyrene. Since they were planning to use plywood sheets as the final material, polystyrene was chosen as a transitional material with which to test their geometry (Figure 4.36). Once they used polystyrene, they realized that their geometry needed adjustment to react to the newly added forces of the structure and gravity. They also realized that they had to add a base to hold the structure. In their fourth iteration, they had to use the final material and build part of their structure in full scale. In this step, they had to learn how to use a CNC router and test two types of plywood to see which one would work best with their structure. This helped them to make decisions and to adjust their geometry further. As shown, at every step their ability to react to the changes grew. Assembling the parts together in the final stage, they realized that the tension and compression forces with the wood were causing the structure to come out of the base. They had to improvise and add small pieces to hold the structure to the base. While working on the physical structure, the group started developing a scenario for how the users would interact with the space, and how the space would respond in return. They created a system in which after the user knocks on the surface of the structure, LED strips from the base light up and the walls play sounds like those of a jungle. Although the system worked, they needed more time to integrate it better into the structure.

The Feeler
The Feeler group decided to make the modules of the structure smaller while keeping the overall concept of the three-sided curved vault. They modeled it digitally, and then laser-cut the mylar modules. In moving from a virtual modeling environment to making a physical model, the group realized that building the structure to scale with smaller modular units of mylar resulted in a structure that was not as steady as they had expected (Figure 4.37).
In their second iteration, the group decided to use the modules as an outer skin attached to a three-legged structure using three full length, bent PVC pipes and 9 shorter ones. They specified the exact dimensions of the structure, and worked on building the structure into two scales. The first scale was the outer skin made of mylar strips. They made the scaled skin mylar modules by laser cutting the small modules in scale 1:4. The second scale was the main frame of the structure by building the full-scale PVC bent pipes. They bent the pipes by first milling a curve into a 4ft x 8ft plywood sheet using a CNC machine, and then bending the pipe into the template by using a heat gun (Figure 4.38). They then 3D modeled a connector piece to connect twelve PVC pipes at the top of the structure (Figure 4.39). In their presentation, the group explained that they wanted to create both exterior and interior interactions: the first would use LED strips on the exterior that would react to users moving around the structure; the second would be some sort of airflow that would move the exterior mylar strips according to users’ arm motions inside the structure.

Figure 4.37 Iteration 1: The Feeler group realized that building the structure to scale with smaller modular units of mylar resulted in a structure that was not as steady as they had expected. Figures by the Feeler Group.
After testing the frame of the structure made out of bent PVC pipes in 1:1 scale, the group realized that the pipes were not creating a strong enough structure. They also decided to change their interaction plans by using small motors above the structure that would pull the mylar strips using threads. Instead of the PVC pipe frame, they decided to build a frame out of wooden elements. As a first step, they built the frame out of cardboard to test it (Figure 4.40). They realized that even replacing the pipes with wooden pieces was not enough. They decided then to add a wooden ring connecting all the elements for more stability (Figure 4.41). Meanwhile, they were also working on the motion of the mylar strips, editing the geometry, and adding small
channels, or straws, for the thread to go through the whole strip and be pulled by the motors (Figure 4.42).

Figure 4.40 The Feeler group decide to build a frame out of cardboard to test it.

Figure 4.41 The Feeler group decide to build a frame out of wood in full scale.
4.3.4 Summary and Analysis of Iteration Case Studies

a. As I explained earlier, Iteration here means making several “guided” iterations in which one aspect of the thing-in-the-making is changed. In many cases, when given the choice to change anything except material in the first iteration, the first aspect the students chose to change was the geometry. The focus on one aspect in each iteration also allowed the students to learn more about the transformed aspect and the consequences of changing it. As we saw in the small scale case study, Pulsepod, the student moved from using Mylar as the main material of the outer geometry to vacuum-forming polystyrene, which produced a different geometry.

b. Making several guided iterations of the same thing enabled the students to learn about material behavior. For example, in the small scale project, Light Between the Folds, the student focused on developing a material with integrated folds to achieve the tessellations introduced by Ron Resh. The students in the large scale case study, The Feeler, had to make several iterations using mylar to achieve the motion of the strips.
c. As in the Imitation stage, with each iteration, a new realization emerges, and students are able to decide on next steps. By making iterations with materials and geometry, and studying the effect of these iterations, the students were able to “see and feel” the links between the physical and phenomenological aspects of what they were making. For example, in the small scale case study, Light Between the Folds project, the student realized the connection between the material properties of different types of mylar and paper its folding behavior and the light and shadow patterns that it creates.

d. The iterations enabled the students to experiment and push the limitations of what they were making and their fabrication techniques. In the small scale case study, Pulsepod, and in the medium scale case study, Inside-Out, students learned to draw and model digitally, and to use digital fabrication machines. For many students, this was a first-time experience using a laser-cutter. As the projects grew and changed, students had to jump from one medium to another. Moreover, as they became more familiar with both the manual and digital modeling and fabrication tools, their confidence in using them increased.

e. In all the case studies, the students enhanced their spatial reasoning and sense of scale. For example, in the medium scale case study, Inside-Out, they had to adjust the openings in their structure in order to allow the children to move in and out of it more easily. In the large scale case study, The Briar, although they were given a maximum volume of 10x10x10 feet, the students gained a better sense of scale and spatial reasoning as they scaled up their structure in the final iterations. First they realized it was too wide and thus had to decrease the width. Their sense of scale and material behavior then improved when they were testing the 1:1 scale CNC-cut plywood pieces of the structure.

f. As in the Imitation stage, students used visual rules to describe what they were copying and to record their making process in step by step. They also used the rules to describe the transformations they made in each iteration. The students basically made the decision on how to divide visually the thing they made in the imitation stage, then they chose the aspect or element they wanted to change, and then they applied a transformation rule to it. Last, they “fused” everything back again into one thing.

4.4 Improvisation case studies

Although both Imitation and Iteration stages include a level of improvisation, the level of improvisation by the students increases as they begin to combine their skills in order to make decisions on how to proceed in their design and making processes. They learn that the further they progress, the more they see and feel new things, and make new decisions.

4.4.1 Small scale: Computational Making

In this course, the students were given the choice to continue working on their lighting units or start working on a new one.

**Pulsepod and the Infinite Mirror**

After finishing her fourth iteration on Pulsepod, Jacquelyn decided to make a new lighting unit, the Infinite Mirror. She explained that she liked the concept of reflection in her iterations, and
decided to use it as a concept for her next lighting unit. She wanted to make an infinite mirror in a portal concept (Figure 4.43). She made the first version in a small scale and then scaled it up. She made it using laser-cut cardboard, clear and mirrored acrylic (Figure 4.44). She added a sensor at the top of the mirror, so that when someone stands and looks at the mirror, the LED strip blinks quickly, as if it is breathing.

Figure 4.43 All stages from Imitation to the 4th iteration, and reflection from iterations 2-4 by Jacquelyn Liu. Figure by Jacquelyn Liu, 2015

Light in Between the Folds
Xinyi decided to continue working on her folding pattern to make a wall installation that would change in shape by pushing and pulling parts from it. For the motion mechanism, she used small circular magnets attached to the paper and metal rods coming out the back side. The change in shape led to a variation of light intensity. Because the folded paper has two different sides, she chose to work on one side, which made it difficult to create the motion she wanted. Then an “ahah!” moment came: by doing a new thing on the fly, she realized that the back of the unit was more interesting than the front (Figure 4.45). Thus, flipping the unit made more sense, especially as the backside of the surface allowed her to achieve the motion she wanted (Figure 4.46 and 4.47).
Figure 4.45 Improvisation: Seeing new things on the fly. Xinyi Ma discovers that the back of the unit is more interesting than the front, and decides to flip the unit. *Computational Making: Light and Motion* course.

Figure 4.46 Improvisation: Measuring distance of how far the magnets could be pushed in the lighting unit in the *Computational Making: Light and Motion* course.

the distance that the folded surface can be pushed varies from center to edge, it is deeper in the center and shallower as it gets closer to the edge. Therefore, the length of the holding steel rods need to be calibrated so the magnet can reach it once it is pushed back.
Figure 4.47 Improvisation: The making process of Xinyi’s lighting unit in the Computational Making: Light and Motion course. Figure by Xinyi.

Figure 4.48 Improvisation: The lighting unit could be pushed and pulled from any point. Showing the difference between the two sides or faces of folded paper in the Computational Making: Light and Motion course.
4.4.2 Medium scale: Istanbul Architecture Studio

In this stage, the students started taking concepts from the results from the Iteration stage and incorporated them in their Improvisation stage. In this project, the student took the structure system, materials, and digital fabrication techniques from the project from the Inside-Out group, and made her kindergarten. She used the structure system and interlocking wooden frames from the other project as the main geometry of her new kindergarten. She used a laser cutter to cut the wooden pieces and then put them together (Figures 4.49 and 4.50).
4.4.3 Large scale: Making Spaces

In this course, each group focused on making one structure. As I explained before, improvisation emerges in every stage in the $I^3$ process and increases over time. In the previous two courses, I approached the Improvisation stage as a separate project from the project in the Imitation and Iteration stages: students could make whatever they wanted. However, in the Making Spaces course, I approached the Improvisation stage as part of a continuity that began in the Imitation stage. The students were not given explicit instruction as to what to do after the Iteration stage, but they were required to improvise if and when they encountered surprises.

The Briar

As I discussed in the Improvisation section in the previous chapter in, the level of improvisation increased in the last part of the process as the students had to respond to surprises arising from scaling up the structure. Although they built parts of the structure at 1:1 scale to test it when they tried to build the actual structure, the walls did not stay in place in the base. They had to add small pieces in order to stabilize the walls the base (Figure 4.51).
In the final questionnaire, I asked the students “At which stages would you say that you utilized improvisational strategies? What were they?” One of the students from the Briar group said that improvisation occurs in every stage. She explained: “I think improvisation being so central to our design process made me more willing to make changes and be more adaptable. It added validity to the uncertainty every designer feels while they’re designing.”
The Feeler

Like the Briar group, the Feeler group realized that when they put the whole, full-scale structure together, it did not perform as expected. They had to make changes manually to the wood frame in order to assemble it. Although they tested the strips separately and adjusted their motion to roll up smoothly, the strips did not move smoothly when the structure was put together. The group needed time to work more on the interaction mechanism (Figure 4.53).

Figure 4.52. Final structure in full-scale. Photo under permission from Joseph Lee Photography.
4.4.4 Summary and analysis of the Improvisation case studies

a- The level of improvisation increased as the students progressed through the Imitation and Iteration stages. They were able to apply the skills and knowledge they had gained to new, uncharted territory. By the time they got to the Improvisation stage in the small scale case study, the Computational Making: Light and Motion course, students were quite capable of creating an entirely new lighting unit. Jacquelyn, the novice student, was able to apply what she had learned in the Imitation and Iteration stages to produce an infinity mirror in her Improvisation stage. In the medium scale case study, Inside-Out, one student integrated the geometry and fabrication techniques she had learned from the final iteration of her group project into her subsequent individual project. I consider this integration an indication of the success of I³ and evidence that the level of improvisation increased in every stage.

b- In addition to adapting to surprises, students saw and sensed new things. The more advanced student, Xinyi, improvised to create a new, unexpected geometry — much different from the one she had been working on. While working in the Improvisation stage, she realized
that the back of the surface of the lighting unit was more interesting than the front. Working on the backside solved the challenge she was facing regarding how users can control the surface of the lighting unit. Thus she was able to take what she saw when she faced a surprise and incorporate it into her design. In both large scale case studies, the Briar and the Feeler, students also had to react to surprises when assembling the full-scale structure. Although both groups had made iterations that demanded changing scale, they faced problems when the final structure failed to fit together because of unexpected forces and tensions of the material. The Briar group had to add a piece to the base to hold the structure’s walls, and the Feeler group had to manually assemble the structure with hammers. Faced with surprises, students were able to adapt.

4.5 Analysis of I³: Reflections on design, technical skills and Computational Making

In this section, I discuss my findings about applying I³ in the three courses I discussed in the previous sections, Computational Making: Light and Motion course, Enormous Smallness Architecture Studio, and Making Spaces for Social Interactions. In order to pinpoint both the successes and shortcomings of the methodology, I present a summary of the observations and analyses I presented in the three previous sections.

As I explained in the Introduction, there are many pedagogical approaches that focus on utilizing making with digital fabrication machines as a way of materializing planned designs, but there are far fewer approaches that focus on making with these machines as part of the design learning process. In this dissertation, I have introduced a methodology that utilizes these machines not only as tools with which to execute designs, but as tools that help the learner to enhance his or her design knowledge through making with them. I conducted a qualitative research approach through documenting and analyzing my observations and the students’ responses to the written questionnaires given out at the beginning and the end of the courses. In general, I wanted to see how effective the I³ process had been in enhancing students’ design knowledge and technical skills and the role that computational making had played in their learning process.

Because I did not have control groups, it is difficult to know exactly how students’ learning was influenced using I³ in comparison to what they might have learned following approaches I discussed in chapter two. However, based on my observations and the students’ comments, I conclude that through I³, the students improved their perceptual experience in design and making and learned more about the capabilities and limitations of several digital fabrication machines. They were able to see and feel in novel ways more than when they started the courses or more than they might have been using in other approaches. Each step in the I³ process contributed to developing aspects of the students’ design and technical skills; they worked with greater surety as they went along. In all the case studies, the students enhanced their spatial reasoning and sense of scale. For example, in the large scale case study: Making Spaces, all students had to think in different scales about the size of the elements of their structure, and how these elements come together. Moreover, their confidence in their design and making processes increased as they progressed through each stage.

I discuss below the effect of I³ on the design process, the technical skills and Computational making.
The Effect of I³ on the Design Process

Each step in the I³ process contributed to developing aspects of the students’ perceptual experience and their approach to the design process. In general, the I³ process encouraged the students to learn to design through an embodied cyclical interaction with tools, materials and the thing in-the-making, rather than going through a typical linear and sequential process of the traditional design studio. The students’ ability to improvise increased by learning to start from a precedent by imitating it and iterating on it.

Having observed the students as they worked and having examined their responses to the questionnaires, I concluded that they came to see making and design as a holistic, embodied process rather than one that proceeds in a universally applicable, linear way. For example, when asked in the questionnaire at the end of the course about what steps they would take in approaching a new project, one student ranked “building a physical model” as a second step, which would come after combining “looking at examples,” “sketching,” and “brainstorming” as a first step. In the first questionnaire, the same student had ranked “building a physical model” as the fifth step after a linear process of brainstorming and then sketching. This indicated to me that the experience the student gained in the embodied approach of I³ had given her greater confidence in her skills and allowed her to approach the design process more holistically. I think now that I should have added “thinking through physical prototypes” to the list of steps. It would have been interesting to see whether after experiencing the I³ methodology, students would elect to take this path earlier.

I also noticed that it is important to discuss and integrate the intangible aspects of a design – user experience and interaction, light and shadow – right from the beginning. Adding these features as a later iteration in a project might make them feel like add-ons, and not key parts of a design. For example, in the first course, Computational Making, adding the interaction or motion was part of the fourth iteration of the lighting unit. Some lighting units needed more work to show that the interaction and motion were inseparable aspects from the unit itself. However, I asked students in the following courses to think about user experience and interaction from the first iteration. For example, in the large scale course, Making Spaces, a group of students integrated the electronic and sensors inside their structure, Triangles. When touched, the colors of the light inside the triangles change (Figure 4.54).
The Imitation Stage

As I explained in the analysis and summary of the Imitation case studies, Imitation is a meaningful exercise in the context of the design studio compared to the traditional design studio. Instead of just analyzing a precedent, students must actually attempt to copy it and make it. Clearly, hands-on imitation of an existing thing contributes to changing the students’ perceptual experience, as they are forced to see and perceive more than they would if they started from a blank sheet of paper. Beginning with imitation obliges students to think about all the materials, structure, fabrication techniques and tools they will need to imitate the thing they choose. For example, in the Computational Making course and the Istanbul architecture studio, students faced the immediate challenge of how to copy the precedent whether a lighting unit or a scaled play space for children. In addition to deciding on the fabrication techniques, they had to think about the thing in-the-making’s materials, geometry and scale. For example, in the small scale case study, Light Between the Folds, the student tried to imitate the folded tessellations of Ron Resh. She had to try a number of different materials to achieve the desired imitation – this exposed her to the unpredictable behaviors of materials she had assumed would perform a certain way and produce the geometry she desired.

Students who already had a background in design resisted this, however, as they felt copying a thing was not creative enough. In these cases, I suggested that the students imitate only part of an object, and use this as a starting point. Yet not all experienced students felt that imitating an entire object was “uncreative.” One graduate architecture student said that in the future she would use imitation as a starting point for a design. In general, students without a design background felt that imitating an object was very useful. In the questionnaire given at the beginning of the course, the students without a design background had ranked “looking at
examples” as a late step in their design process, by the end of the course, these same students reported that they would do this as a first or second step.

The Iteration Stage
Providing clear structure for what students should do in the Iteration stage was a very successful strategy. The structure directed the students to change one aspect at a time in the thing in-the-making —geometry or material, for example—and to adapt anything that depended on that change. In the traditional design studio, iteration on design is open-ended; as a result, sometimes students feel lost as to what to do to enhance their designs. Making several guided iterations of the same thing enabled the students to learn about material behavior. As in the Imitation stage, with each iteration, a new realization emerges, and students are able to decide on next steps. By making iterations with materials and geometry, and studying the effect of these iterations, the students were able to “see and feel” the links between the physical and phenomenological aspects of what they were making. In all the case studies, the students enhanced their spatial reasoning and sense of scale. For example, in the medium scale case study, Inside-Out, they had to adjust the openings in their structure in order to allow the children to move in and out of it more easily.

In the questionnaire given at the end of each course, many students indicated that they would use iteration in future projects. One student from the Making Spaces course submitted her responses to the questionnaire a few months late. One of her responses was that while she had not yet used her newly acquired technical skills directly in any other project, she had used iteration in some projects. This indicated to me that her approach to designing had been positively affected by experiencing the I$^3$ methodology.

Focusing on one aspect at a time allowed the students to gain a deeper understanding of design aspects and to use a greater variety of tools. In every iteration made, students looked at the last thing they made with fresh eyes. In every iteration they were required to look at the thing and choose what to change, so basically they had to sense and see new things every time, and then fuse everything in one new thing.

At the end of the Computational Making course, one of the students commented in her questionnaire that iteration within her making experience was “a way of figuring out how to make something. Making wasn’t following a set of steps in a specific order, but rather developing and repeating and restarting—learning from mistakes or realizing better ways of doing things (after already having done them).”

The main shortcoming of the process is that some students might try to make only minimal changes so that they could avoid unexpected surprises. However, the guided iterations kept the class moving; there was always a next step. The instructor might also try to push the students to have more adventurous changes. Typically, traditional design studios can get bogged down when students panic and bring in an entirely new design halfway through the process. This often leads to a situation in which some students fail to finish a project and experience feelings of failure. Some students through the I$^3$ process tend to change too many aspects in one iteration, as if they are jumping from one design to another. For example, in the Computational Making class, in which students were making lighting units, a student brought in a new design every week instead
of making an iteration of the precedent week as instructed. This lead to an undeveloped project both design-wise and technical-wise.

The Improvisation Stage
As I mentioned earlier in the Improvisation analysis and Summary, the level of improvisation increases through every stage of I³. Contrary to the traditional design studio, where improvisation and creativity are often considered to be innate, the I³ process acknowledges improvisation as an acquired skill. As students become more aware of their actions while designing, they find themselves better able to predict and adapt. They gain confidence in their skills with each step. In the questionnaires, most students defined “improvisation” as “being able to adapt to surprises,” a solution for “a new or an unexpected challenge,” “developing an idea on the spot” or “changing things on the fly.” By the end of a course using I³, students found that they were, in fact, able to do this. In her questionnaire, a student from the Feeler group explained that they had to improvise when doing iterations to the geometry of the modules to make the mechanism of motion work in their structure. Similarly, the Briar group was able to improvise successfully when they had to adapt the walls of their full-scale structure so that they would fit into the base (Figure 4.55).

As I explained earlier, I approached Improvisation first in my early experiments as a separate stage that follows Imitation and Iteration stages. In the small scale case-studies: Computational Making, I asked the students to design and make a new lighting unit as a separate stage from the previous Imitation and Iteration stages. However, as I developed my methodology and tested it, I came to realize that the level of improvisation increases as the students’ progress through the courses.

Students were able to decide which tools and machines to use to make their things. In general, I noticed an improved level of confidence in the students as they went through the stages. This I³ process fosters improvisation, empowers learners to create on their own, and allows the transfer of their learned knowledge to another project. As learners progress through the process, their need for external guidance decreases and their ability to judge for themselves increases.
The Effect of I$^3$ on Technical Skills

In general, the I$^3$ process encouraged the students to learn how to use different mediums of creative production simultaneously, rather than going through a typical linear and sequential process. As I explained in the Analysis of Imitation Case Studies, imitating a thing made students focus on which aspect of something appealed to them, which they felt would be easy or difficult to copy, and which fabrication techniques would be most useful.

From my observations and the students' responses to the questionnaires, students acquired technical skills at different speeds and levels, depending upon the decisions they made while developing their project. For example, in the Making Spaces course, some groups used laser cutters to develop their prototypes, but then became proficient on the router when cutting materials for the full-scale structure. All students were involved in using 2D and 3D modeling software, some manual tools, digital fabrication machines and a coding interface, Arduino. They started making links between materials, tools, and machines. They understood that some machines work on certain materials with specific properties and dimensions. For example, the large scale case study, Feeler Group, cut wooden pieces on the CNC for the main structure then assembled them, then cut mylar on the laser cutter to make the strips, and then assembled the whole thing together. The Triangles group from the Making Spaces course, used the CNC router to cut both wooden sheets and corrugated plastic. They only switched from a mill to a blade as the cutting tool attached to the machine (Figure 4.56). In this way, digital fabrication machines became more than cookie-cutters.
The Triangles group from the Making Spaces course, used the CNC router to cut both wooden sheets and corrugated plastic. They only switched from a mill to a blade as the cutting tool attached to the machine.

As I mentioned in the summary of the Iteration stage section, the iterations enabled the students to experiment and push the limitations of what they were making and their fabrication techniques. As the projects grew and changed, students had to jump from one medium to another and use different mediums simultaneously. Comparing the questionnaires students completed before and after the *Computational Making* course, I found that all students agreed that their technical skills had developed. All felt that they had more confidence with using digital fabrication machines and manual tools and with materials. The student in the Briar Group who handed her questionnaire late reported that she had gained confidence in using the machines in the fabrication shop and had been successful using them in projects undertaken after the course. She also stated that she would make another iteration of the Briar structure the following summer, which she did. It was exhibited in the Wiesner Art Gallery at MIT. Another student reported that she was now "definitely less fearful of doing a hands-on project" than she had been before taking the course.

From the questionnaires, I saw that the students learned that the I³ approach could be used in programming, as well. They learned that they did not have to be fully proficient in programming when starting a new project; instead of starting a code from scratch, they could copy code in Arduino’s user interface fully or partially from examples they find online.

**Computational Making and Rules**

I observed that most of the students understood rules as a way to track their process and ideas and communicate them to others inside and outside their design group. The students used the rules in their in-class presentations as a way of communicating their ideas. In general, students
need time to understand how to use visual rules to describe their physical making process and to describe the changes they have made in their iterations and design generation. I see rules as a way to train students to see and sense more -- or “embed,” as Stiny explains -- every time they interact with the thing they are making.

As I explained in the Analysis of the Iteration stage, Students used visual rules to describe what they were copying and their making process step by step, just like in the Imitation stage. They also used them to describe the transformations they made in each iteration. The students basically made the decision on how to divide visually the thing they made in the imitation stage, then chose the aspect or element they wanted to change, then apply a transformation rule on it. Then they “fused” everything back again in one thing. This is similar to how I learned to design using tracing paper, which I discussed in the first chapter.

In both the *Computational Making* course and the *Enormous Smallness* Istanbul architecture studio the students had time to understand and apply the rules before and during the I3 process. In the *Making Spaces* course, where the sessions were held almost daily and the pace was faster, the students still used visual rules to document their process, but not as completely as in the other two courses.

Even the act of imitation is creative. Although the students copied a precedent in the Imitation stage, some of what they produced looked a bit different from the what they were copying. At first I introduced Imitation as the identity schema of Shape Grammars, \( x \rightarrow x \) to the students. However, since the imitated thing can never be the same as the original thing, it is better described as \( x \rightarrow \text{prt}(x) \), weather it is a partial or full imitation. This allowed them to learn to see new things, and linked what they saw to what they were making. Moreover, the students’ perception of rules changed. When asked in the first questionnaire what they thought about rules, one student replied that she was not sure whether rules were “restrictive or inspiring.” At the end of the course, the same student described rules as “the starting point of Improvisation. By using or changing the rules, you know how to progress.” She also explained that it was very beneficial that she and her group recorded their rules for the making process while applying other changes such as geometry and material so that they could track their process.

In the Iteration stage, computational making became an important communication and reflection tool for the students. As I explained in chapter three in the section “Making Fast and Slow,” segmenting the events or actions of the making process plays an important role in learning. Computational making was useful in that role, as students had to describe their decisions and physical making process using rules. Through the sequence of iterations, students became more aware of the consequences of choosing only a certain part to change in each iteration, \( x \rightarrow \text{prt}(x) \), and of choosing another to apply to that change, \( x \rightarrow t(\text{prt}(x)) \). For example, making a transformation in geometry of a certain part of the object-in-making might lead to a different result than changing the entire scale. Again, every time the students made an iteration, they saw or sensed something new and then were able to make decisions on what to do next.

On the whole, students felt that the I3 methodology was one they would adopt in approaching a new project. Indeed, my experience in developing and testing I3 made me aware of aspects I had not considered before -- thus I3 led me to apply it to myself and to my research and design
approaches. I believe that $I^3$ can be developed for use not only with novice and experienced designers in college or university level architecture and design studios, but also with middle and high school students, and in community maker spaces and fab labs.

Figure 4.57 Human-Machine designing and making through $I^3$. 
5

Conclusions and Future Work
5 Conclusions and Future Work

In-the-Making and Becoming

My motivation for this dissertation began with my realization that in order to improvise and create things independently, emerging designers and makers need to do more than simply learn how to use digital fabrication machines and design software. To address this issue, I introduced I³, a three layered, embodied methodology for making and learning that unites design and construction. This methodology utilizes digital machines and software not only as tools with which to execute designs, but as design companions that help the learner enhance his or her design skills by making with them. While this new methodology could be used in both academic and non-academic settings, my focus here is on using I³ in design pedagogy at both the undergraduate and graduate levels. While the acts of imitation, iteration and improvisation are utilized in many other learning environments, combing the three together in a formalized, cyclic manner using digital fabrication tools in design pedagogy represents a new approach.

The reader will notice that throughout this dissertation, I use the term “the thing in-the-making” in place of “the thing” or the “things the students made.” I believe that things are always in flux. A creative design process is never finished; it is simply stopped at a chosen point. Similarly, the research I describe in this dissertation will always be in-the-making. Both the research and the things I talk about here remain, as in Ingold’s (2011a) description, in a state of “becoming, one that is never complete but [is] continually under construction.” (p. 140) Just as every time we look at a painting, new shapes emerge, each one of us perceives differently, and each time we perceive a thing, whether by seeing, touching or smelling, we perceive something new.

I define “making” here as a situated, embodied action, always in flux. Rather than seeing making merely from the perspective of the “morphogenetic model,” as Ingold (2011a) puts it, I characterize making as a conversation among the maker, the material, the tools, and the thing in-the-making. In the model that I put forward, abstract forms are not imposed on material but are discovered as they emerge.

In the previous chapters, I explained how the hylomorphic model originally conceived by Aristotle has led to a separation between plans and actions, creating a disembodied and discontinuous design and making process. This separation contradicts Dewey’s (1938) notion of “learning by doing” or “learning from experience,” which is understood as a situated and embodied experience resulting from direct engagement among the learner, the tools, and the thing in-the-making. I showed that this separation results in designers using digital fabrication machines primarily as cookie-cutters: designs are planned ahead of time and then executed by the machine taking away any opportunity for improvisation. In this linear process, the design phase stops when representations and execution of drawings begin. Yet despite the meticulous advanced planning allowed by digital tools, surprises may still arise during construction. One reason for such surprises is that the effectiveness of digital technologies depends on the designer’s experience: designers who lack experience with a certain material, for example, may find that this material will not work in the way s/he has foreseen on a 3D screen. It is expected that the designer will be aware of the physical aspects and implications of her or his design: materiality and structure, and intangible aspects such as experience, delight, and gravitational force. Even simulation software depends on representation and the designer’s sight. These
technologies promote interaction with virtual user interfaces without allowing physical interaction with the objects being made. These interfaces and their linear process of production create cognitive and perceptual obstacles, making it difficult for non-experts to create and improvise. Moreover, pedagogical approaches in the design studio have not yet fully integrated digital fabrication technologies as design companions in making; rather, they have been used primarily as tools for representation and materialization. This disembodied process of making is not effective in learning.

I have argued in this dissertation that learning depends upon the skilled coordination of perception and action, where planning is one part of this “situated action.” In this sense, the learning processes of art and craft, which involves action and perception, or physical “recursion and embedding” (Stiny, 2008), inspired my I³ methodology of human-machine making in design pedagogy. In Chapter Three, I discussed the notions and precedents that inspired my I³ methodology, and discussed precedents of each “I” in the arts, crafts, cognitive sciences, organizations design, performance and music. Through I³, students build their sensory experience as they engage directly with the machines and materials, and are able to make judgments independently about the thing in-the-making as the making process progresses.

To test I³, I conducted experiments in several settings. I examined the continuous process of developing and testing I³ during the teaching of the three courses. I described experiments with both novice and advanced students in two courses given at the Massachusetts Institute of Technology and one course given at Istanbul Technical University. In each course, the scale of the thing in-the-making became larger. In Computational Making: Light and Motion, I began with small things – interactive lighting units. In the second course, Enormous Smallness Architecture Studio, the thing-in-the-making became a scaled play space for children. In the third course, Making Spaces: Lightweight Structures for Social Interactions, the thing-in-the-making became a 1:1 scale lightweight structure occupying a space of around thirty cubic feet.

I highlight below some of the contributions that I have made with this dissertation.

The Black box

My first contribution is that I have shown that the ability to design and make something is not a black box; on the contrary, through I³, this ability is very much learned through doing. Digital fabrication machines will no doubt continue to advance, and new ones will be invented; however, there will still be a need for the direct interaction required for learning by doing. Just as sketching and other actions in visual media have traditionally been used as ways to see new things in the design studio, so I³ introduces and fosters embodied interactions between makers, tools and materials that enrich the experience and enable students to see and sense new design possibilities.

Mindful Copying

I have strengthened arguments from other fields that, contrary to common belief, mindful copying is a creative act. I also introduced a new application of mindful copying for making and design pedagogy.
Design pedagogy
I introduced a new design pedagogy methodology, I^3. The early design pedagogy approach at the Beaux Arts depended heavily on copying for learning and, later, the twentieth century Bauhaus pedagogy rejected the act of copying as creative, and depended heavily on hands-on making and material experimentation. However, both approaches relied extensively on the master-apprentice model, leading students to depend on the instructors to judge and validate their work. With I^3, I have brought back the act of copying, and introduced guided iterations in a formalized way as a structured learning approach. I have also utilized and expanded on Schön’s reflection-in-action approach by asking students to describe and reflect on each decision they make. In contrast to the standard linear and sequential process of the traditional design studio, I^3 introduces an alternative design learning approach based on a cyclical feedback. It also enables students to develop judgment skills regarding their work and make decisions accordingly.

Sensory perceptual experience
My fourth contribution is based on how action and perception -- or doing and sensing -- shape human sensory experience and learning. I have also argued that design and making pedagogy should engage all the senses. Based on my observations and the students’ comments and responses in the questionnaires, I conclude that through I^3, the students improve their perceptual experience in design and making. They are able to see and feel in novel ways and develop their sensory perception more than they might have in earlier courses using a different approach. Each step in the I^3 process contributes to developing aspects of the students’ design and technical skills; they work with greater surety as they go along. In all the projects described in the case studies, students enhanced their spatial reasoning and sense of scale.

Human-Machine making
My fifth contribution is that through I^3 students acquire technical skills at different speeds and levels, depending upon the decisions they make while developing their projects. In contrast to the linear process of modelling using digital design software and then printing on a 3D printer, for example, the I^3 methodology introduces students to an approach of working with several tools and machines simultaneously. Throughout each course, students learned the capabilities and limitations of each machine. By the end of each course, the students were able to decide which materials and which machines would fit the things they want to make.

Computational Making
Computational making is an important communication and reflection tool in design pedagogy. Students used rules to communicate to their thought processes to both instructors and classmates. As I explained in Chapter Three in the section “Making Fast and Slow,” segmenting the events or actions of the making process plays an important role in learning. Computational making was useful in that role, as students had to describe their decisions and physical making processes using rules. Instruction and practice in the use of rules and schemas to describe design and making decisions is another contribution of the work I have described here.

Future work
For future work on I^3, I will continue to test how the methodology yields theoretical and pedagogical results. As I explained earlier, I^3 is a design pedagogy approach that teaches design through making using digital fabrication machines and challenges the gap between design and
construction that is reinforced in traditional design studio approaches. I have shown in the dissertation the potentials of the methodology through experiment results and the students’ responses to the questionnaires compared to traditional design studio utilizing digital fabrication machines. However, I have not compared the effectiveness of the I³ methodology relative to other pedagogical approaches that integrate digital fabrication machines in design learning. I have not undertaken a comparison at this stage of my work for several reasons: first, my experiments included students from different fields and with different skill levels, making it difficult to compare results with those from architecture or engineering design courses, where students have received the same preparation; second, the learning approaches I discussed in Chapter Two that integrated using digital fabrication machines varied in terms of their goals. For example, in design schools did not present a formalized learning approach to using digital fabrication machines to be able to compare it to I³. Other formalized learning approaches such as those in the How to Make (Almost) anything course and the Fab Academy have a different learning goal, which is to teach the technical skills of making using digital fabrication machines.

In the future, I would like to strengthen and develop I³ by conducting experiments using control groups and testing the effectiveness of I³ against other learning approaches. Furthermore, I would like to interview educators such as those at the California College of the Arts and the University of Michigan who are integrating digital fabrication machines into design pedagogy, and compare I³ to their approaches. Other experiments would include focusing on students and their cognitive and perceptual development using I³ compared to using other approaches. Another study would focus on using I³ while students work independently and in groups.

It would also be interesting to introduce different types of changes within the Iteration stage. For example, instead requiring students to change the material or geometry of their design, I might ask them to use a different fabrication process, machine, or tool as they move forward. I also think it would be interesting to spend more time in the Iteration stage exploring the making of interactions and physical computing in the things being made such as structures that sense and respond to users, and then seeing how users interact with them. Although I discussed with students how users would interact with the things they were designing and making, I think it would be interesting to do more directed experiments on human experience and interactions as users interact with the things being made.

In her recent paper, Knight (2018) investigated the “temporal qualities of making” (p.205) using making grammars. I would like also to expand the notion of time and segmenting events during the design and making processes. I would like to conduct more experiments documenting the making process to see which events learners see as important to record and reflect on. I am also interested in investigating the cognitive effects caused by segmenting the events while making. In general, the use of rules throughout the I³ process can be better formalized for more consistent data. It is important to formalize how and where in the process rules could be used, which is a key aspect of Computational Making. It would also be interesting to study how calculating with rules could facilitate participation and communication between the students within design working groups. I would like to add to scholarly work on the technological and social implications of digital fabrication machines and fab labs.

It would also be very interesting to see how I³ might contribute to and be implemented in other
fields, particularly in product development in industry. For future work, I plan to look into introducing new interactions and machines that allow greater embodied feedback between the user and the thing being made. I would like to go back to the question I asked in the introduction: How can we create digital design and fabrication machines that act as design companions and allow uncertainty? What do we learn from machines, and what do machines learn from us?

We need to reconsider our learning environments. Making and fabrication labs should become an integral part in the learning process. Hands-on experience and embodied interaction with machines and materials will produce designers who are better able to foresee problems, improvise, and approach their designs with greater confidence. New designers will emerge who can employ technology as an equal partner in a design process that is reflective, responsive, and innovative. I believe that my $I^3$ methodology makes an important contribution toward achieving this end.
6

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All images are produced by or under supervision of Dina El-Zanfaly unless otherwise is noted here.

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6.2 Bibliography


https://doi.org/10.1016/j.destud.2015.09.002


Appendix 1:
Course Descriptions and Assignments samples
Appendix 1: Course Descriptions and Assignments samples
4.552 Computational Making: Light and Motion

Spring 2015  Credits 3-0-9 U; 3-0-6 G  Tuesday 9:30 am- 12:30 pm  Room 9-255

Enrollment:
Limited to 12

Instructors:
Dina El-Zanfaly  Office 3-309  dzanfaly@mit.edu
Terry Knight  Office 7-304F  tknight@mit.edu

COURSE DESCRIPTION
Making is a process of creating artifacts, spaces, buildings and experiences, in which there is a continuous flow between shape and material. How then do we learn to make something? What can we learn by making? What are the potential roles of computational tools, theories, and practices in making? And where do makers, designers, entrepreneurs and students begin? How do they learn how to realize their ideas and to describe their making activities?

Computational Making: Light and Motion introduces a new, embodied process of making and learning called 13. This process, 13, consists of Imitation, Iteration and Improvisation. The course studies this new making process in human-machine interaction, and its application and implications in learning to create objects. However, the course is not just about learning how to make prototypes, it is about building the learner’s sensory experience and spatial skills by teaching him/her a new process of human-machine making. With 13, machines are companions for makers to generate and materialize ideas instead of the means for materializing a prototype for an already designed and planned digital model. Students will be able to apply this process to make almost anything with digital fabrication machines as well as without them. They will make both tangibles, such as physical artifacts, and intangibles, such as experience, light and motion.

For the first half of the semester, students will learn how to use rules to describe and make - design and build - lighting units. Shape and material will be thoroughly examined and tested. For the remainder of the semester, students will develop their prototypes further by adding motion and electronics to their lighting units. Students will be also required to deliver a documented process of their work.

PREREQUISITES
The course brings together graduate and undergraduate students from different backgrounds, including architecture, the arts, engineering, education and management, to develop their Computational Making
skills. No particular skills are required. There will be optional lab sessions for support for software and technical skills.

GOALS AND ACTIVITIES
Through tangible and hands-on exercises, students will use digital fabrication machines, Arduinos, and simple electronics to make their projects. They will learn how to push the machines' capabilities and limitations. Moreover, students will develop and formalize critical views of the role of machines in making and their applications in learning. In addition to weekly sessions, optional lab sessions are offered to cover technical skills (Modeling software, programming, etc). Each weekly session includes an assignment and a text related to the topic.

EVALUATION CRITERIA
Weekly reviews and assignments 50%:
Mid-term review: 25%
Final project: 25%

CLASS WEBSITE
COURSE OUTLINE

Week 1 (Feb. 3) - Introduction
- What is Computational Making?
- What is \( \ell \)? Why?
- Why light and motion?
- Course outline and deliverables.

- Assignments and readings:
  - Readings:

Presidents' day (Feb. 17): No class - Monday classes are held on Tuesday

Week 2 (Feb 18) - Showing Making
Assignment 0 presentations and a discussion on ways of showing making.

- Assignments and readings:
  - Assignment 1: Lighting Units, due Feb. 23.
  - Readings:
  - On instructions, how to make a lamp by Instructables: http://www.instructables.com/id/Universal-lamp-shade-polygon-building-kit/?ALLSTEPS

Week 3 (Feb. 24) - Making :: Rules
- Assignment 1 presentations and feedback.
- Introduction to Shape Grammars with lighting unit examples.
- Hands-on exercises.
- Assignments and readings:
  - Assignment 2: Imitation X → X, due March 2.
- Readings:

- Optional lab session: Introduction to 2D/3D software and Digital fabrication lab tutorial.

Week 4 (March 3) - Making :: Embodiment
- Assignment 2 presentations and feedback.
- Visit to the ceramics lab.
- Assignments and readings
  - Assignment 3: Iteration 1 X → t(X), due March 9.
  - Readings:

Week 5 (March 10) - Making :: Material
- Assignment 3 presentations and feedback.
  - Invited speaker: Dimitris papanikolaou, Adjunct professor, NYU, Doctoral Candidate at Harvard university.
- Assignments and readings
  - Assignment 4: Iteration 2 X → t(X), due March 16.
  - Readings: TBD
- Optional lab session (TBD).
Week 6 (March 17) - Making :: light
- Assignment 4 presentations and feedback.
- Lighting sources.
  - Assignments and readings
    - Assignment 5: Iteration 3 \( t(X) \rightarrow t(X) \), due March 30.
    - Readings:
  - Optional lab session (TBD).

March 24 Spring break: No class

Week 7 (March 31) - Making :: Motion
- Assignment 5 presentations and feedback.
- Programming and micro controllers: Arduino (inputs/outputs)
- Types of motion.
- Introduction to Active Shapes and rules.
- Hands-on exercises.
  - Assignments and readings
    - Assignment 6: Iteration 4 \( t(X) \rightarrow y(X) \), due April 8.
    - Readings:
  - Optional lab session on April 2

Week 8 (April 9) - Mid-term review
- Projects presentations and feedback.
  - Assignments and readings
    - Assignment 7a: Improvisation 1 \( X \rightarrow Y \), due April 13.

Week 9 (April 14) - Making :: Light and Motion
- Assignment 7a presentations and feedback.
- Invited Speaker: Nadya Peek, Center of Bits and Atoms.
  - Assignments and readings
    - Assignment 7b: Improvisation 2 \( Y \rightarrow X \), due April 20.
    - Readings: TBD.

Week 10 (April 28) - Making :: Interaction
- Assignment 7b presentations and feedback.
- Invited speaker: Marcelo Coelho, director, Marcelo Coelho studio.
  - Assignments and readings
    - Assignment 7c: Improvisation 3 \( Y \rightarrow X \), due April 27.
    - Readings: TBD.

Week 11 (May 5) - Making :: Interaction
- Assignment 7c Presentations and feedback.
- Programming and micro controllers: Arduino (inputs)
  - Assignments and readings
    - Assignment 7d: Improvisation 4 \( Y \rightarrow X \).
    - Readings: TBD.

Week 12 (TBD) - Final review
Assignment 0
Part 1
Showing Making

Due: Monday, Feb. 9 at 11:59 pm

To watch
Charles Limb’s TED talk: Your brain on improvisation
http://www.ted.com/talks/charles_limb_your_brain_on_improv?language=en

To read

To do
- In her paper, Lehman introduces visual representations as means for showing and analyzing making. She explains that in order to show making, mediation is considered a material not just a representation process. Explain what she means by “hand in the brain.” Describe the ways of showing making in the examples she mentions.

- Origami instructions usually include dotted lines and arrows to show the folds and each step of making any origami piece. Are there any new ways of showing origami making? Use what you learned from Lehmann’s paper, and show the making of an origami piece of your choice. This origami piece could be a crane, a wheel or anything. More importantly, this exercise is about showing making, so ask yourself: if I give my making instructions of the origami piece to a friend, will it trigger his/her “hand in the brain”? How about the materiality of the visualizations of making?

Upload your assignment to our Stellar class website: https://stellar.mit.edu/S/course/4/sp15/4.552/
Assignment 0
Part 2
Showing Making

Due: Wednesday, Feb. 18 at 11:59 pm

To do
You have already submitted Part 1 of Assignment 0. Here is Part 2:

You will find below that you are assigned origami instructions submitted by one of your classmates.
1- Please use the instructions given to you to build the Origami piece. Don’t use any other instructions, from the internet or elsewhere.
2- Document your process using photos or videos.
3- Add a large image of the final outcome.
4- Describe your experience in a very short paragraph. Were the instructions clear? What wasn’t clear? Did you have any questions while you were making the origami piece? What should have been added to improve your experience while you were making the piece?
5- Compare what you made to the original origami piece made by your colleague. Is it similar? What’s different?
6- Bring to the session on Thursday the origami piece you wrote instructions for, and the origami piece you made following instructions from your classmate.

Anne, you will make with Jacquelyn’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/jliu@mit.edu/

Xinyi, you will make with Kam-Ming Mark’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/kmmtemit.edu/

Tsz Wai Alan, you will make with Anne’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/sschneid@gsd.harvard.edu/

Jacquelyn, you will make with Euipoom’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/euipoomy@mit.edu/

Kam-Ming Mark, you will make with Yichen’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/ayc617@hotmail.com/

Euipoom, you will make with Xinyi’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/xinyima@mit.edu/

Yichen, you will make with Tsz Wai Alan’s instructions: https://stellar.mit.edu/S/course/4/sp15/4.552/homework/assignment1/kwanajan@mit.edu/

Upload your assignment to our Stellar class website: https://stellar.mit.edu/S/course/4/sp15/4.552/
Assignment 1
Lighting Units

Due: Monday, Feb 23 at 11:59 pm

To read


- On instructions, how to make a lamp by Instructables: http://www.instructables.com/id/Universal-lamp-shade-polygon-building-kit/?ALLSTEPS

To do

1- Choose five examples of lighting units from the Internet or elsewhere. They could include table lamps, pendants, modular lighting units, etc. Be prepared to present them in class. Why did you find them interesting?

2- Choose one of the examples from the above lighting units. Analyze this unit and study it in terms of material, geometry, etc. How do you think it is made? How do the parts come together? Use diagrams or illustrations to describe the lighting unit.

Upload your assignment to our Stellar class website: https://stellar.mit.edu/S/course/4/spl5/4.552/
Assignment 2
Lighting Units

Due: Monday, March 2 at 11:59 pm

To read


To do

1 - Continue working on the lighting unit you made in class if you want until you have something you like.
   a) Take photographs of the lighting unit in the best illustrative view.
   b) Illustrate the rules you used to make the unit. You can draw the rules, or use photos of physical models.
   c) Examine the lighting pattern produced by the lighting unit, and draw the rules of this lighting pattern.

2 - After reading the Making Grammars paper and how to make a lamp by Instructables: Think about what you need to add to your rules to illustrate or show the physical process of making? If you have an idea on how to do that, show them in your rules. Also keep in mind what we learned from assignment 0 about the materiality of showing making.

3 – Build a simplified model of the lighting unit you analyzed for assignment 1. It does not have to be full detailed, just the geometry, material, the assembly etc.
   a) Take photographs of the lighting unit in the best illustrative view.
   b) Illustrate the rules you used to make the unit. You can draw the rules, or use photos of physical models.
   c) Examine the lighting pattern produced by the lighting unit, and draw the rules of this lighting pattern.

4 - After reading the Resisting Alignment: Code and Clay paper, write a question you would like to ask the ceramics instructor. We will visit the ceramics lab at MIT next week, so it will be a good opportunity to see the craft in action, and ask the ceramics instructor.

Upload your assignment to our Stellar class website: https://stellar.mit.edu/S/course/4/sp15/4.552/
"Back home on Irving Street, in one particularly enormous tree, Estlin and his father built a small house in the branches. Estlin also liked being there alone. Drawing pictures and writing poems, he would peer out at the world above and the world below."

The quotation is from Enormous Smallness – a picture book on the childhood of the poet E. E. Cummings. Estlin is small but his world, in both the mental and the physical sense, is enormous. Children everywhere deserve places of nurture (a.k.a. cultivation, encouragement, development) to grow into inspiring role models. This studio will focus on design ideas and design skills necessary for creating inquisitive and playful spaces for small children in the city. The aim is to delve into the moral dimension of architecture with regards to a particular user group and to the relation between cityscape and nature. The semester plan will start with two weeks of foundational and four weeks of computational making design exercises. We will then continue dwelling on notions of observation, attention, and listening, as well as small things and enormous ideas, nooks and crannies as playscape, manipulating topography, the relation of indoors and outdoors, color-texture-whimsy, cultivation in all senses, and the last but not the least,
sustainability, aiming at concrete and insightful design proposals for a kindergarten. The studio structure will be open to collaboration and the use of design technology.

**CourseSchedule**

<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>M/D</th>
<th>Activity</th>
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<tbody>
<tr>
<td>Week 1</td>
<td>Sept 14</td>
<td>M</td>
<td>Introduction and logistics</td>
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<tr>
<td></td>
<td>Sept 17</td>
<td>R</td>
<td>Discussing rhythm (spatial relations, repetition, similarity, difference, variance, patterns)</td>
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<td>Assignment 2 – Photographing the designed</td>
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<td>Week 2</td>
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<td>Discussing what makes anything designed</td>
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<td>Sept 24</td>
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<td>Holiday – no class.</td>
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<td>Weeks 3-6</td>
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<td><strong>I³ – Imitation, Iteration, Improvisation</strong></td>
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<td><strong>A computational making workshop</strong></td>
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<td>Guest Instructor: Dina El-zanfaly, MIT</td>
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<td>Week 3</td>
<td>Sept 28</td>
<td>M</td>
<td>Introduction to rules</td>
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<td>Oct 1</td>
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<td>Discussing imitation (rules, repetition, similarity, difference, variance, unity)</td>
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<td>Introduction to materials</td>
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<td><a href="http://transmaterial.net/">http://transmaterial.net/</a></td>
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<td>Pick one method of making: CNC milling, cutting paper, knitting, &quot;throwing&quot; clay</td>
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<td>Week 4</td>
<td>Oct 5-8</td>
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<td>Preliminary review – guest critics</td>
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<tr>
<td>Week 14</td>
<td>Dec 26</td>
<td>R</td>
<td>Term project review: Jury</td>
</tr>
</tbody>
</table>
Assignment 3: Good nooks and crannies
Observe and document a situation that you perceive as a good design in your urban environment.

Nook (noun):
1. a small space or corner that is inside something
2. a part of a room (such as a corner) that is used for a specific purpose
3. a quiet place that is sheltered by a tree, rock, etc.

Cranny (noun):
1. a small opening or space
2. a small break or slit
3. an obscure corner

Children love to squeeze through and nestle in nooks and crannies. They also love to climb, lean on, twist around, and dangle from things. First do a search for how children conduct their bodies during play. Reflect back to your own experiences. Then, do a search for good examples of designed nooks and crannies for children. Recently, there is a growing number of kindergarten designs in architecture blogs. Look for revolutionary examples that emphasize playful learning and offer a plentitude of playing freedom in their architectural spaces. You are then required to analyze and present the manifestation of this good design. You are once again advised to focus on characteristic features including form, structure, and textures. You are asked to present only three images (of your production) to the class. These images are to be analytical and representative definitions of the same design.

Bring printouts of each image as portrait (vertical orientation) A4 sheets. (Margins should be minimal, final page should be exactly A4).

Combine your digital images in a vertical fashion and submit one file in jpg format with resolution at 72 dpi and 21 cm (A4 size) across the top and 89.1 cm on the side. Upload these to the Assignment 1 folder in Drive with your lastname only (e.g. ozkar.jpg).
Making Spaces: Lightweight Structures for Interactions

IAP 2017  Credits: 4  Room: TBD

Enrollment:
Limited to 20

Jan. 9-13 9AM–4PM
Jan. 17-20 9AM–1PM

Instructors:
Dina El-Zanfaly  dzanfaly@mit.edu
Terry Knight  tknight@mit.edu

TAs:
Hunmin Koh Hunmin@mit.edu
Yasman Tahouni Tahouni@mit.edu

COURSE DESCRIPTION
Making is a process of creating artifacts, spaces, buildings and experiences, in which there is a continuous flow between shape and material. How, then, do we learn to make something? What can we learn by making? What are the potential roles of computational tools, theories, and practices in making?

In Making Spaces and Playful Interactions Students will make lightweight simple structures, such as small pavilions, with embedded electronics in them. Students will use digital fabrication machines and tools, and learn the basics of electronics and programming (Arduinos) to create spaces, experiences and interactions.
The class introduces a new, embodied process of making and learning called i^3. This process, i^3, consists of imitation, iteration and improvisation. The course studies this new making process in human-machine interaction, and its application and implications in learning to create spaces. However, the course is not just about learning how to make prototypes; it is about building the learner’s sensory experience and spatial skills by teaching a new process of human-machine making. With i^3, machines are not simply a means for producing a prototype for an already designed and planned digital model: they are companions in the making process, helping designers to generate and materialize ideas. Students will be able to apply this process to make almost anything with digital fabrication machines as well as without them. They will make both tangibles, such as light structures, and intangibles, such as experience, and small interactive installations such as light.

In the first half of the course, students will learn how to use rules to describe and make - design and build - lightweight structures such as pavilions on a small scale. Shape and material will be thoroughly examined and tested. Students will be working in groups for most of the time. For the remainder of the course, students will choose two or three structures to develop and build them on scale 1:1. They will also add some interactive electronic components to their structures using Arduinos and sensors. Students will also be required to deliver a documented process of their work.

**PREREQUISITES**

The course brings together graduate and undergraduate students from different backgrounds, including architecture, the arts, engineering, education and management, to develop their skills. No particular skills are required, but experience in 3D modelling is preferred.

**GOALS AND ACTIVITIES**

Through hands-on exercises, students will use digital fabrication machines, Arduinos, and simple electronics and programming to realize their projects. They will learn how to push the machines’ capabilities and limitations. They will learn about using visual rules to generate designs. They will learn about materiality and material behavior. They will learn to improvise and create things on their own. Moreover, students will develop and formalize critical views of the role of machines in making and their applications in learning.

**COURSE OUTLINE**

**Session 1: Introduction**

January 9, 9 am-4 pm

- Introductions, plan of the day
- Course outline and deliverables.
- Short presentation on pavilion examples and Digital Fabrication techniques.
- 10 minutes break
- Computational Making and Method
- Introduction to Shape Grammars (using visual and physical rules to generate designs) with examples.
- Hands-on exercises on building small structures with rules.
- Showing Making: How to describe the making process.
- Lunch Break (12-1 pm)
- Orientation: Digital fabrication machines in the Shop and materials inventory (1:00-2:30 pm)
- Introduction to Arduino and programming (2:30-4 pm)
- Assignment 1: Build a small structure using the given laser-cut pieces and describe your making process.

**Session 2: First Iteration: Geometry and Structure**

January 10, 9 am-4 pm

- Finalizing Assignment 1
- Lunch Break 12-1 pm
• Assignment 1 presentations, and selected structures. 1 pm
• Forming Groups.
  10 minutes Break
  Arduino Inputs, outputs and wireless at 2:30 pm
  Assignment 2: Iteration 1 \( X \rightarrow t(X) \), Change one element in your structure except material.

Session 3: Second Iteration: Material
January 11, 9 am-4 pm
• Finalizing Assignment 2
• Lunch Break 12-1 pm
• Assignment 2 presentations.
• Groups present their first iteration of their structures and get feedback.
• Students choose 2-3 projects to build in Scale 1:1
• Assignment 3: Iteration 2 \( X \rightarrow t(X) \), choose one element to change its material and anything that depends on it.

Session 4: Third Iteration: Scale and Interaction
January 12, 9 am-4 pm
• Finalizing Assignment 3
• Lunch Break 12-1 pm
• Assignment 3 presentations
• Assignment 4: Iteration 3 \( X \rightarrow t(X) \), Choose two parts from your structure and build scale 1:1. and you can change whatever depends on scaling your Iteration 2. Draw a scenario of how your structure will interact with users.

Session 5: Mid-review
January 13, 9 am-4 pm
• Finalizing Assignment 4
• Lunch Break 12-1 pm
• Assignment 4 presentations
• Finalizing the list of materials and electronics

Session 6: Improvisation
January 17, 9 am-1 pm
• Assignment 7: Develop the structure and build another part of it
• Test electronics

Session 7: Building structure
January 18, 9 am-1 pm

Session 8: Building structure
January 19, 9 am-1 pm

Session 9: Final Review
January 10, 9 am-1 pm
Assignment 1
Imitation

Part 1
1. Build a small structure using the given laser-cut pieces
2. Describe the rules you used.
3. Describe your making process using any method of your choice such as sketches, photos and/or videos

Part 2
4. Choose five examples of lightweight structures and small enclosures such as pavilions. Be prepared to present them in class. Why did you find them interesting?

5. Choose one example from the above examples.
   a. Analyze this example and study it in terms of material, geometry, and fabrication technique. How do you think it is made? How do the parts come together? Use diagrams or illustrations to describe the structure.
   b. Imitation $X \rightarrow X$
      Choose an example online, and sketch and build a scaled physical prototype of the example you chose using any material you want nylon, paper, cardboard or acrylic. Define what exactly are you copying or imitating. It could be the whole structure, Geometry, or Fabrication technique. The structure dimensions should be around 10x10x10 feet, the prototype scale is 1:8
   c. Describe what you are copying in terms of rules $x \rightarrow x$
   d. Document your process using photos or videos.
   e. Prepare a PowerPoint presentation of your process.
   f. Add a large image of the final outcome.
   g. What would you change in your structure?

Upload your assignment to our class website
Assignment 2
Iteration 1

Choose one element or an aspect in the chosen space, and change it and whatever depends on this changes. This element could be the unit geometry, geometry of certain parts of the unit, colors....etc. You can change anything except the material you used in the last prototype.

a. Indicate the transformation you choose to make, and describe it in rules $x \rightarrow T(x)$.
b. Build the new space with the change/transformation Scale 1:8, Please remember that our space should be 10x10x10 feet, 3x3x3 meters.
c. Take photographs of the space in the best illustrative view.
d. Illustrate and describe your manual, digital and physical process of making verbally (maximum 200 words), diagrams and with photos. For example: how you started, an image of your laser cutting files, digital models, sketches, how you put the pieces together, etc. Also keep in mind what we learned from assignment 1 about the materiality of showing making. You will need this material for your final submission as well.
e. Illustrate the rule(s) (in the form $A \rightarrow B$) you used to make the space. You can draw the rules, or use photos of physical models, this could be part of task (d).
f. Add a large image of the final outcome.
g. What would you change in your structure?
h. Prepare a PowerPoint presentation to present at 1 pm tomorrow.

Upload your assignment to our class website
Appendix 2: Questionnaires
4.522 Computational Making: Light and Motion

Questionnaire one - Feb. 18, 2015

Name: _____________________________

Graduate ☐ Undergraduate ☐

Year: ________________

Department: _______________________

If you are a graduate student,

a- what is your undergraduate degree? ________________

b- where? ________________

c- when did you graduate? ________________

Please answer the below questions. There is no “right” answer.

1- What do you expect to learn from this course?

2- What skills do you want to learn or improve?

3- In your opinion, what is “making”?
4- In your opinion, what is “improvisation”?

5- In your opinion, what is the best way to represent or describe any making process? This process can be a craft or it can be making an architectural model or even a software program. If you choose more than one, rank your choices using numbers, number 1 is the best and number 6 is the least.

- Diagrams ( )
- Step by step images ( )
- Video ( )
- A live demo ( )
- Verbal description ( )
- Other ( ):

6- In your opinion, what is the hardest part or aspect in representing or describing any making process?

7- Do you think rules can represent a making process?
   a- Yes ( )
      If yes, How?

   b- No ( )
      If no, why?

   c- I don’t know ( )
8- How you can build a hollow cylinder with a diameter of 5 inches, a height of 10 inches and maximum thickness 0.5 inch. The image below is just for illustration.

- In step by step, draw sketches of the building process. How do the parts come together?
- You can use any tool, machine or materials you like. Specify each one of them in each step.
4.522 Computational Making: Light and Motion

Second Questionnaire

1- When/If you are assigned a new project (a building, product design,...etc). Select and rank your steps below to make this project. It can be one step or more.

- Looking at examples ( )
- Brainstorming ( )
- Diagrams ( )
- Storyboard ( )
- Sketching manually ( )
- 2D drawing digitally ( )
- 3D modeling ( )
- Building a physical model ( )
- Other, indicate: ( ) : __________
     ( ) : __________
     ( ) : __________
     ( ) : __________

2- When/If you are assigned a new programming project. Select and rank your steps below to make this project. It can be one step or more.

- Copying parts of code from old codes ( )
- Writing the whole code from scratch ( )
- User interviews ( )
- Paper prototypes ( )
- User testing ( )
- Mock-up ( )
- Other, indicate: ( ) : __________
     ( ) : __________
3- Have you ever used a digital fabrication machine before?
   a- If yes, which machine(s)? for making what?
   b- No

4- If/when you build a physical model, furniture or an artifact, rank the steps you follow?
   Sketching manually ( )
   Using hand tools to build it ( )
   2D drawing digitally ( )
   3D modeling ( )
   Cutting a 2D file on a laser cutter or any CNC machine ( )
   3D printing a 3D model ( )
   Assembling parts ( )
   Other, indicate: ( ) : ___________
                      ( ) : ___________
                      ( ) : ___________
                      ( ) : ___________

5- What is the most difficult step when you start working on a new project? For example making a lighting unit.
   Where to start ( )
   Coming up with an idea/design ( )
   Building a prototype ( )
   Other ( ) : ___________
6- On scale 1 to 5, rate your making skills. 1 is none 5 is excellent.

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<th>Wood working and manual tools</th>
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<th>2D drawing</th>
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<th>Laser cutting</th>
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155
4.522 Computational Making: Light and Motion

Third Questionnaire

Name:

Date:

1- When/If you are assigned a new project (a building, product design, etc). Select and rank your steps below to make this project. It can be one step or more.

   Looking at examples (  )
   Brainstorming (  )
   Diagrams (  )
   Storyboard (  )
   Sketching manually (  )
   2D drawing digitally (  )
   3D modeling (  )
   Building a physical model (  )

Other, indicate: (  ) : ___________
                     (  ) : ___________
                     (  ) : ___________
                     (  ) : ___________
2- When/if you are assigned a new programming project (coding, arduino, etc), select and rank order your steps below, using numbers, to make this project. It can be one step or more. If you think you want to repeat a step, write multiple numbers beside it.

- Search for examples and old codes
- Copying parts of code from old codes
- Writing the whole code from scratch
- User interviews
- Paper prototypes of the software interface
- (User) testing
- Editing and refining code

Other, indicate:

( )
( )
( )
( )

3- If you are an invited critic to the mid-term of this class, what feedback would you give to your project:

a- Define two main points that need to be developed further. Why? You can illustrations or verbal descriptions.
b- What strengths would you acknowledge in your project? Why? Define two main points. You can illustrations or verbal descriptions.

4- How do you feel about your “making” process and design experience today compared to your process and experience prior to taking this class?

5- After working with different tools, machines, electronics, which part or skill are you interested in developing further?

6- In your opinion, what is improvisation?
7- When looking at your “making” process, you have copied or imitated a lighting unit, and have made 4 iterations from the same unit. You experimented with geometry, material, light and electronics. And now you are building a new lighting unit. At which stages would you say that you utilized improvisational strategies? What were they?

8- You have so far described the changes you have made in the form of rules in iterations your iterations and improvisation phases.

a- In your opinion, what is/are the role(s) of “rules” in the making process?

b- In your making process, how do you use rules?

9- When you are assigned a new project, which strategies from below do you see yourself
employing?

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<td>a- Imitation</td>
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<td>- Check similar projects</td>
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<td>b- Iteration</td>
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<td>c- Improvisation</td>
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<td>c.1) Seeing something new</td>
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<td>c.2) Sensing something new (material, texture,...etc.)</td>
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10- If you are asked to make a new lighting unit: on scale 1 to 5, rate your I³ usage in your making process. 1 is none, 5 is definitely. You can use the previous question as a reference.

1- Imitation: looking at examples and copying it partially or all

h) Copying an example, by just making the first digital or physical prototype

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None Definitely

i) Copying from different examples, by just making the first digital or physical prototype

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None Definitely

2- Iteration: making changes in your first prototype

a) Changing geometry

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None Definitely

b) Changing Material

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None Definitely

c) Changing light

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None Definitely

d) Changing Motion
e) Changing Scale

1  2  3  4  5
None  Definitely

3- Improvisation:

a) Sensing (seeing, feeling ....etc.) something new

1  2  3  4  5
None  Definitely

b) Making or adding something new

1  2  3  4  5
None

c) Changing things on the fly

1  2  3  4  5
None  Definitely
On scale 1 to 5, rate your making skills. 1 is none 5 is excellent.

d) Wood working and manual tools

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e) Digital 2D drawing

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f) Laser cutting

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g) 3D printing

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h) Digital 3D modeling

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i) Arduino

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j) Programming

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k) Overall expertise in making

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Questionnaire one

Name: _____________________________

Graduate ☐ Undergraduate ☐

Year: ________________

Department: ___________________________

If you are a graduate student,

a- what is your undergraduate degree? ____________

b- where? ________________

c- when did you graduate? ________________

Please answer the below questions. There is no “right” answer.

1- What do you expect to learn from this course?

2- What skills do you want to learn or improve?

3- In your opinion, what is “making”?  
4- In your opinion, what is “improvisation”?

5- In your opinion, what is the best way to represent or describe any making process? This process can be a craft or it can be making an architectural model or even a software program. If you choose more than one, rank your choices using numbers, number 1 is the best and number 6 is the least.

Diagrams ( )  Step by step images ( )  Video ( )
A live demo ( )  Verbal description ( )  Other ( ): ________________

6- In your opinion, what is the hardest part or aspect in representing or describing any making process?

7- Do you think rules can represent a making process?
   a- Yes ( )
      If yes, How?
   b- No ( )
      If no, why?
   c- I don’t know ( )
8- How you can build a hollow cylinder with a diameter of 5 inches, a height of 10 inches and maximum thickness 0.5 inch. The image below is just for illustration.

- In step by step, draw sketches of the building process. How do the parts come together?
- You can use any tool, machine or materials you like. Specify each one of them in each step.
**MIM211E Architectural Design III**  
2015-2016 Fall semester  
Enormous smallness

**Questionnaire two**

1- When/If you are assigned a new project (a building, product design,..etc). Select and rank your steps below to make this project. It can be one step or more.

   - Looking at examples (   )
   - Brainstorming (   )
   - Diagrams (   )
   - Storyboard (   )
   - Sketching manually (   )
   - 2D drawing digitally (   )
   - 3D modeling (   )
   - Building a physical model (   )
   - Other, indicate: (   ) : ____________
       (   ) : ____________
       (   ) : ____________
       (   ) : ____________

2- When/If you are assigned a new programming project. Select and rank your steps below to make this project. It can be one step or more.

   - Copying parts of code from old codes (   )
   - Writing the whole code from scratch (   )
   - User interviews (   )
   - Paper prototypes (   )
   - User testing (   )
   - Mock-up (   )
   - Other, indicate: (   ) : ____________
3- Have you ever used a digital fabrication machine before?
   c- If yes, which machine(s)? for making what?
   d- No

4- If/when you build a physical model, furniture or an artifact, rank the steps you follow?
   Sketching manually (  )
   Using hand tools to build it (  )
   2D drawing digitally (  )
   3D modeling (  )
   Cutting a 2D file on a laser cutter or any CNC machine (  )
   3D printing a 3D model (  )
   Assembling parts (  )
   Other, indicate: (  ) : ____________
   (  ) : ____________
   (  ) : ____________
   (  ) : ____________

5- What is the most difficult step when you start working on a new project? For example making a lighting unit.
   Where to start (  )
   Coming up with an idea/design (  )
   Building a prototype (  )
   Other (  ): ____________
6- On scale 1 to 5, rate your making skills. 1 is none 5 is excellent.

j) Wood working and manual tools

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k) 2D drawing

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l) Laser cutting

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m) 3D printing

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n) 3D modeling

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o) Arduino

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p) Programming

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<th>Knitting digitally</th>
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Third Questionnaire

Name:

Date:

1- When/If you are assigned a new project (a building, product design, etc). Select and rank your steps below to make this project. It can be one step or more.

   - Looking at examples ( )
   - Brainstorming ( )
   - Diagrams ( )
   - Storyboard ( )
   - Sketching manually ( )
   - 2D drawing digitally ( )
   - 3D modeling ( )
   - Building a physical model ( )
   - Other, indicate: ( ) : ____________
      ( ) : ____________
      ( ) : ____________
      ( ) : ____________
2- When/if you are assigned a new programming project (coding, arduino,..etc), select and rank order your steps below, using numbers, to make this project. It can be one step or more. If you think you want to repeat a step, write multiple numbers beside it.

Search for examples and old codes ( )
Copying parts of code from old codes ( )
Writing the whole code from scratch ( )
User interviews ( )
Paper prototypes of the software interface ( )
(User) testing ( )
Editing and refining code ( )
Other, indicate: ( ) : ____________
( ) : ____________
( ) : ____________
( ) : ____________

3- If you are an invited critic to the final review of this class, what feedback would you give to your project:

a- Define two main points that need to be developed further. Why? You can illustrations or verbal descriptions.

b- What strengths would you acknowledge in your project? Why? Define two main
points. You can illustrations or verbal descriptions.

4- How do you feel about your “making” process and design experience today compared to your process and experience prior to taking this class?

5- After working with different tools, machines, electronics, which part or skill are you interested in developing further?

6- In your opinion, what is improvisation?

7- When looking at your “making” process in your final project, you experimented with geometry, material, senses and may be electronics. At which stages would you say that you utilized improvisational strategies? What were they?

8- you have so far described your making process and the changes you have made in the form of rules in iterations.

a- In your opinion, what is/are the role(s) of “rules” in the making process?
b- In your making process, how do you use rules?

9- When you are assigned a new project, which strategies from below do you see yourself employing?

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<th>If yes, why?</th>
<th>In no, why?</th>
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<td>d- Imitation</td>
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<td>- Check similar projects</td>
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<td>e- Iteration</td>
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<td>(The class utilized a particular set of iterations)</td>
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<td>b.1) Geometry</td>
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<td>b.2) Motion</td>
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<td>b.3) Material</td>
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<td>b.4) Light</td>
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b.5) Scale
Others:
b.6)

b.7)

f- Improvisation
  c.1) Seeing something new
  c.2) Sensing something new (material, texture,...etc.)
  c.3) Changing things on the fly
 Others:
c.4)
c.5)

10- If you are asked to make a new project: on scale 1 to 5, rate your usage for the below points in your making process. 1 is none, 5 is definitely. You can use the previous question as a reference.

1- Imitation: looking at examples and copying it partially or all
   s) Copying an example, by just making the first digital or physical prototype
      1  2  3  4  5
         None        Definitely
   t) Copying from different examples, by just making the first digital or physical prototype
      1  2  3  4  5
         None        Definitely

2- Iteration: making changes in your first prototype
f) Changing geometry

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None

Definitely

g) Changing Material

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None

Definitely

h) Changing light

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None

Definitely

i) Changing Motion

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None

Definitely

j) Changing Scale

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None

Definitely

3- Improvisation:

l) Sensing (seeing, feeling …etc.) something new

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None

Definitely
m) Making or adding something new

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n) Changing things on the fly

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On scale 1 to 5, rate your making skills. 1 is none 5 is excellent.

o) Wood working and manual tools

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p) Digital 2D drawing

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q) Laser cutting

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r) 3D printing

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s) Digital 3D modeling

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<td>t) Arduino</td>
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<td>u) Programming</td>
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<td>v) Overall expertise in making</td>
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Making Spaces: Lightweight Structures for Interactions

Second Questionnaire

Name: 

Date: 

1- When/If you are assigned a new project (a building, product design, etc). Select and rank your steps below to make this project. It can be one step or more.

   Looking at examples ( )
   Brainstorming ( )
   Diagrams ( )
   Storyboard ( )
   Sketching manually ( )
   2D drawing digitally ( )
   3D modeling ( )
   Building a physical model ( )

Other, indicate: ( ) : __________
   ( ) : __________
   ( ) : __________
   ( ) : __________
2- When/if you are assigned a new programming project (coding, arduino, etc), select and rank order your steps below, using numbers, to make this project. It can be one step or more. If you think you want to repeat a step, write multiple numbers beside it.

Search for examples and old codes (  )

Copying parts of code from old codes (  )

Writing the whole code from scratch (  )

User interviews (  )

Paper prototypes of the software interface (  )

(User) testing (  )

Editing and refining code (  )

Other, indicate: (  ) : __________
(  ) : __________
(  ) : __________
(  ) : __________

3- If you are an invited critic to the final review of this class, what feedback would you give to your project:

a- Define two main points that need to be developed further. Why? You can illustrations or verbal descriptions.

b- What strengths would you acknowledge in your project? Why? Define two main
points. You can illustrations or verbal descriptions.

4- How do you feel about your “making” process and design experience today compared to your process and experience prior to taking this class?

5- After working with different tools, machines, electronics, which part or skill are you interested in developing further?

6- In your opinion, what is improvisation?

7- When looking at your “making” process in your final project, you experimented with
geometry, material, senses and electronics. At which stages would you say that you utilized improvisational strategies? What were they?

8- you have so far described your making process and the changes you have made in the form of rules in iterations.

a- In your opinion, what is/are the role(s) of “rules” in the making process?

b- In your making process, how do you use rules?

9- When you are assigned a new project, which strategies from below do you see yourself
10- If you are asked to make a new project: on scale 1 to 5, rate your usage for the
below points in your making process. 1 is none, 5 is definitely. You can use the previous question as a reference.

1- **Imitation: looking at examples and copying it partially or all**

   u) Copying an example, by just making the first digital or physical prototype

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   v) Copying from different examples, by just making the first digital or physical prototype

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2- **Iteration: making changes in your first prototype**

   k) Changing geometry

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   l) Changing Material

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   m) Changing scale

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### 3- Improvisation:

- **w)** Sensing (seeing, feeling ....etc.) something new
  
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- **x)** Making or adding something new
  
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- **y)** Changing things on the fly
  
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**On scale 1 to 5, rate your making skills. 1 is none 5 is excellent.**

- **z)** Wood working and manual tools
  
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- **aa)** Digital 2D drawing
  
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- **bb)** Laser cutting
  
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- **cc)** 3D printing
DD) Digital 3D modeling

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EE) Arduino

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FF) Programming

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GG) Overall expertise in making

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</tr>
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</table>

11- Have you used any of the skills you learned in the course in other projects? How?