Master Thesis:
Exploration of Natural Design Strategies of Novice Engineers

by

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B.S., University of Massachusetts Lowell (2008)

Submitted to the Department of Computer Science
in partial fulfillment of the requirements for the degree of

Master of Science

at the

University of Massachusetts Lowell

August 2010

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Abstract

This project explores how 7th and 8th grade students approach design problems, with the goal of characterizing the design problems in terms of the student behaviors they ellicit. In this project, we explore student problem solving techniques in relation to different forms of problems and construct a tool to characterize those forms.

Students participated in five 90-minute activity sessions. Each session presented one activity that was intended to exercise different engineering and design principles. Collectively the activities include the principles of iteration, constraint satisfaction, tradeoffs, algorithm development, and problem framing.

Students were video and audio recorded. Students were encouraged to talk through their process and were regularly prompted by investigators to verbalize their thoughts explicitly. The data was coded for important behaviors and analyzed for patterns. The analysis investigated patterns across all students within each activity and the idiosynchosies per individual student across all activities.

It was concluded that iteration and testing schedule was critical to the success of the students. Each activity called for a different rate of testing and improvement. The students who came closest to that rate during each session were most successful both in generating a solution to the problem and in constructing a process for generation of related solutions.

Thesis Supervisor: Fred G. Martin
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Chapter 1

Introduction

Engineering education is a relatively new field of education theory, lacking many of the well-developed and thoroughly-tested tools seen in more traditional subjects. In most areas of education there are volumes of methods for teaching and assessments measuring effectiveness of interventions. These mechanisms of instruction and assessment are generally well-tested in laboratory and field settings. Design and engineering lack such a body of work (Wilson and Guzdial, 2010). Many researchers believe that in order to develop these tools, the natural engineering process (without any formal training) must be rigorously explored and analyzed (Welch, 1999). This project explores the design process of middle school students. The students engaged in five activities, one per week, of accumulating complexity. The activities focus on different areas of design thinking, including electricity, mechanics, and algorithms. The students were documented by video and audio recording, and encouraged to "think out loud," allowing for verbal protocol analysis such as that presented by Atman et al. (1999). The videos will be coded and analyzed.

There are two facets to this investigation. The first is to observe and detect patterns in the students' reactions to the different activities, which may provide insight to their natural design processes. The other facet is to learn from the design of the activities themselves, and how activities can be designed to elicit different design thinking patterns.

Chapter 2

Background

2.1 Brief History of Design Research

Engineering education is a new area of pedagogy that does not yet have the body of teaching tools and assessment mechanisms of other areas (Wilson and Guzdial, 2010). With that, much of the literature used is from closely related academic fields, specifically science and math education. Despite the larger depth of work in those fields, they all succumb to a problem inherent in education research: there is a disconnect between locally generated and generalizable knowledge. Techniques generated in classrooms that are locally usable and effective often do not translate well to other classroom settings. While that knowledge may work in one circumstance, it is little beyond anecdotal to the greater community. Conversely, lab-generated scientific data on education is too abstract to be directly usable for real teachers (Sandoval and Bell, 2004).

Brown (1992) developed much of her work around the development of a learning community in lieu of the traditional didactic classroom experience. In a traditional environment, students are "passive recipients" of information dispatched by teachers and media. The relationship is largely unidirectional, where the only return of information from the students is from assessments that are based on drill, practice, and memorization. In this environment the students needs only to develop skills at storing rote facts and reproducing them on demand. Such an environment is prime for may pedagogical pitfalls, such as the development of a disconnect between knowledge and belief, where students may understand a concept as it was presented but do not believe it to be true (Chinn and Samarapungavan, 2001).

In Brown's community of learners, students begin to act as researchers and co-teachers of the material. The teachers, rather than function as managers assigning repetitive tasks, become facilitators who present the tools and encourage the curiosity necessary for engaging learning experiences. The teacher also serves as a good role model for learners, who show interest and discovery themselves. A classroom in this mode is no longer a work camp producing documents, but a research lab motivated by coherence and deep understanding. Assessments ideally are wrapped in immersive applications of knowledge such as projects and portfolios which can be subjectively as well objectively analyzed. One of the fundamental skills outlined by Brown and others, such as Atman et al. (1999), is that students need to develop the capacity for self-monitoring. When a student engages in self-monitoring, the student can identify when he or she is both succeeding and stuck, and takes appropriate actions to reach their learning goal. This skill considered part of meta-cognition, which is a set of advanced but teachable level of thinking (Beyer, 1988).

Strategies that are today considered meta-cognitive appear early and often in education literature. Bloom and Broder (1950) describe observed differences between successful and non-successful students as they approach problem solving. Successful students were better at, among other things, understanding problem requirements and maintaining contact with those requirments as they worked towards a solution. This is a fundamental element of self-monitoring.

Meta-cognition is, especially in children, hard to train. Children empirically do not employ many meta-cognition techniques, if any at all. Most adults do, using strategies to overcome natural limitations of memory retention and recollection (Brown, 1992). The process of design has an intrinsic emphasis on meta-cognitive processes, as it has been shown to help students effectively learn about complex systems (Hmelo et al., 2000). The effectiveness of a design process is greatly enhanced by the inclusion of a feedback system, where the designer is re-analyzing both the problem and what he or she has done thus far to approach it. This concept is seen throughout the literature, often citing the "reflective practitioner" of Schön (1983).

The stages of congintive development defined by Piaget and Inhelder (1969) help explain the slow development of metacognitive abilities. Children in middle school are only just entering the formal operations phase where they can perform reasoning on abstract representations. Metacognition necessary in engineering requires evaluation of one's self an the abstract in order to predict outcomes. This is certainly not possible to develop until the child is cognitively ready, which does not generally happen until nearly 15-18 years into life.

Building on Schön (1983), Adams et al. (2003) describes iteration as the core tenet of design, triggered by certain cognitive activities: self-monitoring, clarification, and examination. Problem-setting in addition to problem-solving is emphasized. Reasoning is done through experimentation. A variety of representations are generated, and fluidly moved between to best serve the thought of the moment. The reflective practitioner is not just a developer making a solution, he or she is an experimental scientist trying to understand the situation he/she created in solution development. These ideas, executed in tightly iterating loops, are the image of an ideal design strategy as described by Schön.

Many researchers and educators have attempted to model the design process. Most of these models have strong thematic similarities, usually including the following states: learning about the problem, identifying resources and constraints, generating ideas, implementation, testing, and revising. Despite the general similarities, different models can communicate completely different methods for design. For one example, Welch (1999) claims that the states of the design process are essentially unordered, allowing the designer to move laterally to any state at any time. On the other hand, Kimbell and Stables (2007) found numerous models that are linear or have a tightly-prescribed progression through steps. The multitude of contrasting views of the design process is currently a source of conflict in the education community (Scribner-MacLean, 2009), and is an important topic of consideration in this research.

The Boston Museum of Science (2008) created a model designed for use by teachers who may not themselves be trained designers. It is intended to be used as part of a curriculum about design for young students, and may not be based on professional methodology. In this model five states form a ring, where travel is only implied to be possible between adjacent states. The states are Imagine, Plan, Create, Test, and Improve. The literature accompanying this model expresses that the student does not need to be bound by this ring, and may move from any state to any other state at any time. However, the graphic does not represent this and strongly implies the notion of neighbor-only traversal.

Adams et al. (2003) presents a model derived from observations of senior collegiate engineering students. This modelis scientifically accurate to an actual process that took place in research subjects. It is both more complex and less beautiful than the Museum of Science model, and is clearly intended for a different audience. Many would argue that the model presented by Adams is more useful, as it represents a functional process, but that depends on the individual's definition of usefulness. To an elementary school teacher, the Museum of Science model, while clearly incomplete, may be the correct tool for the job at hand.

Most of these models have a heavy emphasis on iteration. Dow et al. (2009) found that iteration was critical to success of a time-constrained design problem. Participants with no prior experience who iterated through their design process performed as well as the participants who had prior experience but did not iterate. The process of repeating design tasks helped the participant explore the problem space and become familiar with the relvant physics. Eckert et al. (2009) found that iteration also takes on additional influence in corporate engineering, where a new design can depend on the proven framework of previous designs.

2.2 Design Activity Studies

Welch (1999) performed an experiment on design activities carried out by seventh grade students. In this study students worked in dyads to build the tallest paper tower out of a finite set of resources within a specific time period. Welch enumerated a design process as five steps that represented a general consensus of concepts available in literature. The steps are:

1. Understand the problem
2. Generate possible solutions
3. Model a possible solution
4. Build a solution
5. Evaluate the solution

Welch claimed that the actual process undergone by both professionals and amateurs of design would not be linear, and that it would recurse on itself many times. The activity was intended to be representative of a real-world engineering task, characterized by having a goal, constraints, and some criteria to recognize a successful solution. The students worked in pairs, which is also an element of simulating real-world design, where most development is the result of combined efforts of two or more people working cooperatively.

Design of activities for this research was informed by the model-eliciting activities of Lesh and Harel (2003). Lesh's work was based in mathematics education, and uses fractions and proportions as the subject to be explored by the subjects. A model-eliciting activity (MEA) is designed such that the students' product is not a single answer, but a rule or process that can be applied to solve similar problems. Three MEAs are presented in the paper. The simplest example is the "bigfoot" activity, where students are told they are forensic examiners and need to identify the height of a person based on a shoe print. The expected response is for students, working in small groups, to observe themselves, and somehow create a proportion between human shoe size and height. The students are not requested to determine the height of the one example person, but to provide the police with a mechanism with which they can identify the height of any person based on shoe size.

The results of the MEA research, besides the concept of the MEA itself, is that problem solving can be viewed as a process of local concept development. Many researchers in the past have studied the process of learning concepts, specifically in math and science. Lesh concluded that the same process and principles involved in normal concept learning occur in a fast, recursive fashion during problem solving. The concepts being developed during problem solving are not general, they are specific to the current problem and the situation surrounding it, but the same development process has been observed. This observation allows the connection to be drawn between local problem solving and general, long-term cognitive development.

Chapter 3

Methodology

Students participated in five 90-minute activity sessions, once per week, for five consecutive weeks. Each session presented one activity that was intended to exercise different engineering and design principles. Students were observed and video recorded as they carried out the activities.

3.1 Subject Selection

This study used seven middle-school students as subjects. Students were in grades seven and eight, with average age of approximately 12 years old. The selection process was done by an after school enrichment program, where this study was advertised as an activity students could elect to participate in. This study was open to all students of the specified grade levels. Selection was simply the first students to volunteer to participate.

All students read, understood, and signed a student assent form and their guardians read, understood, and signed a parental consent form. Parental consent forms were available in English and Spanish. The student assent form was available only in English, as that is the language the research activities were conducted in. Guardians had the option to sign a media release form, which allowed recorded media of their child to be used in publication.

3.2 Session Protocol

In each session, students engaged in an engineering and design activity. Their conversations, problem-solving strategies, and concluding interviews were observed in person by researchers and video recorded.

Each of the five sessions followed the same pattern. Students arrived and were taken to a conference room for snack time, where they were casually introduced to the concepts involved in that day's activity. Loud thinking protocol in the style of TAPPS (Lochhead and Whimbey, 1987) was explained and reinforced every week at this time. After about twenty minutes in the conference room, the students moved to the activity room where the apparatus for that day's study was set up. Working in pairs, students worked through the prescribed activity. The entire time in the activity room was audio and video recorded. Throughout the activity students were prompted by researchers to explain their thoughts, ideas, and understanding of concepts.

At the conclusion of the activity, students were lead in a group conversation about what they learned and developed. The questions asked by researchers during this conversation were variations of this set:

- What did you do to find your solution?
- Did you do anything early on that you did again to help yourself?
- If you had a friend who was coming in to work on this problem tomorrow, what would you recommend they do? (Keep in mind the problem won't have the exact same solution.)
- Are there any other tricks you discovered?

3.3 Design of Activities

The activities performed by the students were designed progressively, so each activity was informed by the performance of the previous. Each activity stressed different areas of engineering space, starting with a simple activity and progressing towards computational thinking, as defined by Wing (2006). Subject areas of activities include:

- Math problem solving
- Parallel and series circuits
- Gear ratios and reduction
- Algorithm design
- String-matching
- Active control systems

In addition to subject areas, the activities will stress different elements of design skills:

- Balancing between contradicting requirements
- Working in time constraints
- Physical construction
- Symbolic manipulation of a system

3.3.1 Week 1: Rush Hour

"Rush Hour" is a sliding tile game where the player must manipulate cars on a small grid. The game has a small set of simple rules, but a high number of possible states for any given puzzle. The object of the game is to slide the target car, indicated in Figure 3-1 by the arrow, out of the grid through the opening to the right of the game board.

Purpose

This activity was an ideal introductory experience for the students. It had very few rules to learn and was fun to play. Students were quickly engaged. As a design activity, this provided observations of the students' methods in navigating the deep state space

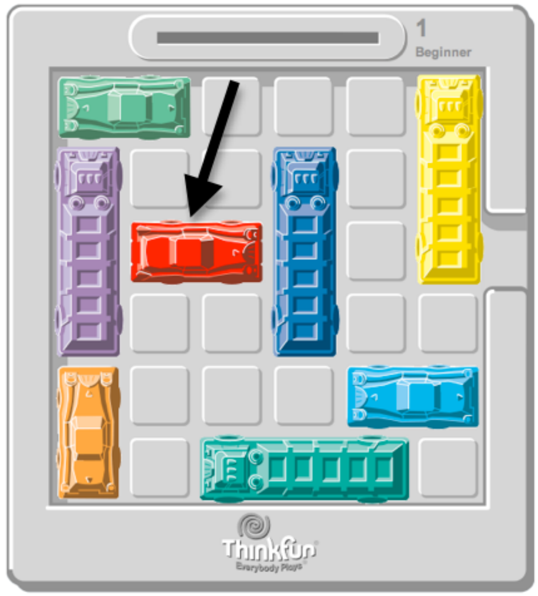

Figure 3-1: Rush Hour game board. The arrow indicates the target car.

of the game. With every move of a game piece the possible states accessible on the next move change. Many times the path the player is on does not have a solution anywhere on it, and the player must backtrack to reach an earlier state where a different decision could yield a solution, or, start over and try again. This backtracking was a primary component of the analysis of this activity.

Welch cites Ericsson and Simon (1984) with the importance of a warm up process, stating that when verbal information exchange is involved a period of warm-up is necessary for the subject and researcher to communicate most effectively. This activity, with such simple rules, provided an opportunity for students to focus on the loud thinking strategy, warming up that skill for the remaining sessions.

Protocol

The students were each given a game unit with a beginner level puzzle to solve. The students were encouraged to "think out loud" during the entire process, and to think about the process they were employing to arrive at solutions.

Once the students felt that they understand the concept of the game, they were put into pairs and given a more difficult puzzle. The students' process of solving this puzzle was video and audio recorded. The camera was positioned above the table to record the game board, the students' hands, and the students' voices. Additional puzzles of increasing difficulty were used as time allowed.

At the conclusion of the puzzle solving session the student pairs were asked to explain the process of solving the puzzle. The students were instructed to explain their process of finding a solution, not the steps to carry out a specific solution. They were then instructed to explain the game strategy for a friend who has not seen the game before.

A semi-structured interview was used to probe students' understanding. The interview was based on these questions:

- Please explain what you did to find the solution to these puzzles.
- Did you do anything in the first puzzle that you did again in the second to help yourself out?
- I want you to explain how to go about solving these kinds of puzzles. Pretend you're explaining it to a friend who has never done this before.
- Are there any tricks you discovered?

Rationale

This game is characterized by its large state space, rapid iteration of ideas, and high level of backtracking. This type of problem is common, and can be generalized to include other games (such as chess) as well as real engineering problems. For example, circuit board routing is a design activity that has a large number of states where decisions progressively lead to new areas of the state map, fitting this general problem type.

3.3.2 Week 2: Light & Power Optimization

Students were presented small light bulbs connected in a certain configuration with a power supply. Their design task was to reduce the number of wires necessary to light all the bulbs without significant sacrifice in brightness. This problem explores basic electrical principles and requires students to balance between contradicting requirements. The students were given a story that they work for a power company, and each light bulb represents a house on their grid. They needed to find a method to light all of the homes at the lowest cost to the company.

Purpose

This activity will generate observations of students exploring natural phenomena and balancing requirements for an optimal solution. The definition of optimal was left partially open, allowing students to construct arguments for the optimality of their solution, which will further promote loud thinking and give insight to the student's thought processes.

Protocol

During snack time, a researcher led a conversation about what "optimization" means, soliciting suggestions from the students. Once in the classroom, the students were presented with a workstation for each dyad. Each workstation had a variable DC power supply, a number of small, low-power light bulbs (holiday mini-bulbs), and connecting wires with alligator clips. Two workstations were initially set up with example circuits. One was a number of lights connected in series, such that the same current flow runs through all the lights, with the power supply operating at 12 volts. The other station had the same number of lights connected in a parallel configuration, such that every light had full voltage from pole-to-pole on the power supply, which operated at 3 volts. The two systems were approximately the same brightness. The terms "series" and "parallel" were never used with the students.

The students were presented with a set of criteria for assessing their solutions. The goal was stated to achieve "reasonable brightness." Costs were associated for number of wires used and amount of voltage required. The final cost of a solution was

$$\frac{\alpha \cdot c + \beta \cdot v}{n}$$

where c is the number of connection wires, v is the voltage being supplied, and n is the number of light bulbs being serviced. The multipliers α and β are the respective costs of wires and voltage.

The students, working in pairs, solved two iterations of this activity. The two iterations had different material costs. The change in cost values was designed to obsolete the first iteration's optimal solution, forcing reconsideration of the problem.

At the conclusion of the second problem iteration, the students, in pairs, were asked to document their solutions and explain how they arrived at them. They were instructed to explain their process as if for a friend who was not present. Interview questions examined the students grasp of the electrical principles, what they considered to be "optimal," and how they went about discovering what they needed to know in order to solve the problem.

Rationale

The electrical concepts in this activity are fundamental to an understanding of electricity and electronics, and create the physical basis of computing technology. The problem is also multi-dimensional, with number of connections, voltage, and number of lights serving as related but axiomatically confounded design parameters (Suh, 1998). This activity emulates real-world design problems that require simplification, satisficing, or constraint of solution space.

3.3.3 Week 3: Gear Reduction

In this activity the students built a transmission from Lego Technic gears and components between a fixed motor and load.

Purpose

This problem allowed for direct access to the students' spatial and mechanical reasoning skills, a domain used heavily in many different areas of design.

Protocol

The students were introduced to the concepts of gear reduction, specifically the nature of "little-to-big" relationships (Martin, 1995). Each student dyad was supplied with a workstation apparatus, constructed of Lego Technic with a motor, a large wall on which to build their transmission, and an output pulley. The pulley was connected to an interchangeable mass. The students are presented with two different tasks, and they may attempt one or both:

1. Lift the greatest amount of weight possible.

2. Lift a specific weight from the floor as quickly as possible.

The students had all the remaining time to design and build their solutions. Paper was provided, and students were encouraged to document their transmissions in the same fashion as was used in the concept tutorial.

At the conclusion of the work time, each dyad's construction was tested individually as the group observed.

Rationale

This activity is very purely an engineering design task. The requirements, constraints, and success criteria are extremely clear. The solution, however, is open-ended, as the gears can be assembled in nearly infinite configurations, many of which may solve the problem. This activity stresses implementation and time management.

3.3.4 Week 4: Word Search

Students designed algorithms to solve word searches, where words are hidden in a two-dimensional grid of otherwise random letters. This activity introduced the concepts of pseudocode and flowcharts for algorithm design.

Y	E	S	L	F
M	N	H	R	I
P	T	O	U	R
A	C	E	M	E

Figure 3-2: Example word search puzzle.

Purpose

The concept of an algorithm was introduced in this activity, which was also used in the following activity. As such, this activity partially functioned as a warm up to the more complex elevator control algorithm activity.

This activity allowed observations of students process in deducing and applying patterns, and observed students' approaches to writing generalized procedures.

Protocol

This protocol was implemented as a worksheet for students, as can be seen in Appendix A.1. The concept of an algorithm was introduced with the game of tic-tac-toe as example. The students were given the instruction set to never lose tic-tac-toe, and were encouraged to study and try it. Once the concept of using instructions to play a game had been mastered, the students were given a very simple word search puzzle. The example puzzle was designed to be nearly trivial, like the one in Figure 3-2. The words hidden in this puzzle are *ace*, *fire*, *shoe*, *tour*, and *yes*.

The students were prompted at this point with questions, which were discussed briefly as a group. The questions were:

- Did you find all the words?
- What did you do to find the words?
- Did the words just "jump out at you?"
  - What if they didn't?

  - How can you know for sure you found *all* the words?

The students will then be prompted to write down any rules or strategies they employed in the example puzzle.

The researcher explained that computers are devoid of the pattern recognition ability that makes words "jump out" for people. However, computers are very fast at simple computation, so they are advantageous to use for extremely large data sets. This provided impetus for the students to develop an algorithm rather than simply solving the puzzle one time.

The students were then given the difficult puzzle, which can be seen in Appendix A.2. The students were encouraged to continue talking through their thought process, and reminded that the process to solve the problem is desired, not the solution itself. If the students completed the puzzle and were confident in the rules they had written, they were given an additional puzzle with the instructions to solve it only by following their rules, not using their human abilities.

Rationale

This activity stresses computational thinking, which causes students to think algorithmically about a normally straightforward task. This activity also has opportunity for cleverness and creativity that may arise from noticing patterns in data. These skills are fundamental to computer science.

3.3.5 Week 5: Elevator Control

Students designed a set of rules to govern the motion of a simulated elevator. Elevators are robotic devices that need to act based on multiple inputs and system states, and require well-thought-out control algorithms to function effectively. The simulated elevator was implemented in Scratch (Maloney et al., 2004) using BYOB (Harvey and Mönig, 2010), allowing for custom drag-and-drop code blocks for high-order control of the graphical elevator system.

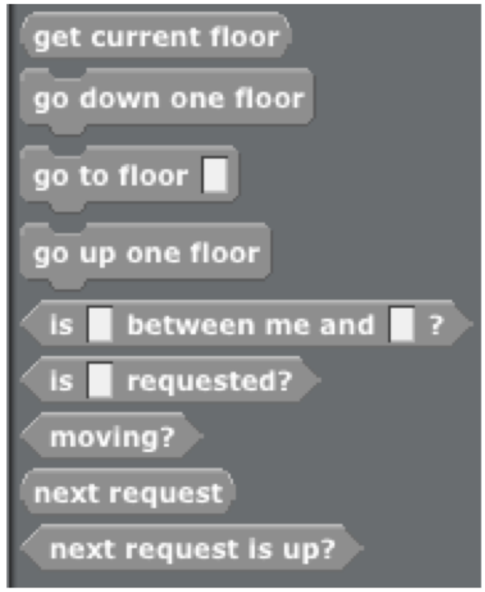

Figure 3-3: Elevator control blocks.

Purpose

This activity explores the students reactions to a difficult optimization problem. Students were observed developing the problem concept as well work towards improved solutions. Unique among the other sessions, in this activity students are also observed working purely symbolically.

Protocol

The students were tasked with a simple goal: develop an algorithm to control an elevator. The concept of simulation was introduced, as was the Scratch programming language subset used by the simulator. The primary elevator control blocks can be seen in Figure 3-3.

The students were provided with a trivial but working solution, shown in Figure 3-4. The first challenge for the students was to understand why the given solution worked and why it was sub-optimal. There was no formal mechanism to prevent students from working on a solution before they fully understand the problem, but they were prompted often by researchers to establish their current understanding of the situation.

Figure 3-4: Trivial solution of the elevator control problem.

The provided solution simply traveled to the next floor that it was called to, in the order that the calls were made. The major flaw of this solution was that people who are waiting for service were passed by the elevator as it traveled blindly to whomever pressed the button first. This inefficiency resulted in unacceptable wait times (and therefore unhappy people), as well as unnecessary energy expenditure by the building owner.

Rationale

This activity is highly abstracted, symbolic, and the problem is difficult to characterize. It also requires understanding of a queue structure, positional queries, and boolean logic. These elements are part of the everyday problems posed by both researching and practicing computer scientists and engineers. Control elements, such as determining location and direction of travel, are specifically common to robotics.

3.4 Analysis Plan

Videos from student sessions were analyzed using coding techniques informed by Welch (1999), where specific codes were defined to describe important behaviors. Additional codes were created as needed as informed by grounded theory. The additional codes allowed for behaviors and patterns that were not predicted to be documented as they were observed.

The initial code list was based on the codes used by Scribner-MacLean (2009), as that research has a similar experimental setup with a similar group of subjects. The codes, in accordance with Scribner-MacLean, were categorized by stages of the design cycle. They are described in Table 3.1.

Design Step	Code	Definition
Understand the problem ("ASK")	RB	Read design brief as given to the subjects by the researcher
	DPER	Discussing/referring to performance criteria
	DCON	Discussing/referring to constraints
	PK	Accessing prior knowledge
	CAR	Check available resources
Generate possible solutions ("IMAGINE")	DIS	Discussing possible solutions
	SBS	Selecting best solution
	MAN	Manipulation of materials to explore properties
Modeling a possible solution ("PLAN")	PP	Planning a prototype
	DRAW	Sketching/drawing possible solutions
	MP	Making a prototype
	TEST	Testing one element as the making continues
	AB	Abandon current solution; begin new solution
Building a solution ("CREATE")	IP	Identify a problem with the prototype
	MDC	Making a design change to the prototype
	REF	Refining construction of prototype
Evaluation ("IMPROVE")	EO	Evaluate as subjects observe prototype
	ET	Evaluate as subjects talk about prototype
	ED	Evaluate as subjects draw possible solution
	EDB	Evaluating in terms of the design brief

Table 3.1: Starting codes.

This set of codes only provided a starting point for analysis. Additional codes were created as needed during analysis, and will be discussed in chapter 4.

Analysis was done primarily using NVIVO software. Codes were applied to specific time spans of the video where the corresponding behavior or activity was observed. Data was analyzed to see how the individual students changed over the period of time (idiographic), and to see trends in all the students as a group (nomothetic).

The plan of analysis was to find emergent patterns in the data consisting of video codes, researcher notes, and student products.

Chapter 4

Analysis

Analysis first looked at all the behaviors present among all students in all the activities. The full space occupied by the data is complex. Students moved between behaviors with varying patterns and levels of consistency. Often no consistency at all was observable. Each student had idiosynchrosies, but they adapted differently to each activity. This created a multi-dimensional space, with one dimension as the activities and another dimenion as the students themselves. Additional dimensions could be considered to be the students' tendencies towards different patterns of transition between behaviors. This space needed to be constrained to gain useful insight. This session had six participants: two girls and four boys.

After analysis of all activities across the selected participants, the rate at which the student tested their designs emerged as a critical factor towards their success in the activity. The selection of participants for the final analysis is described in section 4.1. The following sections 4.2 through 4.6 describe the analysis of the individual activities.

4.1 Subjects

The trial was conducted with seven participants, six of which had sufficiently consistent attendance to be studied. Code names A through F were assigned to these students to anonymize their data. Two of these students were absent for one activity. Students often worked in pairs. When they did, they self-organized into the same pairings in each activity. The dyads are A/B, C/D, and E/F.

4.2 Rush Hour Activity

This activity provided data which helps understand student metacognitive behavior. Students were observed trying to understand their own problem solving patterns. Students of this age generally have not yet reached the formal operations stage of cognitive development (Piaget and Inhelder, 1969), and thus have not fully developed metacognitive skills (Beyer, 1988). These students demonstrated rudamentary ability to analyze their own thinking processes, but were often incapable of explaining how they came to a process or conclusion.

4.2.1 Expected outcomes

The expectation going into this session was that students would demonstrate a high level of backtracking, iteration, and restarting. It was expected that students would run in to many dead end paths, and would have to backtrack through their motions or start over very often. This expectation was largely correct. The period between resets was often mere seconds, where the student had barely executed anything before coming up with another idea to try instead.

4.2.2 Observed behaviors

Unable to repeat

At the beginning of the session it was observed that students were unable to expain how they came to a solution, and claimed that they were unable to repeat it. This behavior was only observed in the first ten minutes of the activity.

Working backwards

Some students elected to work backwards from the goal towards the start state. This strategy was observed at all stages of the session. When using this technique, students never worked their way all the way to the start state. Once sufficient experience with this technique was acquired, the student reverted to a forward-direction method, where they were they were then more easily able to find a solution. Working backwards was also introduced to the session by the female students. Both girls in the session used the technique, but only one of the four boys was observed doing so. The boy used it later in the session, possibly after hearing the idea from one of the girls.

Accounting for impossibilities

Two instances were observed where students told researchers that their strategy included accounting for possible future scenarios. Both of these instances, one during the session and other during the wrapup interview, involved preparing for scenarios that were mathematically impossible. Student BE described why he moved the red car away from goal was "in case a car had to move through," indicating the empty column he created with the move. There were no cars on that column aligned in that direction. There was no case where the possibility he described could happen.

Assessing limitations

Students often described that their strategy included assessment of limitations. Limitations where simple, like "I can't move the green car," so the student would consider how to go about either freeing the green car, or disregard it as immovable. This behavior was very important in finally solving the puzzle, as it constrained the problem. This also seems to contradict the behavior noted above where students accounted for impossibilities, but both were observed in the same students during the same puzzles.

Identifying key move

Researchers prompted students in the middle and late portions of the session to identify the "key move" that unlocks the particular puzzle. Students did not respond well when first prompted, but later in the session they became more confident in their answers. The answers were not necessarily right or wrong, but provided insight to what the student thought was important.

Theory development and testing

Students developed theories and ideas very rapidly, but did not generally test them fully. When testing a theory, the student would proceed a few moves, then interject with a new idea and pursue that. This is similar to when the students worked backwards, where they never worked through an idea to completion, but moved on when they gathered enough experience to think of something else.

4.2.3 Wrapup discussion

In the wrapup discussion students made many suggestions on how to go about solving the problem, but often little reason behind the suggestions. Studens provided summaries of their tactics that were inconsistent with the observations during the activity. Many students changed their responses while explaining them. Those students had a different answer at the end of their explanation than they had at the beginning.

There were some points that were made by the students and were supported by earlier observations. One of the first points to emerge from the discussion was also that the loud thinking technique actually helped them solve the problem. The process of verbalizing the thought process had observably improved results in solving the problem.

Students generated many strategies that they claimed worked for them, outlined below. These strategies contradict each other, but each one was defended strongly by the student who presented it. Every strategy presented that was specific (move a certain piece a certain way) could be disproven by counterexample. The first three strategies in the list beow are in this category. The general strategies, however, could be useful if presented to other students, which was the question posed by the researchers.

- Move trucks down
- Move little cars first
- Move towards exit to get out
- Look for the key piece
- Go with the flow
- Look ahead at least two moves
- Take it slow

Students were asked how they knew when to backtrack or start over. The responses were as expected: when totally stuck or stuck in a repetitive loop. One student claimed he never restarted, only backtracked. Observation of that student supported this, which was an anomaly. Every other student did full restarts many times over the course of the session.

The student who never reset was also observed solving the puzzle accidentally. He set an intermediate goal and was focused on solving that when he created an opening to solve the whole puzzle, but he did not notice that opportunity.

4.3 Lights Activity

This activity was highly structured for time usage and metric of success. The session was broken into two phases, with each phase containing a complete problem solving cycle. The second phase presented the same problem as the first, but with component price values modified, changing the location of the optimal point in the solution space. Testing was also very deliberate, as it required the use of the power supply. Rules were in place that students could only turn on the power supply when when their system was safe and nobody was touching the circuit. Unlike other activities, very test feedback could be generated without the power supply being on, making the test cycles relatively formal.

The metric of success was formulaic, and students turned to arithmetic throughout the activity to help them plan and check their designs.

4.3.1 Expected and observed outcomes

With two deliberate phases it was expected that students would be more successful in the second phase. The first phase should be mostly exploration, and the second one was expected to be higher in iteration and testing cycles. This was shown to be at least superficially accurate, as more iteration cycles occurred across all the students in the later portion of the session. When disregarding the two phases, however, the concentration of iterations was congruent with that of other activities that did not have deliberate phases. It is possible that the increase in testing cycles indicates a greater pattern of developing comfort with the problem over time, and the forced phases may have had little effect.

4.3.2 The 1-wire misconception

One misconception was observed that was completely unexpected and provided a serious problem for the students experiencing it: thinking power can flow over a single wire. The students BB and BC created their first design to look like a lollipop. One wire came from the power supply and connected to one point in a series loop of lights. The other terminal of the power supply went to a similar loop. Clearly this circuit did not function, as there was no circuit created between the two terminals of the power supply.

4.3.3 Notes for future work

The total cost of the system, which is the student's score of success, uses the number of lights in the system as a dividing term. By adding more lights the overall cost could be greatly reduced. Students utilized this behavior more than was expected, so it should be further explored by researchers before being deployed again.

Students stated multiple times that this activity was fun and that they liked it. One student likened it to hot wiring a car (which it is really nothing like), but the student found “cool.”

After each phase students were instructed to draw the circuit they had made. This failed, as students were entirely unmotivated to draw. Exactly why this is the case should be further examined, and the activity can then be modified to create improved documentation procedures. It is possible that the needed drawing skills could be taught in a preparatory session, much like Lesh and Harel (2003) suggest.

Additional circuit theory could be taught in a preparatory session, which should help the 1-wire misconception discussed above. This session could also include introduction of the safety protocol regarding the power supply units.

The question “what did we find out?” should be added to the group discussion prompts.

4.4 Gears Activity

4.4.1 Expected and observed outcomes

This activity was intended to be an exercise in gear spacing, meshing, and reduction. Students were expected to choose testing patterns somewhere on the continuum between large numbers of small, local tests and small number of large, entire-system tests. The best solutions were expected to come from students who iterated more often. This theory proved generally correct, but was convolved by the unexpected level of difficulty of the activity.

In most of the activities presented here the students are designing against a highly constrained subset of physics or a simulated, abstract environment. In this activity the student design is tested directly against nature, which provides many unapparent complications. The challenge was not focused on gear ratios as expected, but was a more general and difficult task of building well. Students were plagued with a vastly unconstrained design space in the form of part selection, structure design, gear choice, and component connections. Despite the unexpected difficulty, most students did succeed in solving the problem. However, the process-oriented model that was desirable was lost as students focused entirely on finding a single working solution.

4.5 Word Search Activity

This activity was designed to have very low cognitive start-up costs, as most students are very familiar with word searches. It also provided a good introduction to algorithms, where students can easily see the application of a pedantic process on the matrix.

4.5.1 Expected and observed outcomes

The word search was expected to be easy for the students to gain traction with, enabling them to focus on the algorithm design component. The students were expected to have a few test iterations as they work through how action rules work. The activity itself is relatively simple, and may fall victim to short attention spans. In practice this session was very successful. Students maintained engagement for the majority of the period and held to the rules of the activity to facilitate the desired learning experience. Only half of the students actually created legitimate algorithms. The other half created short lists of human-targeted instructions rather than break them out to component operations.

4.6 Elevator Activity

Building on the algorithm writing experience from the word search activity, the elevator control problem is the culmination of the activity sequence. Students built and tested in a simulated environment where the researchers had control of all system physics, allowing for only the pertinent dynamics to be available. This still allowed for a complex interaction to take place, as the students were not tasked with filling in the solution space between two points, but to write actual code with very little provided structure.

4.6.1 Expected and observed outcomes

This is the most difficult activity, so it was expected that students would have a hard time gaining traction with the problem. Before a student could be productive, the student needs to understand the constructs of the programming language, begin to comprehend the programming concepts available to them, and form a good understanding of the problem. The most difficult part of this was the latter. This activity ended up being focused primarily on problem framing. Once students began to comprehend what they were actually trying to do their productivity improved greatly. Student competence with the programming tools seemed to increase once the problem was understood, indicating that understanding the tool is in part related to having a clear need for it.

Chapter 5

Discussion

The behavior that rose above the noise as a critical component to design is iteration. The literature supports that iterative design cycles are critical for design tasks across academics, children, and industry. In this study, the iterative nature of the different students was accessible for investigation. By analyzing the schedule by which students test and modify their solutions a characteristic pattern can be determined. From this pattern, a tool can be created that may help in the design of student design activities, providing a guide for creating activities that elicit specific iteration behaviors from students.

5.1 Defining characteristics of iteration behavior

Iteration characteristics were reduced to three properties: the percentage of time spent in preparation, the count of iteration cycles performed, and the average time per iteration. These characteristics are shown per student pair across three selected activities in Table 5.1.

5.1.1 Iteration Count

The primary indication of how well a student conducted an iterative design process is the number of times that student was observed performing an iteration. An iteration was defined by the student testing a design or a component of a design against the world. The student trying different constructions trying to meet his/her internal vision is not considered a test, as no new information is gained. Every test was marked with how many minutes into the session it occurred. The most iterations observed by one dyad in a single activity was nine, and the least was zero. Excluding the zero, which is a peculiar case, the lowest amount of iteration was three cycles.

5.1.2 Iteration Time

The time between tests is an indication of how long it took the student to assess the newly discovered information from the last test and integrate it into the solution. Knowing how long a cycle typically takes can be helpful in designing activity schedules. This metric is a simple interarrival time between test events. Only times between tests were counted. The time from the start of the activity to the first test was observed to be introductory and explorative for the student, which is addressed in the next section. The time ends at the student's final test where the solution is declared to work or not, and development ended. Across the three selected activities interation times varied from one minute to over a half hour. Within a single dyad and one activity the standard deviation of average iteration times did not exceed five except in one outlier case, which was nearly 18.

5.1.3 Preparation Time

The time before the first test is considered preparation time, during which the student explores the problem and assembles an initial prototype. The shortest preparation time was three minutes which was one group during the elevator activity. The pure software activity makes it very easy to "dive right in" and start trying things nearly immediately. The other two dyads in that activity waited ten and over twenty minutes before their first test. The preparation was usually around ten minutes, but the actual value of that absolute number is relative to the total time the student spent working on the problem. For calculation the preparation time as expressed a percentage of the

	Student Dyads					
	A,B		C,D		E,F	
Lights	prep	21%	prep	35%	prep	20%
	count	3	count	8	count	7
	itime	17.75	itime	4.71	itime	6.6
Gears	prep	16%	prep	42%	prep	100%
	count	7	count	8	count	0
	itime	5.42	itime	3.07	itime	0
Elevator	prep	7%	prep	37%	prep	64%
	count	9	count	6	count	5
	itime	5.38	itime	3.6	itime	3.38

Table 5.1: Characteristics of student dyads across three selected activities.

total time spent working on the problem so that the metric can be easily compared across activities and students.

5.2 Conclusions

This section should give a concise narrative of the significant conclusions drawn from the thesis/dissertation.

5.3 Recommendations

This section should include suggestions for future work on the thesis/dissertation topic or analogous problems.

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Appendix A

Student Handouts

TODO I can also make these not full-page if that is better. It would allow for captions like normal images or the insert to be on the same page as its title.

A.1 Word Search Handout

The following pages are the document given to students at the beginning of the Word Search activity session.

Your task:

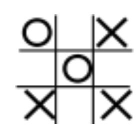
Develop a process to find all the straight-line words that are hidden in a grid.

Example: Tic Tac Toe

Solving tic-tac-toe is pretty easy. There is a simple series of rules, which if you follow, will guarantee you won't lose. You can think of these rules as a *strategy*, but when you follow them all strictly is can be considered an *algorithm.* An algorithm is just a set of instructions that make up a process.

Instruction Set for Tic Tac Toe

1. If you have two in a row, and the third is empty, take the empty to make 3.
2. If the opponent has two in a row, and the third is empty, take the empty to block.
3. If a fork can be created, do it. *(In the figure to the right X has created a fork, where O needs to block in two places at once.)*



4. If the opponent is about to make a fork, block the fork.
5. If the center is open, take it.
6. If a corner is open, take it.
7. If a side is open, take it.

Algorithm

A process or set of rules to be followed in calculations or other problem-solving operations.

Design Strategies Week 4: Word Searches
Presented by Prof. Fred Martin and Mark Sherman

The Word Search

Y	E	S	L	F
M	N	H	R	I
P	T	O	U	R
A	C	E	M	E

Word list:

- Ace
- Fire
- Shoe
- Tour
- Yes

Did you find all the words?

What did you do to find them all?

Did the words just "jump out at you?" …. What if they don't? How can you know for sure that you found *all* the words?

Your Algorithm

Write down any rules or strategies you used.

1.

2.

3.

4.

5.

Your Algorithm for Word Search

1.

2.

3.

4.

5.

6.

7.

8.

9.

10.

If you need more rules, grab some more paper and add your own numbers. You can have as many as you want.

A.2 Word Search Puzzle

The following page contains the puzzle given to the students with solution highlighted.

Harder Puzzle 1
Mark Sherman

E	G	T	N	E	I	N	E	S	V	P	A	R	T	I	C	L	E
E	E	P	Y	T	D	U	G	A	E	Q	U	A	D	R	A	N	T
C	E	B	I	Y	T	C	A	Y	L	N	E	R	M	I	G	G	D
U	R	E	O	A	I	L	T	R	E	O	I	N	A	I	D	E	M
R	B	E	E	R	V	E	L	O	C	I	T	Y	N	D	S	I	O
R	Q	A	C	T	P	U	O	E	T	T	L	E	Q	I	C	E	A
E	X	U	N	O	N	S	V	H	R	A	E	I	G	O	T	C	L
N	I	L	A	B	O	R	A	T	O	R	Y	N	O	N	C	Y	G
T	C	O	T	N	I	R	C	B	M	E	P	R	E	E	T	S	O
R	C	E	S	G	T	I	D	A	A	T	D	M	L	R	C	M	R
N	Y	E	I	R	C	I	N	I	G	I	I	E	E	I	O	O	I
T	I	A	S	A	E	C	T	T	N	R	R	P	E	T	M	O	T
T	N	R	E	E	V	T	T	A	E	A	O	N	A	E	P	R	H
V	Y	G	R	E	N	E	T	P	T	R	T	I	O	B	U	R	M
P	T	O	E	I	O	E	X	E	P	I	A	E	T	I	T	I	E
O	T	E	C	T	C	E	I	X	S	Y	V	C	I	A	E	T	E
D	O	H	T	E	M	I	N	T	E	R	N	E	T	N	R	T	R
C	U	N	N	M	S	A	R	I	I	E	E	E	E	P	R	E	C

accelerate
algorithm
atom
circuit
computer
convection
coordinate
coordinate
current
design
electromagnet
energy
engineer
experiment
interact
internet
ion
iteration
laboratory
median
method
nucleus
particle
probe
property
quadrant
quantitative
ratio
resistance
scientist
Theory
Velocity
Voltage

A.3 Elevator Control Activity Instructions

The following page is the instruction sheet that was given to students at the beginning of the Elevator Control Activity.

Design Strategies Week 5: Elevator Control Algorithm
Presented by Prof. Fred Martin and Mark Sherman

Your task:

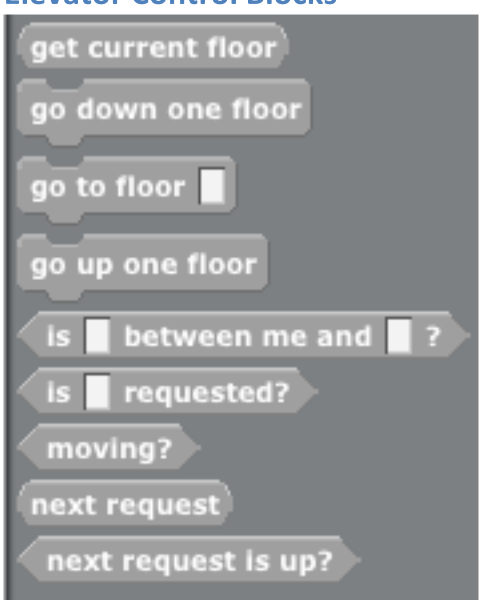
Develop an algorithm to control an elevator.

Your tools

Instead of trying to use real elevators, or doing everything with paper and pencil, we are going to use a simulator. Drag and drop command blocks into the center panel to add them to the program. Connect command blocks together to create sequences of events.

Command blocks are organized into categories. The ones you will be using are **Control, Operators, and Variables.**

Elevator Control Blocks



To get to the Variables panel, click the red Variables button. Scroll all the way to the bottom and you will see gray blocks. These gray blocks control the elevator.

The other categories also hold important blocks.

- Control
  - If a condition, do something
  - Wait until something happens
- Operators
  - Compare numbers: >, =, <
  - NOT operation: reverse yes and no

Appendix B

IRB Compliance Documents

B.1 Parent Consent Form

The following pages are the Parental Consent Form completed by the legal guardians of all participants in the study. This form is also available in Spanish.

TODO This form provides identifying information (the YDO/Howard). Should it be included? Censored?

UMASS

IRB INFORMED CONSENT or AGREEMENT TO PARTICIPATE FORM

IRB No.:10-046-MAR-XPD Rev. No./Date:2/4-21-10

Consent Form Title: Parent Informed Consent Form

Project Title: Exploration of Natural Design Strategies of Novice Engineers
Principal Investigator: Dr. Fred Martin Associate Professor
Contact Information: UMass Lowell Computer Science, 1 University Avenue, Lowell MA 01854, fredm@cs.uml.edu, 978/934–1964
Co-PI(s):
Student Investigator(s): Mark Sherman
Date Submitted: April 21, 2010

This form has been approved for use by the UML IRB and is valid for up to one year from the approval date. (PIs -Give a copy of this form to the study participant after they sign it. Originals are to be retained by the PI.)

Authorized IRB Approval Signature: Stephen Tozer **Approval Date**: April 21, 2010

The following are essential elements of Informed Consent (these section titles may be edited to suite your needs but the information for each element must be included):

1. Study Purpose: Mark Sherman is a student at the University of Massachusetts Lowell who is exploring how students solve engineering and design problems. This research study will document the design strategies of subjects with little formal design training. This data will help us create better engineering courses and teaching tools.

2. Procedure and Duration: Your child will be asked to participate in a research program called "Engineering & Modeling Activities." This program will involve meeting with your child for 90 minutes on six Thursday afternoons where he/she will be presented with simple engineering activities. Your child will be asked to solve the activity as well as develop a procedure for solving problems like it. All activities will be based on critical thinking and problem solving with technology. Your child will not require any special training to be eligible to participate.

Your child will also be asked to complete a questionnaire to describe their educational interests, including questions about their heritage and your educational background. This questionnaire will not have any identifying information on it and will only be used by the researchers to evaluate the program.

Your child will be selected to participate on a first-come, first-serve basis through the Youth Development Organization. Your child must be in grades 6-8. The YDO will also provide transportation to and from the program.

We ask for your permission to use parts of your child's work (such as writing, diagrams, and explanation) in articles and electronic publications. We also ask your permission to use video recording in the project classroom. The recordings will be used to construct an understanding of student thinking as they carry out and discuss work. No identifying information will be associated with this material. Videos and images of your child will only be used for research analysis and will not be released in any publication without additional written permission from you and your child.

This class will meet in Olsen 302 on UMass Lowell's North Campus.

3. Potential Risks and Discomfort: There is no risk involved in your child's participation in this study.

4. Incentives/Compensation (if any): There is no payment or financial reward that is provided as compensation for participation in this study.

5. Anticipated Benefits to the Subject or to Non-subjects: We wish to work with your child because we believe this study will lead to improved engineering curriculum for the educational community. Your child may personally gain skills in abstract problem solving, and/or increased understanding of and interest in design principles.

6. Right to Refusal or Withdrawal of Participation: Participation in this study is completely voluntary. This program is only for parents and students who agree to participate in this research study. You may decide not to participate at any time without any penalty. This decision will not affect other services provided to you by the Youth Development Organization or the University of Massachusetts Lowell.

7. Assurances of Privacy and Confidentiality: Only the researchers will have access to recorded materials. All research data will be strictly confidential. Your child's name and all other identification will be removed from everything that is collected, including images, audio recordings, and video recordings. Every precaution will be taken to protect your child's privacy and confidentiality in the data collected. Recorded videos will be destroyed no later than three years after the completion of this research project. Publications based on this research will not include any participant identifiable information.

8. Additional Information (Include contact information for researchers): This form is also available in Spanish. Please contact the researchers to obtain this version. If you do not understand any portion of this form we will be happy to provide a complete explanation. Questions relating to this research project are welcome at any time. Please contact Dr. Fred Martin, Associate Professor, UMass Lowell Computer Science, 1 University Avenue, Lowell MA 01854, fredm@cs.uml.edu 978 -934-1964 Thank you.

PRINCIPAL INVESTIGATOR SIGNATURE(S) -See definition of PI for who is authorized to sign here.
1. Printed Name: **FRED MARTIN** Signature: Fred Martin Date: **APRIL 21, 2010**

PERSON OBTAINING CONSENT
Printed Name: **HOWARD STICKLOR** Date:

Signature:

PARENT/GUARDIAN SIGNATURE
I understand the risks, requirements, and protocols that have been described in this document. I have read this entire document, have had the opportunity to fully discuss my concerns and questions, and fully understand the nature and character of my child's involvement in this research program as a participant and the possible risks and consequences.

Parent, Guardian, or Legal Representative (if applicable):
Printed Name: Date:

Signature:

Child's Name:

B.2 Student Assent Form

The following pages are the Parental Consent Form completed by the legal guardians of all participants in the study. This form is also available in Spanish.

IRB INFORMED CONSENT or AGREEMENT TO PARTICIPATE FORM

IRB No.: 10-046-MAR-XPD Rev. No./Date:

Consent Form Title: Student Assent Form

Project Title: Exploration of Natural Design Strategies of Novice Engineers
Principal Investigator: Dr. Fred Martin Associate Professor
Contact Information: UMass Lowell Computer Science, 1 University Avenue, Lowell MA 01854, fredm@cs.uml.edu, 978/934–1964
Co-PI(s):
Student Investigator(s): Mark Sherman
Date Submitted: April 21, 2010

This form has been approved for use by the UML IRB and is valid for up to one year from the approval date. (PIs -Give a copy of this form to the study participant after they sign it. Originals are to be retained by the PI.)

Authorized IRB Approval Signature: Stephen Moss **Approval Date:** April 21, 2010

You are being asked to enroll in a program titled "Engineering & Modeling Activities." This program is a collection of interesting activities that involve thinking like an engineer. Part of the each activity will be to design instructions that could be used to get another person to solve the activity like you did. This program will meet for 6 sessions, each session is 90 minutes long. This class will meet in Olsen 302 on UMass Lowell's North Campus.

We are interested in how you think about design problems. We are asking for your permission to use parts of your work for publications about this program. Things we may use include your writing, drawings, and explanations. Your name, grade, town, and any other information that can be used to identify you will be removed from everything we use right away. We won't keep your name or identifying information at all.

We are asking for your permission to video and audio record you during the activities. These videos are for us to better understand how you are thinking during the activities. Your name and other information that can be used to identify you will not be attached to video or audio. These videos will only be seen by the teachers conducting the activities, and will not be published without additional written permission from you and your parent/guardian.

You will be asked to fill out a questionnaire about your favorite subjects, your heritage, and your parents' education. Your name will not be on this.

There are no risks involved in being a participant in this study. There is no payment or financial reward that is provided as compensation for participation in this study.

If you change your mind, you may leave the program at any time without any consequences to you from the Youth Development Organization or the University of Massachusetts Lowell.

All information collected will be confidential. Your name or any other identification will never be disclosed. We will protect your privacy and confidentiality. Recorded tapes will be destroyed no later than three years after the completion of this research project.

If you do not understand any portion of this form we will be happy to provide a complete explanation. Questions relating to this research project are welcome at any time. Please contact Dr. Fred Martin, Associate Professor, UMass Lowell Computer Science, 1 University Avenue, Lowell MA 01854, fredm@cs.uml.edu 978 -934-1964. Thank you.

PRINCIPAL INVESTIGATOR SIGNATURE(S) -See definition of PI for who is authorized to sign here.
1. Printed Name: **FRED MARTIN** Signature: Fred Martin Date: **APRIL 21, 2010**

PERSON OBTAINING CONSENT
Printed Name: **HOWARD STICKLOR** Date:

Signature:

PARTICIPANT SIGNATURE
I understand the foreseeable risks and/or discomfort that have been described in this document. I have read the statements contained herein, have had the opportunity to fully discuss my concerns and questions, and fully understand the nature and character of my involvement in this research program as a participant and the attendant risks and consequences.

Research Participant:
Printed Name: Date:

Signature: