NORTHWESTERN UNIVERSITY

Perceptions of Feedback Systems: Learning an Expert Model through Comparison and Design

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

for the degree

DOCTOR OF PHILOSOPHY

Field of Education and Social Policy – Learning Sciences

By

Joyce Ma

EVANSTON, ILLINOIS

June 2001

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UMI Number: 3012034

UMI Microform 3012034

Copyright 2001 by Bell & Howell Information and Learning Company.
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

© Copyright by Joyce Ma 2001

All Rights Reserved

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT

Perceptions of Feedback Systems:

Learning an Expert Model through Comparison and Design

Joyce Ma

This dissertation explores how students understand feedback systems, specifically, how high-school students reason about feedback system behavior and the underlying relationships students use in their descriptions and explanations. It looks at how students' understanding can change with comparison tasks and design activities that introduce students to an expert model that partitions feedback systems according to a uniform set of functional subsystems and integrates those subsystems according to a shared signal flow.

The first part of this document describes the learning environment, including the comparison activities, the articulate virtual laboratory (FAVL) in which students build and simulate their designs, and the design projects, and it gives the cognitive science basis for its design. The second part of this thesis explores students' changing understanding of feedback systems in the context of this learning environment. It proposes a typology of mental models that can be used to characterize student explanations of feedback phenomena and describes the relationships students use to reason about the behavior of feedback systems. Analyses using a diverse set of methods including analysis on pretest-posttest scores and detailed qualitative case studies were performed to describe how students' understanding changed. In so doing,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

this dissertation identifies aspects of the expert model that students were able to learn as well as those that students struggled to apply to their system descriptions.

This work contributes to the ongoing effort to understand how students reason about systems and how pedagogical tools can make system modeling and understanding more accessible to students without the advance mathematics typical of the discipline.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ACKNOWLEDGMENTS

I would like to thank my thesis committee. My advisor, Ken Forbus gave me the support, the opportunity, and the freedom to explore infinitely fascinating aspects of student learning. His prototype and vision for FAVL provided the spark for much of this thesis work – to make FAVL into a tool that students can use and learn with. Dedre Gentner was generous with her time and insights and provided many theoretical points to ponder as well as practical advice on methodology and analysis. She was instrumental in introducing comparison activities into the learning environment described in the thesis, activities which were critical to helping students learn the feedback model. Bruce Sherin always encouraged me in my research and convinced me that characterizing learning was a difficult but worthwhile endeavor. He pushed me to think more deeply about the complexities of learning and patiently worked with me to make sense of my qualitative data.

I would also like to thank Kelvin Gilchrist and Mark Sauerland for welcoming me into their classrooms at Evanston Township High School during the earlier stages of this work. They made me appreciate how challenging teaching can be. And, I am glad that there are teachers like them.

Also, many people provided support through the day-to-day grind that can be graduate school. I am grateful for the kindness and concern that my colleagues showed me over the past years. I would especially like to thank Hyuk for making me laugh and the Women of QRG, Julie,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Karen, Maddy, and Radha who listened to me and talked with me about feedback systems, research, bubbles, and life.

Finally, none of this would have been possible without the support of my family. Although they did not quite understand why I gave up my day job to return to graduate school, they always offered me safe harbor when the seas got too rough.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE OF CONTENTS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF TABLES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF FIGURES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1 Introduction

> the feedback concept...I ponder still how my education could have missed it. A powerful way of thinking - linking concepts of control and self-reinforcement, stability and instability, structure and behavior... and uncounted numbers of the deepest ideas
>
> - G. Richardson in *Feedback Thought in Social Science and Systems Theory* (p. ix)

In recent years, there has been an increased emphasis within the education community towards teaching pre-college students "to think and analyze in terms of systems...an organized group of related objects or components that form a whole" (National Research Council, 1996). This drive is in part motivated by what the National Research Council sees as a tendency for students to "interpret phenomena separately" without making appropriate connections to other ideas introduced within or between subject topics. This emphasis on the systems concept also reflects a movement within the scientific and engineering community begun in the 20th century to analyze and understand natural and technological phenomena in terms of the interaction of parts that leads to the behavior of the whole. The idea of systems is a unifying concept which "transcend[s] disciplinary boundaries and prove[s] fruitful in explanation, in theory, in observation, and in design" (American Association for the Advancement of Science, 1991) by making apparent general patterns of organization common across many different fields of study. Students should "appreciate the organizational structures responsible for the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

manner in which materials and information circulate in and out of ...dynamic systems" (National Research Council, 1996).

Feedback is one of those general patterns of organization pervasive in the natural and man-made world that is critical in understanding many systems. Engineers have applied feedback to inform their design and analysis of devices and processes from home heating to satellite attitude control. Scientists have used feedback as a conceptual frame to analyze biological and social phenomena including human thermoregulation and economic cycles. It is a central concept in communications theory and in cybernetics, two important scientific movements of the 20th century (von Bertalanffy, 1968). It has been proposed as the mechanism behind all purposeful behavior in machine and in society (Wiener, 1961). The concept of feedback, therefore, is a useful engineering design principle as well as a framework for explaining a large class of systems both natural and artificial. Feedback has been identified by the National Research Council as well as the American Association for the Advancement of Science as being fundamental to understanding systems, a "unifying concept" in K-12 education (American Association for the Advancement of Science, 1991).

Despite the prevalence and usefulness of the concept of feedback, there have been relatively few studies on how novices understand and learn about feedback systems. The few include studies that have looked at people's intuitive understanding of specific feedback systems such as home heating (Kempton, 1987) and automatic open-close door mechanisms (Mioduser, 1996), and at how their understanding of specific feedback systems change with instruction (Mioduser, 1996) and with computer interaction (Brandes). The interpretation of these study

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

results is complicated by a lack of a consistent definition for what is meant by feedback in the first place. Additional work is needed on how novices understand feedback systems in its many manifestations and how they construct a more expert understanding of feedback.

An understanding of how students learn this important subclass of systems would be useful for pedagogical reasons not only because helping students learn the concept of feedback may give them an inferentially powerful means of viewing the world but also because there is a growing emphasis on systems in secondary school education. Learning about feedback systems entails learning about many of the same principles central to a systems viewpoint: the idea of a set of interacting parts that give rise to overall system behavior, and the idea of information transformation and propagation from part to part that can be used to characterize local and system level behavior (American Association for the Advancement of Science, 1991).

More broadly, learning a way of thinking about feedback systems encompasses many of the same issues that students face in learning any scientific or technological domain. "In teaching science we are leading pupils to 'see' phenomena and experiential situations in particular ways; to learn to wear scientist's models for entities which are not perceived directly." (Driver, Guesne, & Tibeghien, 1985) When we ask students to think of a collection of objects as a feedback system, we are asking them to understand that collection of objects in a certain way using specific entities that describe qualities shared by all feedback systems and that interact with each other in prescribed ways to reveal underlying principles and enable broader predictions. Central to learning about feedback, therefore, is learning how to parse the world into the entities that experts use to describe these systems and how to derive local and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

systemic behavior based on the individual parts and the reintegration of those parts, key aspects in learning any scientific and technological field.

1.1 Purpose and Scope

This dissertation addresses the question: How do students learn to understand feedback systems? In particular, this research looks at how high school students learn a way of thinking about feedback systems that is based on a model of feedback systems defined in control engineering. It explores students' changing understanding of this model in the context of a learning environment that makes use of comparison and design activities.

The control model of feedback systems has found application in scientific disciplines as well as within engineering. It explains all examples of feedback control systems in the same terms regardless of specific physical implementation, which enables the derivation of system behavior from the interactions of those parts. Learning this model of feedback systems depends on recognizing and using the entities that experts use in characterizing these systems. An analysis of how novices learn to parse a system according to common entities used in an expert model and to then use these parts to predict and understand system behavior is an important chapter in the novice to expert story.

Our learning environment design makes use of two type of activities: 1) comparison tasks guided by the relational terms that experts use, and 2) design tasks in an articulate virtual laboratory that uses this relational vocabulary. In the following chapters I describe and analyze the use of these two types of activities as implemented in a particular learning

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

environment called the Feedback Articulate Virtual Laboratory (FAVL). Although embodied in a specific implementation, this research contributes to the body of work on how instructional tools such as comparison tasks guided by relational vocabulary and computer-based design activities can be used to change and enrich prior knowledge and to help novices construct a new frame for the understanding and description of their world.

1.2 Document Organization

In the remainder of this document, I will describe

Section 2	The model of feedback systems we wish to teach, the learning environment, and the rationale behind its design
Section 3	An overview of the student participants and the key activities in the study
Section 4	An analysis of student understanding of feedback systems before and after the intervention
Section 5	A closer look at the role of comparison in model instruction
Section 6	A set of case studies on student learning within the virtual laboratory
Section 7	A summary of the overall study findings with implications on instructional design

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2 Learning a Model of Feedback

In this chapter, I will describe the model of feedback systems that we wish to teach within our instruction, the possible challenges students face in learning this feedback model, and the learning environment we designed to address these challenges.

2.1 What is Feedback?

> I think that feedback is more of ummm [pause] it's essentially inputs from outputs. It's in a loop ... the object itself is directly controlled, modified, by its output.
>
> - 9th grader after working with the Feedback Articulate Virtual Laboratory

Feedback systems are a category of systems characterized by certain structural and behavior similarities. At its most basic definition, a feedback system is a collection of parts that interact in such a way as to use information about its current condition to determine how to change its future condition. For example, a typical home heating system uses information about the current room temperature to determine if the furnace turns off or on, which, in turn, affects the room temperature. Feedback systems are further distinguished as either negative or positive feedback systems. Negative feedback exists when the information fed back to the system is used to maintain or regulate a certain condition in the system. These systems are oftentimes called goal-seeking systems since they self correct to bring a parameter value within a certain range or to a certain value. For this reason, negative feedback is equated with

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

feedback control and has been posited by some as being the root of all purposeful behavior (Wiener, 1961). The home heating system is an example of a negative feedback system because it is designed to maintain the room temperature within a set range. Alternatively, positive feedback exists when the information fed back to the system continuously amplifies a certain condition in the system. Figure 2-1 illustrates an example of a positive feedback system. In this study, I will focus on negative feedback systems because of its prevalence in engineering design and in explanations of natural and social phenomena.

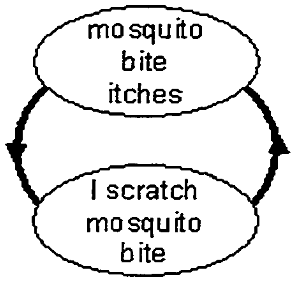


Figure 2-1. An Example of a Positive Feedback System. A mosquito bite itches so I scratch the mosquito bite which causes it to itch more which causes me to scratch the bite more (and harder) and so on in an 'infinite' loop. This example is described in Resnick (1996).

Some theorists define feedback simply as an information flow that loops back onto itself with no further structural criteria (Richardson, 1991). However, with such a definition it becomes easy to define any dynamic system as a feedback system through mathematical formalism and manipulations since the current condition typically depends in part on its past condition. Instead, in this study I adopt a more specific definition of feedback borrowed from feedback control engineering, the technological origins for the more general concept of feedback (Rubin, 1968; Mayr, 1970).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.1.1 *Parts of the Feedback System Model*

In control engineering, a feedback system is an abstract model of components and interactions exemplified by the canonical structure shown in Figure 2-2.

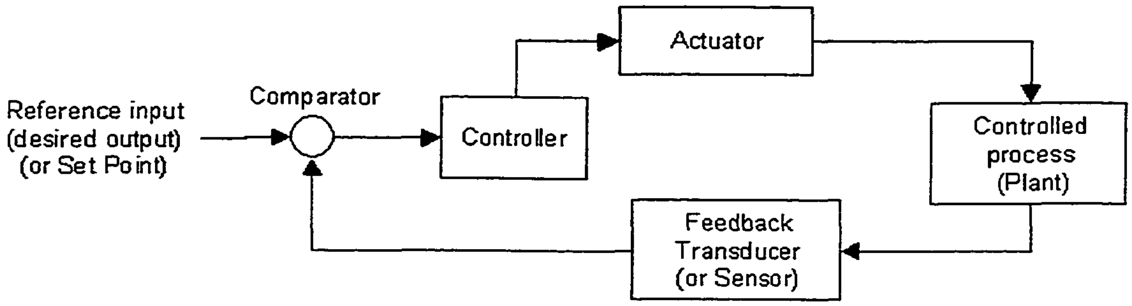


Figure 2-2. Canonical Structure of a Negative Feedback Control System (copied without permission from Milsum (1968, p.41)

According to this model, a feedback system consists of the 'parts' listed in Table 2-1. These parts generally do not represent discrete physical objects; rather, the parts are defined in terms of functional roles within the system. Each function describes a *relationship* between the behavior of a physical object or set of objects in the system and the overall purpose of the feedback system. For example, a bimetallic strip in the thermostat moves up and down depending on the ambient temperature. Its position can indicate how warm the room is. Therefore, the bimetallic strip serves as a sensor in the home heating system. The functions outlined in Table 2-1 describe the relationships that exist in all feedback systems regardless of physical implementation and provide a level of system abstraction divorced from physical parts.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 2-1. Parts of the Feedback Model

Part Name	Part Description
Controlled Process	Represents the system that is to be controlled
Sensor	Takes measurements to determine the current state of the system that is to be controlled
Setpoint	Gives the desired condition of the system
Comparator	Compares two values (typically the desired value and the measured value) to determine any discrepancy (also called the error signal)
Controller	Maps the comparison result to an appropriate amount of action to be taken to change the current condition of the system. (Note that there are different types of controllers such as proportional, integral proportional, and on-off controllers which are made of more basic parts.)
Actuator	Takes action to change the current state of the system

2.1.2 Information Flow -The Interaction Of Parts

The functional partitioning is tied to the concept of a signal, or information flow, in the feedback system model. That is, each functional part, or subsystem, can also be defined according to how it transforms the information that traverses the system. For example, the comparator is defined as the part that processes two pieces of incoming information, the measurement of the current state of the system and the desired state of the system, and outputs the discrepancy between the two.

The information flow also describes the connections between the components of the system; information travels from the output of one subsystem to the input of the next, is transformed, and then sent from its output to the next input, and so on around the feedback system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Although information sometimes correlates with material flow, it is more representative of the causal sequence of events in which one function affects the next, which, in turn, affects the next, and "expresses a pure relation of mutual dependency" (Cassirer, 1923). It is, therefore, a way of capturing the causality as well as the interdependencies between the variables within the system that is independent of physical implementation.

2.1.3 Why This Model?

The engineering model of feedback systems, like any model, chooses certain aspects of real example(s) to highlight while obscuring others. Which aspects are highlighted and which are obscured depend to a large extent on the purpose of the model. This particular model places emphasis on a functional partitioning of feedback systems which is useful to engineers who are in the first stages of conceptual design, when they are more interested in characterizing the major subsystems than in the details of physical implementation. A functional level of description provides a way of analyzing the system without becoming mired in parts specification. A study of expert technicians show that identifying functional subsystems is part of a strategy often used to troubleshoot a malfunctioning system (Rasmussen, 1986).

Also, the information flow characterization helps link the different functional parts together to help the engineer characterize local and system-wide dynamics, making it clear the relationships between relevant variables. Viewing the system as a set of information transformations is also a precursor to a more detailed, mathematical analysis and design of feedback system dynamics.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Although rooted in engineering, these principles have also found their uses in other disciplines. This includes the life sciences where a basic understanding of the necessary functions needed for regulation has motivated biologist to search for underlying mechanisms for these functions and has revealed how feedback systems can be realized in biological entities (Wiener, 1961). The information flow concept has also been useful in the mathematical modeling of biological systems: "All functions associated with the phenomenon of life can be described in physical terms as the processing of information" (Stark, 1973, p. 17). The ideas of functional decomposition and information flow, which lie at the heart of this feedback model, are therefore powerful constructs for viewing the world.

2.2 Learning the Feedback Model

2.2.1 What Does Learning This Feedback System Model Encompass?

The description above identified at least two central ideas that are entailed in learning the expert model of feedback systems. These both involve describing feedback systems on a certain level of abstraction that captures relational commonalities among all negative feedback systems independent of physical instantiation:

Partitioning the system into functional components. A critical part of learning to think in terms of this feedback model is learning to partition a system into its functional subsystems and not only according to physical makeup. Thinking in terms of functions is key not only to understanding this feedback model but also, more broadly, to engineering design where functional specifications (e.g., deliver x amount of water by y time) and not physical structure requirements (e.g., use this pump and that pipe to build a water tower) are often the norm, and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

to scientific analysis, where interpreting system behavior often depends on identifying the functional interactions between system components (e.g., predator and prey instead of lion and wildebeest). Functional decomposition is one means by which students can carve up a system into its constituent subsystems along lines that can promote further meaningful analysis (Miyake, 1986), and is, in fact, an important skill in understanding any system (Goel & Pirolli, 1992; Lesgold & Lajoie, 1991). Functional decomposition is part and parcel of engineering design work as well as in technical repair work (Rasmussen, 1986) and plays an important role in facilitating system design and troubleshooting.

Identifying and reasoning from the information flow among components. In addition to functional partitioning, learning this feedback model also involves learning to see the key causal interactions between its parts as a set of successive information transformations. Because it captures the causality within the feedback system, the information flow is critical in helping the student synthesize system behavior from its parts, in predicting, explaining, and troubleshooting behavior. This idea of an information flow is central for thinking not only about feedback systems but all types of systems; according to Science for All Americans, "the way that the parts of a system influence one another is not only by transfers of material but also by transfers of information" (American Association for the Advancement of Science, 1991).

In addition, learning the feedback model should also include the ability to apply these models where appropriate to a larger context of activities including using the model to explain and predict a wide range of regulatory behavior and using the model to inform design work.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.2.2 Possible Difficulties In Learning This Feedback System Model

Although most individuals come in contact with feedback systems even in the course of daily life, the few studies done on people's understanding of feedback systems indicate that novices often do not see the underlying feedback relationships in a regulatory system. For example, a study by Kempton (Kempton, 1987) showed that some people have a 'valve' model of the home heating system. Instead of a system that turns the heater on and off, they believe that the thermostat allows the user to adjust an opening that releases the right amount of heat to keep the temperature in a house at a comfortable level. A study by Mioduser, Venezky, and Gong indicate that students have "very poor knowledge and understanding [of control mechanisms] prior to instruction" (Mioduser, Venezky & Gong, 1996, p. 380). These studies do not offer a comprehensive view of people understanding of feedback systems nor do they in and of themselves mean that learning feedback with appropriate instruction will be particularly difficult. However, they do suggest that feedback is not a model that novices typically use to explain the workings of the world. There may be several reasons why this may be the case:

<u>Feedback is “hidden” from daily experience.</u> In many cases, portions of a feedback system are partially hidden from the causal observer. Parts of a system, such as the inside of a thermostat remain encased in a 'black box' which most people have little reason to open up and investigate. Some parts of a feedback system may now be implemented with microchips whose inner workings are impossible to see. This problem becomes more pronounced for biological systems, which are predominantly opaque to direct observation. Even practicing scientists have great difficulty understanding the feedback mechanisms within biological

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

systems because of system complexity and observational challenges. This is an important consideration because expert-novice studies (Lesgold & Lajoie, 1991; Larkin, 1983; and Penner, 1998) suggest that device knowledge often differentiates the experts who can see patterns in systems from the novices who cannot. Moreover, novices tend to focus on the parts of the system that are immediately accessible to the user. For example, a study by Penner (1998) looking at how novices and experts partition a bicycle system shows that novices are best at describing the functionality of the parts of the system that are "directly experienced, and personally important" (p. 828) For feedback systems, this may mean that the setpoint unit, such as the control dial on the thermostat that a user directly manipulates, will be the only part of the system that will be well understood because the rest of the feedback system is hidden from direct experience. In addition, it may be a challenge to find a good intuitive base for teaching a deeper understanding of feedback systems.

<u>Feedback is about relational patterns.</u> Feedback is a pattern of interaction common to many different types of systems that can have very different physical instantiations. For example, both a home heating system and the human blood sugar regulation system are negative feedback systems although the two systems share no common physical parts. Learning the feedback model depends on the ability to recognize these underlying relational similarities. However, studies in cognitive science (Gentner & Landers, 1985; Gentner, Rattermann & Forbus, 1993; Novick, 1988; Chi, Feltovich, & Glaser, 1981) suggest that novices have difficulties seeing (i.e., retrieving and possibly encoding) the underlying relationships in a system and, instead, tend to focus on the more superficial object descriptions (e.g., material, size, and shape). Thus, the higher-order, abstract relationships, which characterize all

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

feedback systems, are often not easily accessed or even available to the novice. For feedback systems, these higher-order relationships include the functional definition of feedback parts. (Recall that each function relates physical parts and their behavior to the overall purpose of the system.) Higher-order relationships also include the common manner in which information traverses the system from one functional block to the next that gives rise to the system's overall behavior.

Moreover, seeing these underlying patterns of interaction depends on a common way of partitioning the system into key functions. However, studies on expert-novice reasoning indicate that novices have difficulty partitioning a system into its functional subsystems. Instead, novices tend to group the objects of a system according to surface characteristics whereas experts group objects according to the functions the objects have within a system (Penner, 1998). What may make functional partitioning of feedback systems even more difficult is that in many instantiations, one physical part is designed to serve several functions. For example, the bimetallic strip is both a sensor and a comparator in the home heating system. A functional partitioning, therefore, may at times force a division across physical lines.

Dynamic analysis traditionally relies on college-level mathematics and calculations. Feedback behavior arises from the interactions of different parts of the system over time. Within our model, these interactions are described by information that is propagated and transformed from one part to the next through the system. Traditionally, one of the key advantages to modeling systems this way is that this provides a means of expressing system behavior and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

interactions in mathematical terms and allows for mathematical analysis of system dynamics. Unfortunately this traditional, quantitative approach to deriving system behavior often depends on either college-level mathematics and/or time consuming calculations. This presents several difficulties. For one, the dependence on college level mathematics makes this feedback model inaccessible to most secondary school students. Second, the quantitative approach often eclipses qualitative means of system analysis which, studies suggest, is a powerful means for understanding a problem. In fact, research in problem solving suggests that qualitative reasoning often precedes quantitative analysis and is critical in helping an expert decide the appropriate approach to a problem (de Kleer, 1984; Glaser & Chi, 1988; White & Frederiksen, 1990; Ploetzner & Spada, 1993; Clement, 1994; Sime, 1996; Sherin, in press).

Thinking in terms of signals. The idea of a signal is a core concept in an expert's conception of feedback systems and is tied to the definition of the functional components that make for a feedback control system. Therefore, in order for a novice to develop a more expert understanding of the functional make up of feedback systems, there must be a parallel development in the student's understanding of signals: the information communicated and the communication pathways. The use of the idea of signal and information flow to express causality may be unfamiliar to high school students.

It seems, therefore, that learning this particular model of feedback system may meet with several challenges.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.3 The Learning Environment

To meet the pedagogical challenges outlined in the previous section, I used two pedagogical tools in the learning environment we designed:

1. Analogical comparisons guided by relational vocabulary are used to help confer a basic understanding of the parts and interactions within a feedback system. They are designed to help students highlight relational commonalities between feedback systems, learn the relational abstraction that defines the expert model, and see the common structure that all feedback systems share.
2. An articulate virtual laboratory allows students to design feedback systems from functional components and to simulate system behavior without advanced mathematics or tedious computations. Through design work in an articulate virtual laboratory, students can develop a deeper understanding of the parts and interactions that give rise to feedback system behavior.

In the following, I will explain the theoretical rationale and past work that support the choice of these tools for teaching feedback systems. I will also describe how these activities were incorporated into a curriculum designed to help students explore the expert model of feedback systems described in Chapter 2.1.

2.3.1 Analogies

2.3.1.1 Learning with Analogies

Researchers and educators have long argued for the value of using analogies in education. (See Duit (1991) for a review.) Analogies are credited with acting as a bridge between what

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

students know and what students learn, with making similar relationships shared between physically dissimilar examples apparent, and with playing a critical role in the formation of more abstract principles.

Learning from analogies, however, can be difficult for students. Students' mental representations of a case can be very rich consisting of many objects, attributes, and relationships. Often, students with limited guidance see similarities that are inferentially useless or, worse yet, inferentially unsound. Analogies are more likely to produce useful information when they are based on relational commonality and higher-order structure. Unfortunately, novices tend to look for surface similarities (e.g., same shape, same material) while ignoring deeper, underlying commonalities (e.g., feedback systems, central force systems) when they retrieve a similar case from memory to help them reason about a problem (Novick, 1988) and when they compare two cases set before them (Chi et al., 1981).

Studies on using analogies to help students see common relationships or underlying principles have been filled with examples of students' reasoning from shared surface features instead of relational commonality. Brown and Clement's case study (Brown & Clement, 1989) of using analogies to teach Newtonian physics found that some students tend to use surface features to explain phenomena that share the same underlying principle. For example, students would explain the resistance between two combs rubbing against each other and the resistance of a puck sliding on the floor as a result of 'bumpy' surfaces rubbing against each other. Likewise, static upward force exerted on a book lying on a table is explained by 'springs' in the table. It is not clear if the students in this study ever go beyond these initial physical explanatory

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

constructs, or what going beyond these physical explanatory constructs may mean. A study (Duit, Komerek, Wilbers, & Roth, 1997) on teaching chaos theory with analogies also gives examples of students' retrieving cases based on surface similarities (i.e., similar geometric shapes) to reason about underlying principles, sometimes unsuccessfully. It seems, therefore, that student use of analogies in understanding more fundamental (relational) principles must be better guided.

Recent studies in cognitive science have shown that the process of analogical comparison can help people focus on relational similarities (Gentner & Markman, 1997; Gentner et al., 1997). Furthermore, the process of analogical comparison not only highlights the relational similarities during comparison but also promotes the encoding of those examples according to those shared relationships. This, in turn, facilitates retrieval according to relational similarities and not just surface similarities (Gick & Holyoak, 1989; Loewenstein, Thompson, & Gentner, 1999; Gentner & Namy, 1999; Loewenstein & Gentner, 2001). Analogical comparison also, therefore, fosters the construction of relational abstractions. The expert model of feedback systems is by definition a relational abstraction.

In addition, studies on analogical reasoning and child development suggest that one important contributor to analogical insight is a relational vocabulary (Gentner & Rattermann, 1991). In a study done by Gentner and Rattermann (1991), very young children who were taught relational terms (e.g., Daddy, Mommy, and Baby to describe relative size) were able to perform relational matches better than their counterparts who were not taught these terms. The former group was able to perform relational matches in a mapping task despite distracters,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

competing correspondences with similar surface features but different relational similarities. Likewise, Loewenstein and Gentner (1998) found that children who were taught to use the terms, "top, middle, and bottom," for a vertical array, performed far better in a mapping task than children who were not so taught.

Studies on analogical retrieval in adults also indicate that adults are better able to retrieve analogies when they are given a uniform set of relational terms as compared to when they are not (Clement, Mawby, & Giles, 1994). Relational terms - terms that denote the common relationship shared by two examples - therefore, seem to play a key role in the types of similarities recognized and retrieved. Hence, they can be instrumental in guiding the novice in comparing the right similarities between two examples and in helping the novice recall an example based on shared functional structure of feedback systems and not just surface similarities.

2.3.1.2 Analogical Comparisons for Learning the Feedback Model

> It's not like a strong comparison... cause you're dealing with two different elements and they, they do it by different ways.
>
> - Student before instructional unit comparing a water regulation system to a home heating system

The work on comparisons and relational terms points to a potentially fruitful way of allowing students to learn the expert's model of feedback. In particular, I posit that comparisons between feedback systems can help students see commonalities between physically dissimilar feedback systems, and moreover, when the comparisons are guided by relational terms,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

students can align feedback examples according to the shared set of functions defined in the expert model. Furthermore, these functional subsystems are connected by information that is passed from each subsystem to its downstream neighbor; therefore, understanding this model will also entail that students learn the idea of signal propagation through a system. To incorporate comparison and relational terms to help students partition systems along similar functional lines and to tie together those functions according to signal flow, I needed to address a set of challenges particular to teaching this feedback model.

First, previous studies on people's understanding of how specific feedback systems work have shown that people may not have an accurate understanding of why a system can regulate its own behavior. One of the benefits of using analogies in education lies in the fact that students can use an analogy to create a bridge between what they already know to what is to be learned.[1] However, novices may not have the prerequisite base example about feedback systems to learn from. For example, in a study on adults' mental models of home heating control, Kempton (1987) found that some of his subjects did not have any idea of the constant readjustments that allow the home heating system to control the temperature in a house. Instruction using analogies, therefore, should include an easy to understand example of a feedback system that students can use as the analogical base.

---

[1] Note that this is not the only educational use for analogies. The process of making a comparison between two examples reveals shared relationships for both examples through mutual alignment (Kurtz, Miao, & Gentner, in press). In this study, I chose to first introduce students to an easy to understand base example.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Second, according to the Structure Mapping Theory (Gentner, 1983), a cognitive model of the analogy process, comparisons are based on one-to-one mappings between elements in the target and the base domain. However, in most practical implementations of feedback systems, multiple functions are often encompassed in one physical object.[2] This can potentially make it difficult for students to notice functional commonalities: If students have mental representations based on the different physical objects in the system, then certain functions will be encapsulated within an object. Mappings between such systems may not promote differentiation between or even identification of certain functions in the feedback system model since mappings are based on one-to-one object correspondences. In fact, in earlier pilot studies, high school students who were asked to compare examples of feedback systems that had one part serving multiple functions had trouble attributing multiple functions to one physical part (Ma, 1999). A somewhat similar result was found in a study on 6th graders' perception of automatic open/close systems that use feedback control. In that study, however, Mioduser et al. (1996) attributed student misconceptions about component functions to the students' lack of accurate device knowledge. I propose that to come to an expert's formulation of feedback systems, learning how a particular system's device works is only a part of the answer. Since an expert's formulation is based in part on an understanding of the interaction of functions, students need to also learn to differentiate functions, which are oftentimes realized in one physical object. Designing the comparison tasks, therefore, must include examples in which each object is physically distinct and corresponds to only one function in the feedback system model.

[2] For example, the bimetallic strip is both the sensor and the comparator in the home heating system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.3.1.3 Materials and Activities

To help students see the relational similarities between feedback systems, in consultation with Dedre Gentner, I created a set of analogous examples of feedback systems to be used in the following instructional sequence:

1. Introduce students to an easy to understand base example. Students are given a story about how a therapeutic spa maintains the water temperature within a safe range. The story outlines the cause and effect relationships between the different, physically discrete parts of the system and summarizes the overall effects of these interactions on the temperature in the spa's hot tub. To help focus students on the functions, the base example describes each of its physical components according to the function it has within the larger system, and each physical component serves one and only one function within the system. This design allows students to perform one-to-one mapping in the subsequent comparison activities between objects in the base and target example that align according to functional similarity. This serves to highlight shared functions in both examples.

   Notice that the base example describes people who pass information to each other. In order for one component in the story to affect the next, that component must communicate information to the next one in the causal chain. This design introduces students to the idea of information flow within feedback systems and makes explicit the signal that is passed from one part to the next.

   Students are asked to read the story and to look at the accompanying diagram (Figure 2-3) when they read. This is followed by a short discussion during which the interviewer asks

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the student to reason about the possible effects different types of failure scenarios might have on the operations of the system.

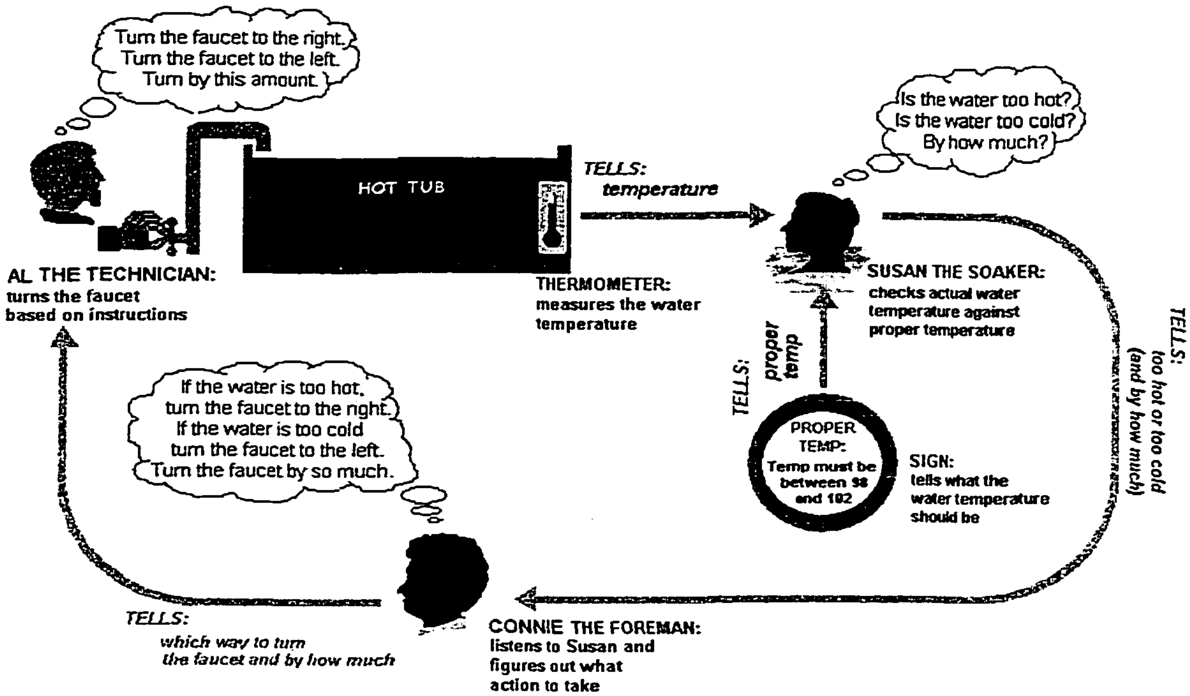


Figure 2-3. Base Example Used in Model Instruction

2. <u>Introduce students to the canonical model and the relational terms for describing feedback systems.</u> Students are given a description of the feedback model that introduces the relational terms for the common functions shared by feedback systems as well as the type of signal that is communicated between the subsystems. This description, like the base example, presents a causal story (in both text and diagram) of how the different parts of the system work together to control an aspect of the system. To help students connect these more general terms to a specific model, students are asked to map the base example

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

to the general template shown in Figure 2-4. In the study, students found this mapping to be straightforward.

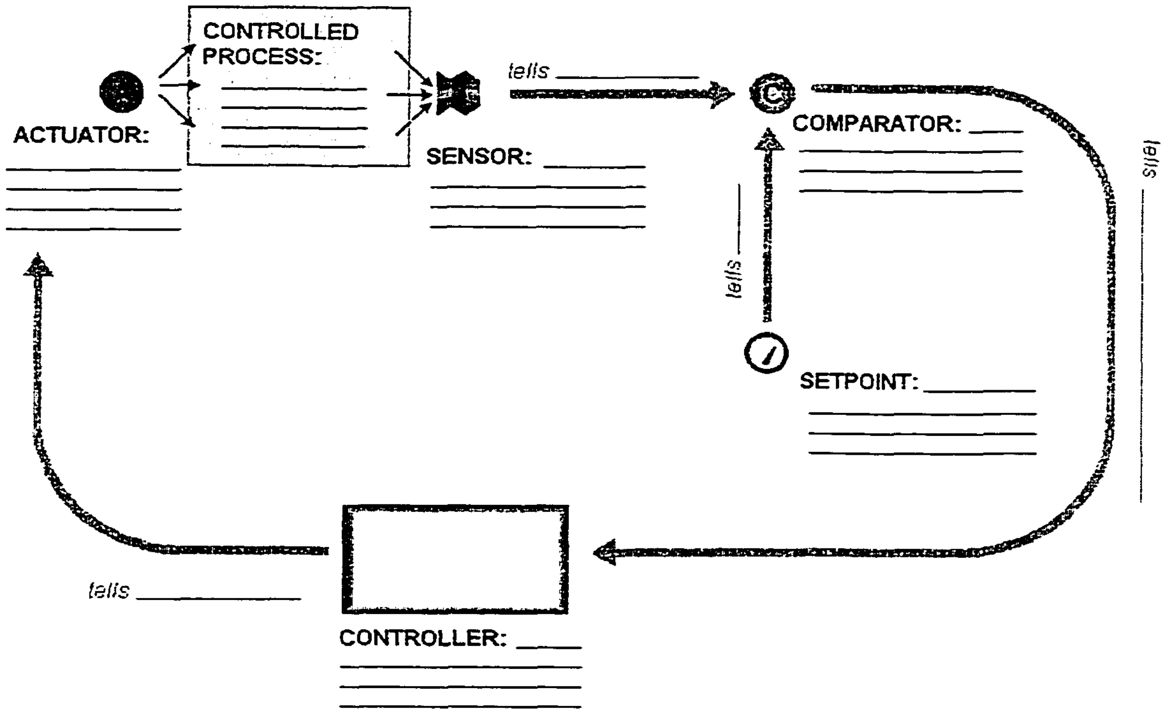


Figure 2-4. Template of the Canonical Feedback System with Relational Terms

3. Students compare a target example to the base example. Students are asked to read another example of a feedback system (a heat regulation system for an aquarium) and to look at the accompanying diagram. They are then asked to compare this example to the base example introduced earlier and to map each object from the target example to an object in the base example using the template shown in Figure 2-5. This template provides both the base object and the term for the function that that base object performs. In the target example, just as in the base example, one physical object serves one and only

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

one function in the system and one object affects the next by passing information to the next object. This design should allow students to perform one-to-one mappings between objects that perform a similar function in their respective system. In addition, the target is similar to the base example in many object features as well as in structure. For example, the physical placement of the objects and corresponding functions in the target diagram is the same as that in the base diagram. These similarities help students notice and align the functions, and with each match, I hope that students reinforce the relational similarities between the two systems. A study by Kotovsky and Gentner (1998) indicates that this technique of progressive alignment can help young children to align examples according to relational commonalities.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

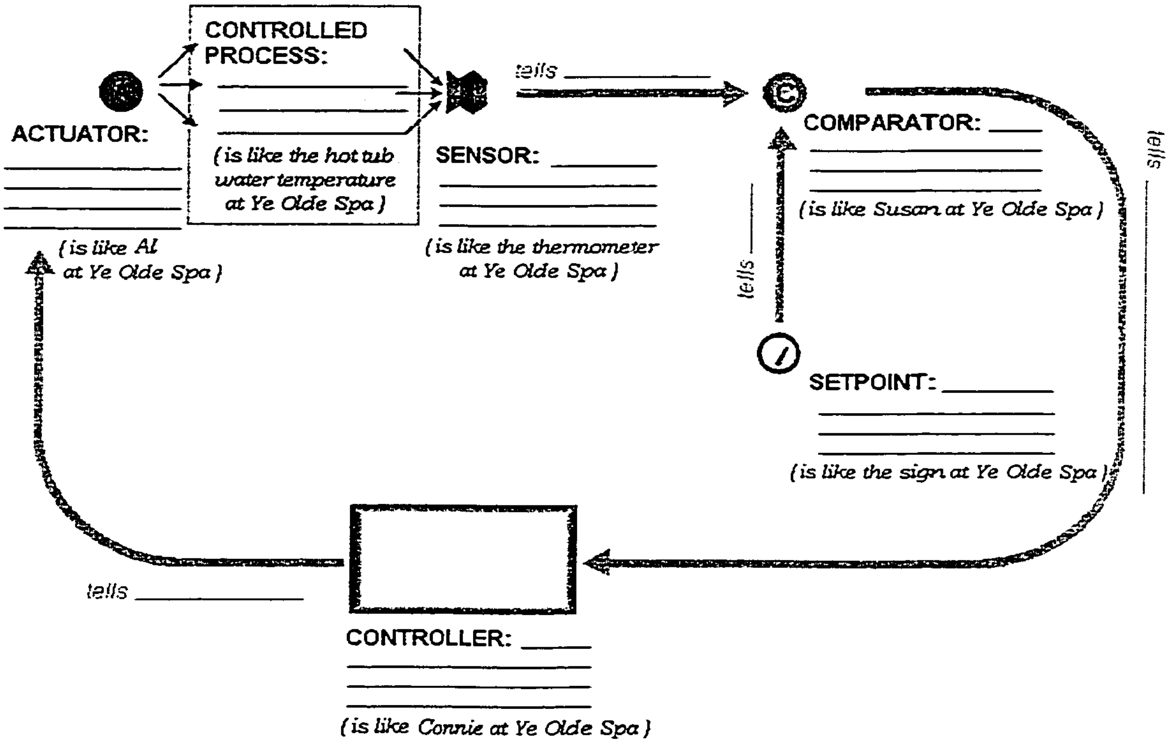


Figure 2-5. Template of the Canonical Feedback System with Relational Terms and the Objects of the Base Example.

4. <u>Students compare another target example to the base example</u>. Students are then asked to look at a third example of a feedback system (a salinity regulation system) and compare and map this example to the base example. That is, they repeat the previous activity for this new feedback example. This second mapping task is used to reinforce alignment between these examples along the same relational lines. The conjecture is that with each successive comparison, students are constructing an abstraction that captures the canonical functions and their interactions without the specific features of the examples used in the comparisons. This is in accordance with the schema-abstraction theory posited in

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Kuehne, Forbus, Gentner, and Quinn (2000) and Skorstad, Gentner, and Medin (1988). Students in the study had no difficulties mapping the base example to either target examples.

These activities and accompanying material are summarized in Table 2-2.

Table 2-2. Activities and Material for Model Instruction

Activity	Material
Introduce students to an easy to understand base example.	Appendix B.1
Introduce students to the general model and the relational terms for describing feedback system functions	Appendix B.2 and Figure 2-4
Students compare a target example to the base example	Appendix B.3 and Figure 2-5
Students compare another target example to the base example	Appendix B.4 and Figure 2-5

The above set of activities was designed to help students see relational commonalities in feedback systems, specifically the functional makeup of the canonical feedback model. The activities serve to encourage students to highlight relational similarities, to see the shared feedback structure that characterizes the expert model and to learn the relational abstraction for feedback systems.

2.3.2 Computational Tools For Designing And Simulating Feedback Systems

In addition to guided comparison tasks, I use a computational tool to help students learn the feedback model. Design work with the computational tool is intended to help confer a deeper understanding of the parts and interactions of a feedback system that give rise to system

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

behavior. The computational tool, called the Feedback Articulate Virtual Laboratory (FAVL)[3] allows students to design feedback systems and then to simulate their behavior while avoiding the costs, the possible danger, the impracticality or impossibility (in the case of biological systems) associated with assembling a physical system. Computer-based design and simulation tasks should provide several advantages to learning about feedback systems:

1. It situates the learning within an activity that makes use of feedback loops in control problems and, therefore, helps clarify the power of feedback within systems.
2. Design projects require iterative refinement towards a solution that encourages students to refine their understanding.
3. Design activities focus students on articulating the functional building blocks and their interactions that give rise to system behavior.
4. Computer simulation automates the number crunching and circumvents the advanced mathematical analysis used in college level feedback control courses.
5. Computer simulation helps students evaluate their model against the desired performance.

Design and simulation work on the computer is intended to give students experience with feedback systems that extends beyond casual observation to defining feedback interactions typically hidden behind the 'black box'.

2.3.2.1 FAVL – A Description

The Feedback Articulate Virtual Laboratory is a computer-based learning environment in which students can design feedback systems and simulate their behavior in a virtual design

---

[3] FAVL was designed by members of the Qualitative Reasoning Group at Northwestern University.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

space. FAVL has its roots in a BBN project from the 1980's called STEAMER, an intelligent tutoring system designed to help naval personnel learn a mental model of steam propulsion plants on large ships. FAVL's earlier incarnation, called the Feedback Mini-Lab (FML), was designed by Kenneth D. Forbus (Forbus, 1984) and many of the core ideas behind the current version of FAVL comes from his definition of FML.

FAVL belongs to a class of educational software called Articulate Virtual Laboratories (AVLs). AVLs are designed to provide students with tools that can make conceptual design tasks more accessible by giving them:

- a computer-aided design tool that students can use to generate designs,
- a test environment that allows students to run simulations of their designs,
- and a set of visualization tools including graphs and animations that shows the system's dynamic behavior.

AVLs also provide explanations of the "how" and "why" of the interactions behind students' designs to help students reason about their designs. A computer-based coach helps students evaluate their designs and suggests design improvements.

To date, two different AVLs have been developed. The first, CyclePad (Forbus et al., 1999), was created for university engineering students to help them come to a conceptual understanding of thermodynamics. FAVL was designed for high school students to help them develop a richer understanding of feedback systems through design work.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

With FAVL, a student can build systems by adding and connecting icons that represent the functions found in most feedback systems. These functional building blocks are listed in Table 2-3.

Table 2-3. Functional Components in FAVL (continued on next page)

Icon	Name	Function Represented
(Icon is specific to the process modeled)	Controlled Process	Represents the system that is to be controlled
	Sensor	Takes measurements to determine the current state of the system that is to be controlled
	Threshold comparator	Compares two values to determine if one is larger than the other
	Difference comparator	Takes the difference of two values
	Actuator	Takes action to change the current state of the system
	Set Point Unit (SPU)	Gives the desired value of the system
	Controller	Maps the comparison result to an amount of action to be taken to change the current condition of the system. Note that there are different types of controllers such as proportional, integral proportional, and on-off controllers which can be further decomposed to more basic parts. (Students are encouraged to work with these basic parts only after they've completed more complicated designs.)
	Multiplier	Multiplies two values
	Adder	Adds two values
	Min	Takes the minimum of two values

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 2-3. Functional Components in FAVL

Icon	Name	Function Represented
	Max	Takes the maximum of two values
	Counter	Counts repeatedly from a low to a high value
	Integrator	Integrates the incoming value over the period of the simulation run
	Derivative	Calculates the rate of change of the incoming signal
	Switch	Opens or closes the connection

Each functional component can have inputs, an output, and internal variables. Connecting two components involves connecting the output from one component to the input of the next. In doing so, the student specifies a relationship between the two in which what is represented by the first component affects what is represented by the component immediately downstream. The first component now sends information to the next component and changes certain internal variables associated with the receiving component. That component, in turn, sends another signal to the next component downstream to change that next component's internal variables. System behavior can, therefore, be described by this propagation of information around the system. FAVL calculates all these variable changes during a simulation run that a student initiates.

In addition to selecting and connecting components, students can set the initial value of the internal variables associated with each component. For example, a student can change the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

initial value of the room temperature for the controlled process that models a room in a home heating system.

A completed feedback system design for an on-off controller is shown in Figure 2-6 along with the graphical results of a simulation run for that design. An animation of the controlled process is also provided in the interface for a pictorial display of the dynamic behavior.

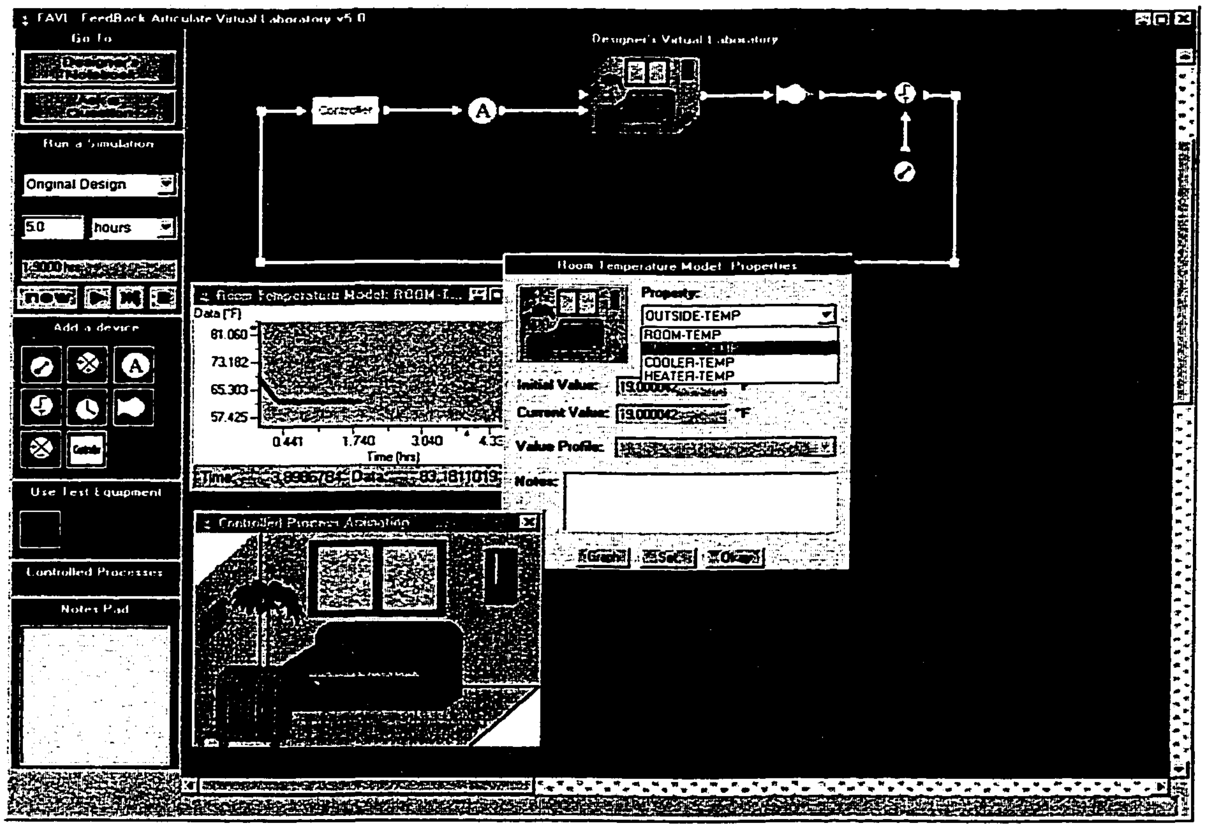


Figure 2-6. An On-Off Feedback Design for Regulating Room Temperature. This shows an on-off feedback system design in the Virtual Laboratory along with a graph of the room temperature and an animation window of the controlled process (the room), which is in the lower left corner of this screenshot. The window in the center shows the internal variables associated with the controlled process.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

To complement the numerical simulation, a rudimentary coach has been implemented in FAVL. Students can ask the coach questions such as

- 'What happened?' for a qualitative explanation of controlled process behavior, and
- 'How can I improve my controller?' for hints about what might be missing in the current design, how well the current design meets the design requirements, and for ideas on what to do next if the design is not meeting requirements.

An example of the coach is shown in Figure 2-7.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

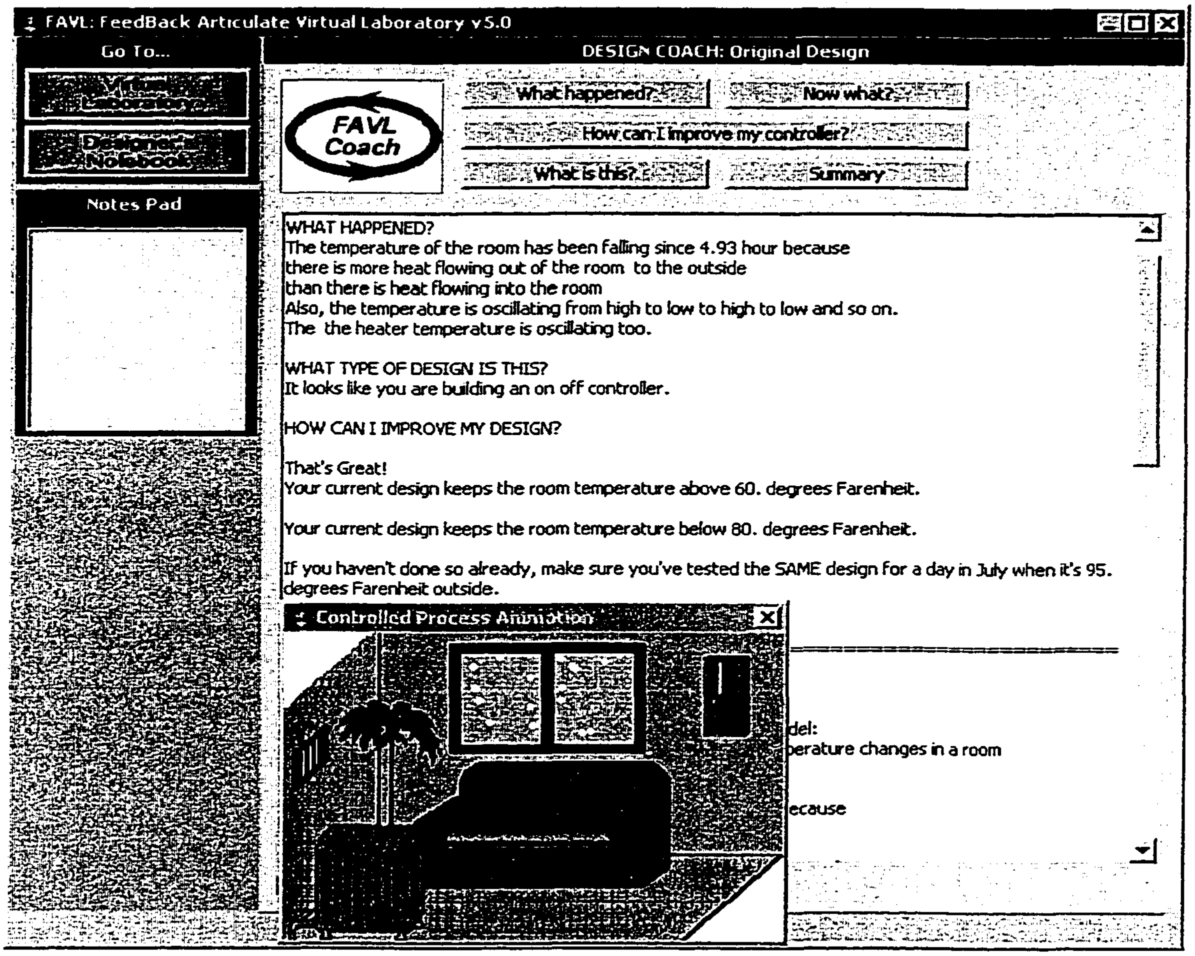


Figure 2-7. The FAVL Coach. This shows the results of asking the FAVL Coach 'What happened?' and 'How can I improve my controller?' after a simulation run of an on-off feedback system for regulating home heating.

In addition to the virtual design space, FAVL provides students with a virtual Designer's Notebook, a place where students can find relevant information about their design challenge including an overview of the design project, some background information about how these designs may be implemented in real life, the requirements that students need to meet for the particular design project, and a design plan that outlines recommendations for approaching the challenge. Figure 2-8 shows the layout of the Designer's Notebook.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

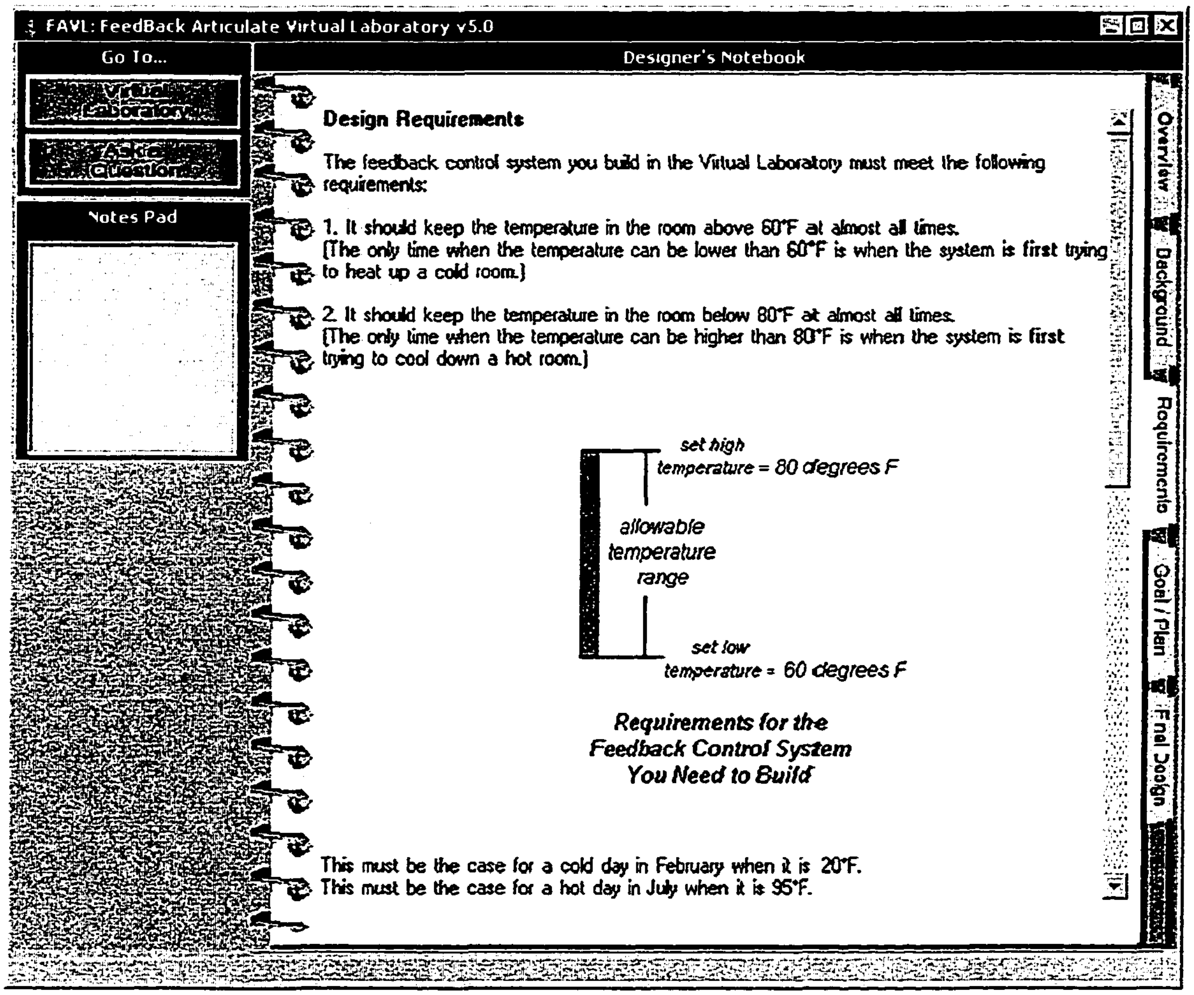


Figure 2-8. The Designer's Notebook. This screenshot shows the requirements section for the home heating and cooling control project. It lays out the detailed specifications that the student design must meet for this project.

2.3.2.2 FAVL's Relationship to Other Tools

Computational tools for exploring systems are by no means new, and many of the advantages listed for FAVL can apply to other tools as well. Packages such as MatLab and SimuLink have made systems modeling and analysis easier for the college students and professionals by providing a numerical tool to automate computation. More recently, software packages such

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

as Model-It, STELLA, and StarLogo have made systems exploration more accessible to pre-college students by allowing students to model systems in software and then run simulations to see how their systems behave over time. These tools have been used to encourage students to articulate, refine, and sometimes redefine their own ideas about the interactions in systems and to test their models by simulating their system's time varying behavior (Jackson, Stratford, Krajcik, & Soloway, 1994; Mandinach & Cline, 1994; Resnick, 1996). Research about these tools in educational use show varying results in helping students learn system behavior. (See Stratford (1997) for a review.) In many cases, these tools have been used to allow for deeper exploration of a particular content area (e.g., stream ecology) by allowing students to build systems.

Tools such as Model-It, STELLA, and StarLogo are in many respects general modeling tools that students can use to model a large set of dynamic phenomena. The power of these tools lies in their versatility and their expressiveness. Although each has a different underlying metaphor for the parts and interactions that occur within a system - STELLA is based on Forrester's conception of systems dynamics with an underlying metaphor based on flow and accumulation (Steed, 1992); Model-It carves up the world into objects, factors and relationships between them (Jackson et al., 1994); and, StarLogo is based on a cellular automaton and creature-colony model of systems (Resnick, 1996) - none of these models require a view of systems so closely tied to an expert's model. Instead, students are given a great deal of freedom, and, alternatively, little guidance within the interface to specify the nature of their building blocks.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

FAVL, on the other hand, is based on a specific conception of feedback systems that depends on functional decomposition and integration through signal propagation and transformation. Along these lines, then FAVL could be more aptly grouped with computer tools such as ThinkerTools designed by White (1993), the conceptually enhanced simulation tools designed by Snir, Smith, and Grosslight (1995), and Wiser and Kipman's HEAT & TEMPERATURE computer model (1995).[4] That is, the design of these tools is motivated chiefly by a desire to convey a particular conception of certain principles, whether Newtonian mechanics, volume and density, or heat and temperature. One way in which they try to accomplish this is by making the "unobservable into the observable"(Snir, Smith, & Grosslight, 1995) by giving abstract concepts a visual representation within the interface. For example, ThinkerTools uses arrows to represent momentum, and HEAT & TEMPERATURE uses dots to represent energy units. Likewise, FAVL reifies the abstract by representing the functional subsystems typical of feedback systems as components, or blocks, similar to those found in a traditional block diagram description, that can be added, deleted, and edited and that can be connected to each other to describe the signal flow within the system modeled. By asking students to design with the entities that experts use in describing feedback systems, FAVL aims to help students to see the common structures and behavior that underlie all feedback systems.

This is something that the other tools' flexibility may forfeit. That is, general modeling tools do not in and of themselves facilitate students' discovery and exploration of common principles or patterns of interactions that span different systems. So, although these tools

[4] FAVL also differs from these tools in one crucial regard. FAVL includes a coach that provides qualitative explanations of the interactions in the system and suggestions for design improvements.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

may facilitate a very detailed exploration of a particular phenomenon and a specific system, a student using these tools may never make connections between the different systems that they model to see their shared underlying structure. Instead, the models that students build can remain disparate explanations of phenomena.

2.3.2.3 The Design Principle Behind FAVL

FAVL's design is based on the principle of conceptual fidelity (Hollan, Hutchins, & Weitzman, 1984). That is, it makes evident in its interface the underlying conceptual entities that experts use to describe the domain. It does so by reifying the functions that are typically found in the construction of any feedback loop so that students can use these entities in their design work. The basic building blocks that students can add, delete, and connect in FAVL are, therefore, functional components, and not physical parts that are specific to a particular physical implementation. Beyond making the unobservable observable, FAVL also makes the functional abstractions manipulable; they become "objects, supporting exploration of possibilities and evaluations of relations" (Greeno, 1997, p. 13) and are posited to play an important, though currently unclear, role in orienting people's attention in situations .

What may be the advantages of a model built from key functional building blocks? One of the fundamental design assumptions behind FAVL is that by making these functional blocks available to students, students can work with the parts that an expert works with in thinking about feedback systems.[5] Furthermore, a uniform vocabulary of these relational terms may help students encode their experience with feedback systems in terms of these functions which

[5] Experts may, in fact, use many different levels of description to analyze and design a feedback system. This instructional model represents just one of these levels.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

transcend physical instantiations, instead of in terms of physical characteristics, which would change across system implementation. If they encode their designs according to these shared relationships, then students may be more likely to retrieve a previous feedback system to help them reason about a new feedback system. Like the comparison tasks described in Section 2.3.1 working with the relational entities in the FAVL interface may help students think about the feedback systems they analyze and build as sharing relational similarities that may not be apparent if students build physical models or use representations of specific physical parts. Design work with FAVL complements the comparison tasks that students do outside of the software by giving them a context for working with the functional parts of a system and by providing an opportunity to articulate the relationships between these parts which can then be tested through simulation.

This approach may also address the problems novices seem to have in seeing functional subsystems, a problem that is related to difficulties novices have in connecting physical structure to function. By providing students with the function divorced from any physical instantiation, FAVL offers easier access to ideas such as functional subsystems and information flow and processing.[6]

2.3.2.4 FAVL Design Projects

I defined a set of design projects that students can work on within FAVL to encourage students to explore different aspects of feedback system design and behavior. In this section, I

---

[6] In doing so FAVL sacrifices experiences students can have with linking structure to function, which is also a part of design work. (Future work on curriculum design may need to incorporate such experiences into student work.)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

will give an overview of these projects and their design rationale. This is done to give a flavor of the type of activities students do in FAVL and is not meant to be an exhaustive description. Additional descriptions about each design project can be found in Section 6.1.2, which provides a more detailed account of how students' designs evolved for each of these design projects.

Currently, there are four design projects available in FAVL[7]: 1) designing a home heating and cooling system, 2) modeling how a frog catches flies, 3) designing a cruise control system, and 4) designing an automatic collision avoidance system for a car. A brief description of each of these designs and the learning objectives of each are given in Table 2-4.

---

[7] Other designs can be added by ambitious curriculum designers who know how to program in Common LISP.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 2-4. FAVL Design Projects (continued on next page)

Design Project	Design Goal	Objectives
Home Heating and Cooling System	Design a system that will always keep the temperature of the house between 60°F and 80°F.	To explore the behavior of on-off control systems
Object Tracking System	Model a frog's fly tracking system. The model must allow the simulated frog to catch 10 flies in 10 minute. It must catch moving as well as stationary flies.	To explore • the behavior of proportional control systems • the relationship between the overshoot and the system gain • the relationship between the response time and the system gain • the use of feedback for object tracking as opposed to regulation around a constant value • using feedback to explain natural and not just technological processes
Cruise Control System	Design a cruise control system for a car that can meet strict requirements on overshoot, response time, steady state error, and settling time	To explore • the behavior of proportional control systems • the relationship between the overshoot and the system gain • the relationship between the response time and the system gain • the relationship between settling time and gain

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 2-4. FAVL Design Projects

Design Project	Design Goal	Objectives
Automatic Collision Avoidance System	Design a system that will automatically stop a car from plowing into the obstacle in front of it. Build this system on top of the cruise control system.	To explore • interactions between multiple feedback loops • the behavior of proportional control systems • the behavior of on-off control systems
Others	For the few students that finish all the above design activities, they can revisit their designs and add in other forms of feedback control including derivative and integral controllers.	To explore • the behavior of integral and derivative control systems

Students work through these projects one at a time in the above set sequence. With this sequence, students progress from one design project to the next along the following dimensions:

<u>Working from a partially completed design (which I give to the students) to defining a design from scratch</u>. For the first design project on home heating and cooling, students are given a heating control system, asked to simulate the behavior of that design, and asked to build from that design. This helps students become familiar with the parts and with experimenting with a partially working system. In latter projects, students are only given the controlled process and asked to build an appropriate set of feedback systems to control the behavior of that process to meet requirements.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Designing an on-off system to designing proportional control systems to designing systems with a mix of the two. In their work on QUEST, an intelligent learning environment designed to teach novices to reason about electrical circuits, White and Frederiksen (1990) proposed that developing expertise in a field involves refining, differentiating, generalizing and sometimes even completely changing mental models. Presenting students with a progression of models that become more and more elaborate and detailed can help students with this process of model transformation. One of the dimensions of progression that White and Frederiksen proposed is in the order of the relationships embodied in the different electrical components. That is, students should first reason about binary states and then reason about incremental changes within a circuit. I adapted this design principle to the sequencing of the FAVL design projects. I assumed that students would have an easier time reasoning through the behavior of an on-off system as opposed to a proportional system. This is because behavior in an on-off system can be more readily analyzed in terms of discrete state transitions in each of the components (e.g., is the furnace on or off, is the temperature too high or too low), whereas reasoning about proportional systems may require first-order qualitative reasoning about values (e.g., the error signal is increasing and the amount of gas supplied to the engine should be increasing proportionally).

Working with a given, detailed design plan to defining one's own design plan. In order to help familiarize students to FAVL, I gave each student a plan (i.e., a set of design steps) for the initial design projects. The design plan for the first project is quite detailed, but these plans become more open-ended with each successive project. This was done to encourage student

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

exploration and creativity while providing scaffolding for FAVL use. The design plan for the first set of projects can be found in Appendix C.

Despite the many advantages of situating learning within design activities, design requires content and strategy knowledge that many novices do not have. Therefore, when necessary, I would provide guidance for thinking about the design problem as well as answer student questions about software features. This included interpreting requirements that students might not understand, helping students troubleshoot, and otherwise tutoring students when necessary.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3 Study Design – An Overview

This chapter presents background information on the study's participants and describes the sequence of student activities. These descriptions are outlines only and serve mainly to help orient the reader. More detailed descriptions of the students, the activities, and the data collected are provided in the corresponding analyses in the chapters to follow.

3.1 Participants

The data for this study were collected over two summers from 30 high school students who volunteered to come to Northwestern University to work on this research project. Fifteen students participated in summer 1999. These students constituted the "FAVL" group of students who worked through the entire nine-hour sequence spread out over 6 days. The final day, which is spent on the post interview, was always scheduled after a weekend break. Another fifteen students worked with me the following summer; however, this second group did not do any design work within FAVL. Students in this "Non-FAVL" group came to Northwestern University for 4.5 hours over a three-day stretch with the last day scheduled a week after their start date.[1]

[1] This study design raises time-on-task issues when contrasting learning gains between the FAVL and Non-FAVL groups. The case studies presented in Chapter 6 are used to show that FAVL students were learning to refine the model beyond what was taught in the Model Instruction portion of the curriculum.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

I solicited student participants for the two summers through the same teacher contacts and similar flyers posted at local schools and libraries in the Chicago/Evanston area. As it turned out, most students who volunteered were academically tracked students who had taken some honors courses in high school. (See Table 3-1, Table 3-2, Table 3-3, and Table 3-4.) All students were paid for their time. Note that pseudonyms are used to identify the student participants here and throughout this dissertation.

Table 3-1. Science Classes Taken by FAVL Group Participants

FAVL Group								
Student	*Grade Completed*	*Earth Science*	*Biology*	*Chemistry*	*Physics*	*AP Biology*	*AP Chemistry*	*AP Physics*
Becky	Freshman		Honors					
Curtis	Freshman				√			
David	Sophomore		Honors	Honors	Honors			
Peter	Sophomore		√	√				
Phillip	Sophomore		Honors					
Alice	Junior		Honors	Honors	Honors			
Anna	Junior		Honors	Honors	√			
Irene	Junior		Honors	Honors	Honors		√	
Nancy	Junior		Honors	Honors	Honors		√	
Yvette	Junior		Honors	Honors	Honors	√	√	√
Cheryl	Senior	√	Honors	Honors	√			
Gus	Senior		√	√	Honors			√
Lee	Senior		Honors	Honors		√	√	√
Max	Senior				√	√	√	
Randall	Senior	Honors	Honors	Honors	Honors			

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3-2. Science Classes Taken by Non-FAVL Group Participants

Non-FAVL Group								
Student	*Grade Completed*	*Earth Science*	*Biology*	*Chemistry*	*Physics*	*AP Biology*	*AP Chemistry*	*AP Physics*
Collins	Freshman		√					
Valerie	Freshman		Honors					
Aaron	Sophomore		Honors	Honors				
Loni	Sophomore		Honors	Honors	Honors			
Susan	Sophomore		Honors	Honors	Honors			
Tracy	Sophomore		Honors	Honors	Honors			
Charles	Junior		√	√	√			
Elliot	Junior		Honors	√	√			
Kimberly	Junior	Honors	Honors	Honors				
Lily	Junior		√	√	√			
Nathan	Junior		Honors	Honors	Honors		√	
Nicole	Junior		√	√	√			
Ursula	Junior		√	√	√			
Rory	Senior		Honors	Honors	Honors		√	√
Rose	Senior		Honors	Honors	Honors		√	√

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3-3. Math Classes Taken by FAVL Group Participants

FAVL Group						
Student	*Grade Completed*	*Algebra*	*Geometry*	*Algebra 2 /Trig*	*Math Analysis/ Precalculus*	*Calculus*
Becky	Freshman	√	Honors			
Curtis	Freshman		√			
David	Sophomore	Honors	Honors	Honors		
Peter	Sophomore	√				
Phillip	Sophomore	√	√			
Alice	Junior	√	Honors	Honors	Honors	
Anna	Junior		√	√	√	BC
Irene	Junior	Honors	Honors		√	
Nancy	Junior		Honors	Honors	√	
Yvette	Junior	√	Honors	Honors	√	BC
Cheryl	Senior		√	√		AB
Gus	Senior		Honors		√	BC
Lee	Senior	Honors	Honors		√	BC
Max	Senior	√	√		√	AB
Randall	Senior	√	√	√		AB

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3-4. Math Classes Taken by Non-FAVL Group Participants

Non-FAVL Group						
Student	*Grade Completed*	*Algebra*	*Geometry*	*Algebra 2 /Trig*	*Math Analysis/ Precalculus*	*Calculus*
Collins	Freshman		√			
Valerie	Freshman			Honors		
Aaron	Sophomore	√	Honors			
Loni	Sophomore	√	√		√	
Susan	Sophomore	Honors	Honors	Honors	Honors	
Tracy	Sophomore	Honors		√	√	
Charles	Junior	√	√	√	√	
Elliot	Junior	Honors	Honors		Honors	
Kimberly	Junior	Advanced	Advanced			
Lily	Junior		√	√	√	
Nathan	Junior	Honors	Honors		Honors	
Nicole	Junior	√	√		√	
Ursula	Junior		√	√	√	
Rory	Senior		Honors	Honors		BC
Rose	Senior		Honors	√	√	BC

3.2 Activity Outline

The study's design can be broadly partitioned into five sections: Pre-Instruction, Model Instruction, Intermediate Interview, FAVL Design Projects, and Post-Instruction. The Model Instruction and the FAVL Design Project sections serve an instructional purpose. To reiterate, Model Instruction is designed to help confer an understanding of the parts and interactions that define the expert model for feedback systems. The comparison activities that are used as part of the Model Instruction are intended to help students highlight relational similarities shared by all feedback systems, learn the relational abstraction that define the expert model, and see

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the common structure that underlies in all feedback examples. The FAVL Design Projects are designed to help students develop a deeper understanding of how the parts and their interactions give rise to feedback behavior. The rationale behind the design of the Model Instruction and the FAVL Design Projects is described in Chapter 2. The Pre- Instruction, the Intermediate Interview and the Post- Instruction sections of this study were designed to probe for students' changing understanding, and they are summarized here.

Pre-Instruction	**Model Instruction** (Described in Section 2.3.1)	**Intermediate Interview**	**FAVL Design Project** (Described in Section 2.3.2) *4 ½ hours*	**Post-Instruction**
			No Activities for Non-FAVL Group	
1 ½ hours	*½ hour*	*¾ hour*		*1 ½ hour*

Figure 3-1. Sequence of Activities. The time spent on each section is an approximation only.

3.2.1 Pre-Instruction

This portion of the study was designed to help characterize initial student understanding of feedback systems. Both the FAVL and Non-FAVL group of students work through the pre-instruction activities.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3-5. Pre-Instruction Activities and Accompanying Materials.

Pre-Instruction Activity	Material
One-on-one semi-structured interview about home heating	Appendix D
Watch and describe an animation of a water level regulation system.	Appendix G.1.1
Compare a home heating system to the water level regulation system.	Appendix G.1.2
Answer a set of multiple choice questions regarding a feedback system	Appendix E
Create a model to explain eye pupil dynamics	Appendix F
Answer a set of multiple choice questions regarding a home heating system	Appendix E

3.2.2 Intermediate Interview

The intermediate interview followed the Model Instruction activities and provides an intermediate measure of student understanding for both the FAVL and Non-FAVL groups. These activities are summarized in Table 3-6.

Table 3-6. Intermediate Interview Activities and Accompanying Materials.

Intermediate Interview Activity	Material
Answer a set of multiple choice questions regarding a humidity regulation system	Appendix E
Compare three systems, one pair at a time.	Appendix G.2
Identify the feedback system from among three examples.	Appendix G.2
Map feedback system examples to model template	Appendix G.2

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.2.3 Post-Instruction

After working on design projects in FAVL, the FAVL group was asked to work through a set of post-instruction activities. The Non-FAVL students were asked to return for the post-instruction activities one week after completing the intermediate interview. These post-instruction activities were designed to capture student understanding after the instructional sequence.

Table 3-7. Post-Instruction Activities and Accompanying Materials.

Post-Instruction Activity	**Material**
Answer a set of multiple-choice questions regarding a feedback system.	Appendix E
Create a model to explain eye pupil dynamics	Appendix F
Answer a set of multiple-choice questions regarding a home heating system.	Appendix E
Compare three systems, one pair at a time.	Appendix G.3
Identify the feedback system from among three examples.	Appendix G.3
Map feedback system examples to model template	Appendix G.3

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4 Characterizing Student Understanding of Feedback Systems

The purpose of this chapter is to characterize the ways in which students understand feedback systems with a particular focus on how students construct explanations of system behavior. I use two different methods to look at students understanding: First, using the expert model as a basis, I characterize student understanding according to the nature of the parts and the relationships between the parts that they use in constructing system predictions and explanations. A progression of model types with increasingly detailed parts specification that correspond to increasingly sophisticated levels of explanation is proposed as one way of characterizing student understanding of feedback systems and capturing change before and after instruction. Second, I analyze students' answers to multiple-choice questions regarding the parts and interactions for a set of feedback system examples. Student scores, coupled with a talk-aloud protocol analysis, afford a closer look at how students reason about a system when they are given a description of the functions and interactions of that specific system.

Analyses using these measures indicate that students use more sophisticated models in their system explanations after instruction and can generate more detailed explanations once they understand the constituent parts of the feedback system. Furthermore, the multiple-choice test analyses reveal that students use a variety of relationships, correct and incorrect, to reason

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

about system behavior and that some of these relationships appear stable, changing little between pre and posttests. Some of those relationships are incorrectly used and are inconsistent with the other interactions students describe for the same system example, suggesting the potentially piecemeal construction of answers that are based on a stable set of relationships students see within feedback system examples. Learning to understand a feedback system, therefore, does not only encompass learning its functional subsystems but also learning to integrate a set of relationships into a coherent whole to explain all the different types of behavior, short term and long term, of the system.

4.1 Theoretical Framework

Understanding a dynamic system includes the ability to generate explanations and predictions of a system from its constituent parts. As such, I will begin to describe the nature of student understanding in terms of mental models. A mental model is an internal model that people form of their world to "provide predictive and explanatory power for understanding ... interactions" (Norman, 1983, p. 7). Researchers have advanced various theories about the nature of these mental models regarding their construction (e.g., (Collins & Gentner, 1987) and (Vosniadou & Brewer, 1992)), the nature of their underlying representations (e.g., (Larkin, 1983), (diSessa, 1993), and (Chi et al., 1981)), and the stability of the underlying cognitive structures that make up these models whether they be coherent and systematic like theories (e.g., (McCloskey, 1983) and (Samarapungavan, 1997)) or fragmented (diSessa, 1993; Forbus & Gentner, 1986). The primary purpose of this work is not to address these fundamental and as yet outstanding issues on the nature of mental models in general. This study, however, does adopt the following theoretical assumptions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

A mental model can be defined by its constituent entities and the interactions between the entities. The entities are hypothesized to "determine the kinds of information that are available for reasoning" (Greeno, 1983, p.228) and to remain stable throughout an explanation of a system. Although they can be constructed during an explanation, once constructed, they are not deleted from the explanation. These entities are akin to the conceptual entities proposed by Greeno (Greeno, 1983) and are most similar to the autonomous objects posited by Williams, Hollan, and Stevens (1983). That is, they are divisions of the system into parts that have some independence in that they hold internal parameters and explicit states but are linked to other parts of the model through interactions that can change these internal states. It is the interactions, or relationships, between these entities that give rise to the dynamic behavior of the model (Williams et al., 1983) although different relationships between the parts can become obscured, highlighted, and altered depending on the question being asked about a system.

A mental model is constructed on the fly to provide answers to specific questions regarding a particular system at hand. As such, the entities and interactions that make up a mental model are partly tied to the particular problem context and specific to the feedback instantiation if not the particular questions being posed within a problem context. Nonetheless, mental models for different feedback instantiations can be characterized and categorized according to the nature of their constituent parts and their interactions. In fact, part of learning the expert model involves aligning a particular feedback example with a common structure. One of the assumption of this study is that as a student's mental models of a feedback example begins to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

align with the expert model, the model becomes more inferentially powerful and allows the student to give more detailed and accurate explanations of system behavior.

Learning to align a mental model to an expert's definition does not involve replacing a naïve model with a new and improved model, wholesale. Instead, I posit that this process leaves many of the relationships of the previous model intact. Change is a gradual process and entails a series of model transformations through "addition, modification, differentiation, or generalization of model features" (White & Frederiksen, 1990, p. 105). In particular, transformation towards the expert model of feedback includes a process of differentiation of the systemic whole into its constituent subsystems and an integration of those subsystems according to, predominantly, causal interactions between those parts. Learning also includes a process of generalization in which a student comes to see the commonality of the functional subsystems and interactions across different feedback examples.

In the following analysis, I will define a sequence of mental model types according to increasing differentiation of system parts that describe students' progression towards alignment with the expert, or canonical, model. The classification scheme proposed is defined according to the different types of entities that make up student models and the corresponding behavior explanations. Using the canonical model in this analysis also provides a means to assess student learning from the instructional material.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4.2 Classes of Mental Models of Feedback

In this section, I will define a set of mental model classes for describing feedback systems and apply those classifications to students' explanations before and after instruction to gauge changes in understanding. These categories find some basis in prior work done by Mioduser et al (1996) on elementary school students' understanding of simple open/close systems. These open/close systems are characterized by a similar set of functions as for feedback systems including a sensor, an actuator, and a controller, and, therefore, their model types served as a check for the categorization scheme presented here for feedback systems.

4.2.1 Method

4.2.1.1 Activities and Material

For this portion of the study, I collected data during pre and the post instruction in the form of clinical interviews. These are highlighted in Figure 4-1 and are described below. Each student's explanations were recorded and transcribed for analysis.

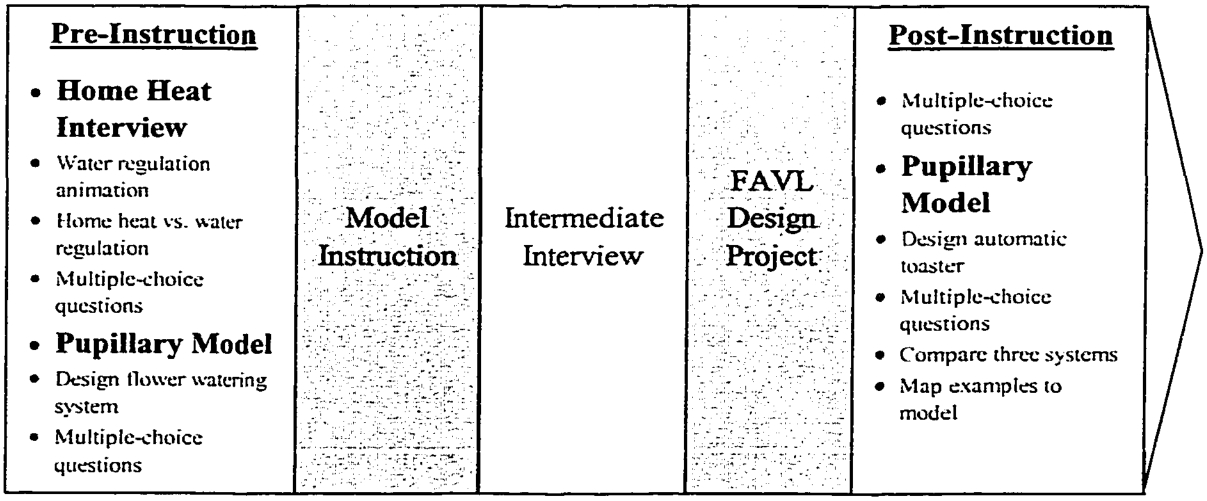


Figure 4-1. Sequence of Pre and Post-Instruction Activities

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Pre Interview. I conducted one-on-one interviews with high school students on two example feedback systems, a home heating system and an eye pupil control system. For the home heating system, I encouraged students to talk about how they think a house or a room in a house manages to stay at a comfortable temperature when it is cold outside. For the pupillary control system, I asked students to read a short paragraph taken from the Encyclopedia Britannica on how the pupil size changes over time when lights are turned on in a previously dark room, and then to explain the dynamic behavior of the eye.[1] These interviews were semi-structured, guided by a common set of questions outlined in Appendix B and D. The initial questions were left intentionally open-ended to avoid biasing students to predetermined models. However, I did use more directed questions to prompt students, as necessary, as the interviews progressed. These questions were used when appropriate during the interview to try to distinguish between models I felt that the student may be describing. These questions and the models that they helped discriminate are described in the analysis section.

Post Interview. As part of the post interview, I asked students to revisit the eye pupil system that they first encountered as part of their pre-instruction interview. They were asked to reread the description of how the eye pupil changes when exposed to bright light and then to try to explain the changes. After their initial description, I asked students to try to draw a diagram using the parts that they have learned since their pre interview as best they could and then to try to use the diagram to explain the behavior if possible. This interview was designed

[1] Note that the eye pupil responds to a step increase in ambient light by first overshooting and then settling to its setpoint value. This kind of response is typical for many systems that can be approximately modeled as a proportional feedback control system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

as a posttest measure that can be compared to the pretest results to assess learning in terms of behaviors explained and parts used in their explanation.

4.2.1.2 Coding Procedure

The videotapes of the home heating and pupillary interviews were transcribed for analysis. To develop categories of mental models, I masked the identity of each student's explanation by randomly assigning a unique numerical tag to each transcript and accompanying diagrams that each student drew for the home heating interview and for the pupillary system interview. I scrubbed the beginning and end of each pupillary system transcript to remove phrases that would indicate if the interview was part of the pre or the posttest. I then read through each transcript and coded for the functional parts they described and the type of behavioral explanations they gave.

In particular, I looked for examples of functional subsystems that aligned with those of the canonical model. If a student had detailed mechanical knowledge of a system, which was more likely the case in the thermostatic control system than in the pupillary control system, I looked not only for description of mechanism but some articulation of its functional role within the system. Specifically, I looked for

- explicit identification of the part by name followed by some explanation of its function within the system. The name can be a general term or a term specific for that feedback example.
- a description of the function necessary in the system,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- or a detailed description of the specific parts that make up that function within the instantiation.

In addition, I looked to see how students explained different types of behavior for the two systems. For the home heating system, I focused on 1) how students explained fluctuations around the set temperature value, 2) what students predict would happen with a degraded furnace, and 3) how students explained the rise in temperature to the steady state value. For the pupillary control system, I looked at how students explained 1) the damped oscillation behavior and 2) the continuous oscillation (known as hippus) described in the Encyclopedia Brittanica's article on the dynamic behavior of the eye.

I then assigned a model class to each student interview according to the most detailed level of description the student gave that used the parts they enumerated to explain behavior. Note that student models that listed parts but did not describe what the parts did or how they relate to other parts to explain system behavior, were coded according to the level of explanation provided for system behavior and not according to the parts enumerated. The categories of mental models including the parts described and the behaviors explained are described in Section 4.2.2 along with examples to help clarify the coding scheme.

4.2.2 Model Classes - Definitions

The home heating and the pupillary control interviews provided a detailed and extensive set of data for understanding student models. Transcripts of each student's clinical interviews as well as any accompanying drawings and graphs from these interviews were analyzed for

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

common patterns. A categorization scheme of model classes that generate different levels of explanations evolved over several coding iterations where a candidate code was applied to the data and subsequently refined.[2] After repeated coding, I defined a progression of model classes, ordered according to the level of detail each provides in explaining system behavior. Table 4-1 summarizes these model classes. In what follows, I will describe in detail each of these classes and give examples from the data to illustrate how these classes are manifest in students' descriptions of the home heating and pupillary control systems.

Table 4-1. Summary of Model Types for Feedback Systems (continued on next page)

Model Class	Description
System as Whole	The feedback system is described without any internal details beyond possibly the type of action that is taken in response to an outside stimulus, and the focus is on the overall system instead of the internal interactions that can explain its behavior.
Boundary	This model type is characterized by the addition of a sensor and a more defined actuator function. Students with this model suspect that the system takes readings of its environment; however, any further internal details are lacking.

[2] The final coding scheme emerged after several iterations where a candidate scheme was defined, applied, and refined until the coded results began to converge. At that point, I asked an undergraduate work-study student to apply the coding scheme over 60% of the data set. This yielded an inter-rater reliability value of 80%. Most discrepancies were resolved through subsequent discussion. However, the discussion also revealed difficulties in distinguishing the comparator and the controller parts from a more general regulator part in student models. Consequently, I revised the model categories to eliminate this distinction, which may exist in the expert model, but which we could not reliably detect in student descriptions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4-1. Summary of Model Types for Feedback Systems

Model Class	Description
Connected Internal Parts	In addition to a sensor and an actuator, students with this model articulate a function or process that makes decisions about what action to take. However, there is limited specification about how this regulator works or the algorithm used to make its decision. The internal interactions between the sensor, regulator, and actuator explain the system's adjustments to changing environmental conditions.
Algorithmic Regulator (most similar to expert model)	This model type is characterized by an algorithmic description of the regulator process. Student with this model also articulate a sensor and an actuator function. With this added level of detail, students can start to explain and distinguish between damped and continuous oscillations.

4.2.2.1 System as Whole

The feedback system is described without any internal structural or functional subsystems beyond possibly the type of action that is taken in response to an outside stimulus. The reaction that students describe is very roughly related to the actuator function within the canonical model, but this description is rarely a mechanistic description of what performs the action but rather is simply the action, or reaction to an outside stimulus. For example, in the case of the eye pupil, the reaction is the contraction of the pupil to strong light and not the movement of the iris that leads to the contraction.

Students whose descriptions fall under this model class are focused on the overall system behavior: They identify the overarching regulatory purpose of these systems. The interactions articulated consist of relationships between the system and its environment that

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

cross system boundaries, instead of internal interactions that give rise to the adjustment behavior. This model type corresponds to Miosuder et al 'black box' model (Mioduser, 1996).

Home Heating System

For the home heating system, students with this model identify the system's regulatory purpose but do not give any details on how that regulation is achieved within the system. Explanations, if any, of how regulatory behavior arises come from a sense that the "right" amount of heat is supplied to the room, and the more heat that is supplied to the room, the hotter it becomes. However, there is nothing within these students' explanations that indicates how it can adjust to changes in the environment. Becky, for example, was one student whom I coded as having a system as whole model:

> Interviewer: So does it stay around that comfortable temperature?
> Becky: Yeah
> Interviewer: How does it do that?
> Becky: You just put the thing on whatever you want.
> ...
> Interviewer: So how do we get that [getting it to stay at the temperature you set it at] to happen?
> Becky: I don't know. Hire somebody to do it for you.
> ...
> Interviewer: Can you make a guess as to what that person did?
> Becky: Uh
> Interviewer: How does that thing work?
> Becky: Well he probably just. Umm. I guess if you keep on doing the same thing, it'll stay at the same place. If you just like put on a fire and you just stop adding logs or whatever you add to fires, then it'll eventually get lower again.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Also, later in the interview when I asked Becky what would happen if the furnace were not working properly and were producing less heat, Becky answered:

> Becky: I think it would just be lower. It would move down to like 65 [when the thermostat is set to 70°]. You know. And, it'll just stay at like 65.

This answer is consistent with Becky's earlier explanation based on the relationship that more heat means higher temperature. Note that in an actual home heating feedback system, the temperature would rise to 70° albeit more slowly because the system would monitor the room temperature and continue to add heat until it reached that temperature. Although the qualitative proportionality is correct, when embedded within the larger set of internal system interactions, the conclusions should be different.

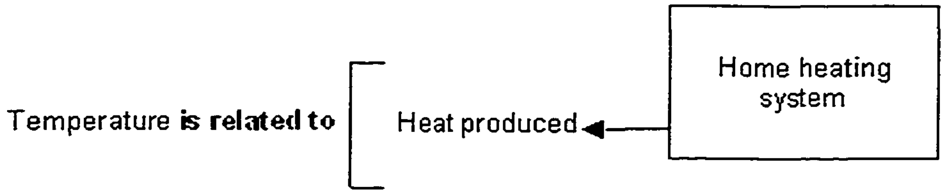


Figure 4-2. The System as Whole Model for Home Heat Control. In this model, a stable temperature is achieved by producing the right amount of heat. There are no internal details of how the system determines the correct amount to produce.

Pupillary Control System

For the pupillary system, this model class manifests itself as a system that as a whole changes with changes in its environment. As with explanations of home heating systems, student descriptions of the pupillary system often include the overall purpose of the pupillary system, in this case, of keeping the light coming into the eye at an acceptable level or more simply to help the person see. However, there is less focus on the need to maintain a desired value and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

more focus on the adjustments the eye makes to the ambient light. Steady state and transient behavior are explained as either adjustments to continuously changing ambient light levels or a vague notion of acclimation, but there are no details about the internal functions that explain the continuous adjustment, nor are there details about the acclimation. The following excerpt is taken from a student who I believe held a system as whole model type.

> Becky: So like if it were dark then it'll get bigger so that they'll be able to see more. And then when it's lighter you don't really need to strain to make them bigger. You just have it like keep small.
>
> ...
>
> Interviewer: Why does it like get small? And why does it, especially after it's gotten small, it kind of opens up again? And why does it then oscillate a little bit? That's kind of like weird isn't it?
>
> Becky: Well I guess the lighting like maybe the lighting is not always perfect.
>
> ...
>
> Becky: Or maybe even if it's like you're watching like something and like there's like a lot of movement.
>
> Interviewer: Uh huh
>
> Becky: Or something like that.
>
> Interviewer: Uh huh why would that
>
> Becky: because of different lighting or something.
>
> Interviewer: Okay, so the lighting may be different?
>
> Becky: and it could be like block illumination coming through. So you could like, so if you're like at a party or something and they have like strobe lights and like
>
> Interviewer: oh ok.
> What if the light level stayed the same, would you see something like this? Would you see this oscillation thing?
>
> ...
>
> Becky: I could see why it wouldn't stay exactly the same because it's there's always going to be like different shadows or different things moving.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

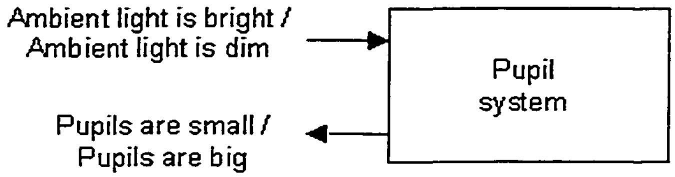


Figure 4-3. The System as Whole Model for Pupillary Control System. In this model, the pupil responds to the ambient light condition. There are no details of the internal workings that explain its reactions.

4.2.2.2 Boundary

Students describe the system as having the ability to measure a condition within the environment, similar to the sensor function in the canonical model. However, there is no explicit regulator which connects this sensing function or mechanism to the resulting reaction and which determines the amount of action that the system should take. Although the sensor and the actuator functions are now identified, their interactions are vaguely described. This model type corresponds to the 'reactive' model in Miosuder et al. study (1996).

Home Heating System

For the home heating system, this means that there is now something that can measure the room or house temperature as well a heater or furnace that heats up the house. Note that adopting this model does not necessarily invalidate the key relationships in the systemic whole model: A comfortable temperature is maintained by generating the 'right' amount of heat for the room, and more heat translates to a higher temperature. What does begin to change with this model, however, is the focus of attention, which begins to shift to how the system can keep the room at the desired temperature. Kimberly is an example of a student whom I categorized as having a boundary model for home heating.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Kimberly: How does the heating system work?
I don't know. It probably heats up like gas or something like that. I guess you could use gas stove or something like that. And it circulates warmer air through the house.
Interviewer: Ok. So it circulates warm air through the house. And the house gets What happens to the temperature in the house?
Kimberly: It would go up.
Interviewer: Uh huh. Then what happens?
Kimberly: And then they try to keep it at the same temperature that you want it to be or something.
...
Interviewer: So somehow
Kimberly: It could read the temperature in the house or something. I don't know.

Because the complete set of interactions is not clear within the model, when I asked Kimberly what would happen if the heater were working at only 75% capacity, Kimberly, like Becky, answered:

Kimberly: It'll get lower.
Interviewer: It'll get lower. Ok. Can you make a guess how low it might get?
Kimberly: Like a quarter lower than what it was.

That is, the temperature is proportionally lower. Even though there is a sensor that measures the temperature in the house, within Kimberly's explanation, she has not yet make the connection between the temperature measured and the amount or duration of the action to be taken.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

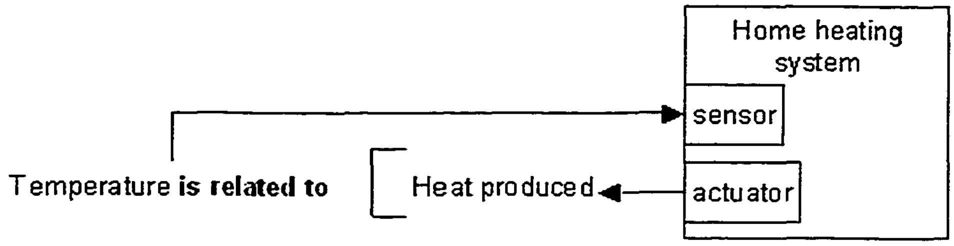


Figure 4-4. Boundary Model for the Home Heating System. The system description includes a sensor and an actuator function.

Pupillary Control System

For the eye pupillary system, students who I believe have this model type describe something within the eye that detects the light and consequently changes the pupil size. Although they can begin to associate behavior to the different internal parts of their system model, because the relationships between their parts remain unclear and unspecified, it is difficult to generate a causal story for the behavior. Notice in the following excerpt that Aaron only identifies the sensor and the actuator and attributes behavior only to these two entities.

> Aaron: Light enters through the pupil and after going through the lens and stuff like that, then it finally deflects off the retina. I think, I'm not sure if it's the cones or the rods. I think it's the rods. They sense light and then judging on how much light is sensed by the receptors, the pupil either expands or contracts by way of the iris which is the color of the eye. It let's in difference amounts of light.
>
> ...
>
> Interviewer: Why do you think that it, when he first turns on the light, why do you think there's that constriction and then there's that expansion?
>
> Aaron: Maybe because the light differs from the darkness after its initial constriction of the pupil. But then it gets used to it, I guess. And then the pupil once again increases.
>
> ...

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Interviewer: Why in constant light does it go back and forth?

Aaron: I guess this would be...the pupil size gets smaller, bigger, smaller and bigger. I'm just guessing that if it differs greatly which is exaggerated, then hippus might be caused by constant dramatic changes in the modified light to the eye.

Interviewer: What if it was constant light outside? Does your explanation still hold?

Aaron: I think so. It says during study condition, the pupils do not remain at the exactly constant size. There is a dramatic oscillation in size. It's called hippus. If the amount of light outside is constant, then I'm guessing according to the definition of this, the pupil size increases and decreases which causes hippus. Assuming hippus is caused by dramatic differing light.

Interviewer: Why do you think

What might be wrong with the eye to cause that to happen?

Aaron: I guess there's something wrong with either the location or the number of receptors on the retina.

Interviewer: How so?

Aaron: I'm not sure. I don't even see how that would work but I can't think of anything else. Maybe there's something wrong with the iris.

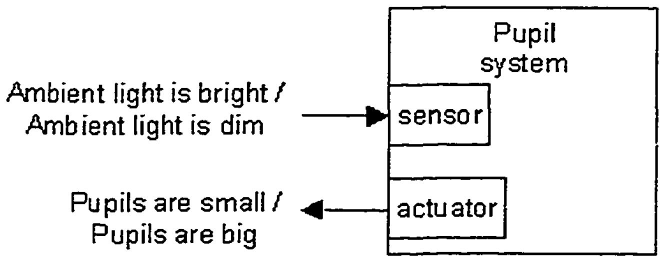


Figure 4-5. Boundary Model for the Pupillary System. The description includes a sensor and actuator function.

4.2.2.3 Connected Internal Parts

The feedback system is described as consisting of a regulator as well as a sensor and an actuator. Students with this model articulate a function or process that makes decisions about

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

what action to take but there is limited specification about how the regulator works or any descriptions about the algorithm used to make this decision. In some cases, the regulator function is further differentiated into a comparator and a controller where the comparator is described as the function that determines what is missing, or the discrepancy between the current and the desired state of the system, and the controller is the function that uses that discrepancy to decide what action the actuator should take. However, it is difficult to identify a reified comparator within the protocol, especially before instruction; instead the comparator function often is embedded within the description of the algorithm. Because of the difficulty in distinguishing the comparator from the controller, I do not make the finer distinction within model definitions.

Home Heating System

Student models that fall in this category include descriptions of the interactions between the internal parts that give rise to the output of the feedback system. Their interactions are often a narrative account starting from a change in an outside condition to the reaction the system takes in response to the environment. Although these accounts can include detailed mechanistic accounts with physical parts particular to a system instantiation, they can also include accounts of a more general nature where physical mechanism is encapsulated within a 'function' placeholder. For example, sometimes students who are unfamiliar with how a thermostat works, nonetheless, point out that there must be something that senses the temperature and decides what to do.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

To reason through time varying phenomena such as oscillations, some students account for changes in the system over time through multiple iterations through the feedback loop. This can include tracking how a variable changes over several iterations of the feedback signal or through a causal account of changes in the feedback system's parts. Note that not all students use cycle-by-cycle accounting. Consequently, their explanation of time varying behavior are vague and still depend on a sense of acclimation to the environment even though they have the internal details for how the action amount is determined from environmental readings.

With the home heating system, the regulator now connects the sensor to the heater and determines how much heat to produce. The following excerpt is from a student who held the internally connected model:

> David: I believe there is a boiler in my basement where there's a little flame under a huge tank or something
> and somehow through little ducts in my house either the steam or something the energy of the water is transferred through all the ducts and kind of comes up through the bottom of the floor, you know.
> ...
> David: I guess it does all the measurement of how much heat it needs to put in there for the house to stay at that temperature. It's got thermometers all over the place.
> ...
> Interviewer: Why does it go up and down?
> David: because heat is being released and I'm sure it can't perfectly calculate when, you know, how much heat is being
> released. And I'm sure it's not at a very constant rate so at points it'll need to use much more energy to get it back up to
> Say somebody walks in with a big ice cube and it cools off the house, it would need to kind of heat it up.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Some students now see the system as effecting a type of balance to maintain the set temperature within the house or room:

> David: It's balancing the the heat.
> Interviewer: The heat?
> David: I guess it's balancing the loss of heat and the gain of heat. So it's staying at, you know, the correct area or temperature that it wants.
> Interviewer: Ok, so the loss of heat
> Where is the heat going?
> David: going to the environment. It's going out of my house and possibly a little bit is going into things, but most of it is going through the tiny cracks in my house out into the outside.
> Interviewer: Where is it coming from?
> David: it's coming from the energy created I guess when the water is boiling.

Compared to students who had the systemic whole or boundary models, some students now give a different prediction when asked what happens to the temperature for a system with a degraded heater. For example, at first David responds:

> David: The temperature of the house is going to go down and you'll be colder then.
> Interviewer: Why would the temperature of the house go down?
> David: because when the thing
> When it works at 75% you want it
> You set it at 68 and it's only going to get 75% of 68 [starts to write number and make calculations] which would be about
> I might be right. I don't know, 50.25 degrees.

Later, after he begins to describe a regulator function, David begins to become uncertain of his original prediction:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

David: I don't think that 50 thing would be right because I guess any heater if it could it would try to keep it at 67 the whole time. Maybe that would be very inefficient because the energy use output would give you a very big electrical bill, the heating bill.

But, he then goes back to his original hypothesis that the room temperature will be 75% of the set temperature if the furnace is operating at 75% capacity. Other students (three out of the other five) who have this model do not equivocate, but instead argue that the heater would continue to work as long as the room temperature is below the set value.[3] The difference is not the final temperature but the rate of change:

Randall: Well, it would still probably reach the right temperature but it would take longer.
Interviewer: ok
Randall: because there would be less hot air coming out each time so the rate would be less so therefore it would just take longer to get up there.

It seems that even if there is a connection between the sensor, the regulator, and the actuator, predictions regarding the system's behavior are not always based on the relationships between all these parts but can be based on local relationships (e.g., less heat leads to a colder room) without consideration for the constant correction that occurs when the part interactions are seen over time and embedded within the larger system.

[3] Some of these students are unsure because they do not know how well insulated the house is, but once I tell them to assume that the house is well insulated, they answer that the system will reach approximately the same temperature if given enough time.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

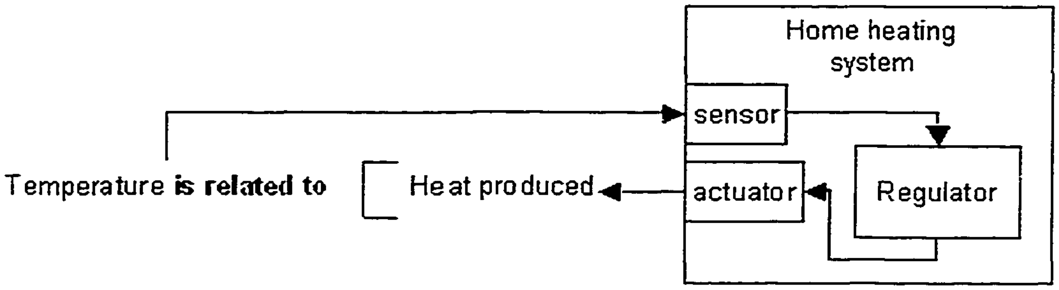


Figure 4-6. Connected Internal Parts for the Home Heating System. The description includes a regulator function as well as a sensor and actuator. The regulator determines the appropriate response to what is sensed.

Pupillary Control System

With the eye pupil control example, students begin to describe a regulator, in this case the brain, which issues commands to the eye pupil or iris to open and close. However, the explanations for the damped or small continuous oscillation remain limited to an unspecified algorithm for adjustment.

> Curtis: It's constant light? Maybe it's just trying to adjust kind of like with that plan [referring to the controller in a previous example]. It's trying to adjust to the perfect kind but it's not. And it's, you know, going up units, 2 units, 1 unit, you know.
>
> Interviewer: Ok.
>
> Curtis: And it's trying to get it just right, but can't.
>
> . . .
>
> Curtis: I don't know how it works, but it's almost um well the nerves, I mean, the nerves tell it like from the brain how much to expand. I don't know how the actual thing works but like a camera or what not. But I guess it's just nerves senses almost like, you know, how much it needs, you know, kind of like sensing how many jeans were sold or how much water was missing or what not [referring to comparator function in previous example].
>
> Interviewer: What do you think it's trying to do?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Curtis: I think it's just trying to get to a perfect line, almost like the 29 dollar line with the jeans going back to that [referring to SPU in previous example]. It's kind of similar.

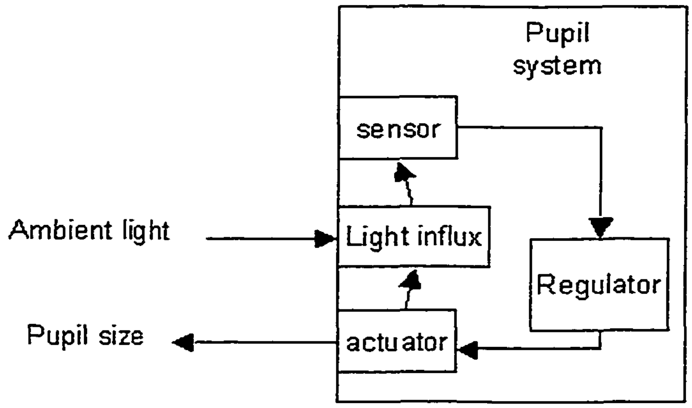


Figure 4-7. Connected Internal Parts Model for the Pupillary Control System. The description includes a regulator function as well as a sensor and an actuator. The regulator decides how to respond to what is sensed.

5.1.1.1 Algorithmic Regulator

This class of mental model is the most similar to the expert model. Students describe the algorithm for the regulator process including how the controller determines how much action the system should take based on the discrepancy between the actual and the desired state of the system. This sometimes but not always coincides with a clearer differentiation between the comparator and the controller. The model also is characterized by an increase in details on how a parameter of a part changes a parameter of the next part in a directed loop around the feedback system. For example, instead of articulating a notion that the regulator controls the action taken, students specify the qualitative relationship between the variables of the sensor and comparator and the amount of action taken. With this increased level of detail, comes

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

more detailed explanations of system behavior including explanations for damped and continuous oscillation.

Home Heating System

For the home heating system, students point out a sensor, an actuator, and a comparison process as well as some information about the control algorithm. They notice that the overall system purpose is to keep the temperature of the house at a constant level or within an acceptable range, but they also give more detailed explanations for time varying behavior that is attributed specifically to the controller algorithm. For example, the periodic fluctuations that occur around the desired temperature value arise from the on-off controller algorithm.

> Alice: It should go up to about 75 [the desired temperature]
> and then it kind of stays constant, but it's also
> But when the heat is off it'll start to cool off again and in an hour it should go back. You know, when it gets back to 60, it'll turn on again or it'll just start automatically. So it'll go back to 75. So this is kind of
> It'll just stay constant and then it'll drop and then at that point it'll drop again.
> Interviewer: ok
> Alice: and repeats
> ...
> So I guess there's a thermometer for the heat and when it reaches the temperature we want it to it'll just turn on. It's not a manual thing that we have to do. It kind of goes with the
> I guess. I think it's some kind of computer in there that does it.
> Interviewer: ok
> Alice: We get to program it but it'll start and it'll stop by itself. It knows the temperature.
> Interviewer: Um what kind of information do you think that computer needs?
> Alice: Um well it needs to know the temperature and then um
> it has some sort of thermometer to know what the temperature is.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Pupillary Control System

For the eye pupil control system, students who identified an algorithm for the regulator function explain the damped oscillation behavior of the system over time as a result of diminishing action amount with every iteration. In the particular excerpt below, Curtis is trying to piece together an explanation for the damped oscillation using ideas of overshoot that is based on a sense of momentum, or lack of instantaneous action, and diminishing action amount dictated by a controller that proportionally adjusts the action amount based on the error between the current and the desired state:

> Curtis: It has the ability to control it based what it's sensing the light level is.
> ...
> Curtis: So like there's sunlight that's coming in. 'Whaa'
> and then there's this sensor thingy that, you know, sees
> 'Ahh' that there's that much light and then it goes to the comparator thing that
> has like a setpoint like if it's, if you want it
> You know, like when you look it's like a certain brightness
> and so that would 'certain brightness' and that compares the two and like
> sends the difference to the controller obviously which tells like the actuator
> how how much to open and close the pupils
> ...
> Interviewer: Why does it dip more right there [the first overshoot] than it does
> here [the rest of the oscillation]
> Curtis: because
> ...
> Curtis: Let's see. It speeds up 'urrrr'. Oh, because of momentum. It's the same
> thing as like a car, you know. Objects tends to stay in motion, you know.
> ...
> So it overshoots this much right, and then it says 'oh dear I have to go back'
> and you don't
> Does it have to go back the whole way? Or, I mean, can't it just go back a
> fraction of that?
> ...

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

it looks for the comparator before it goes to like this next bubble and it goes ' oh you're, you're this distance off '

...

Ok, so the comparator [Curtis confuses comparator for controller] can't multiply it by 1 it has to be like .98 or something so it only goes over like 1.9 or something. So then it says ' oh you're 1.9 over' and it sends 1.9. The controller goes 'ok I'll go back uh 1.9 times .98' or whatever and it gets to 1.7 from, you know, where it should be. That's how it would work. It would decrease

...

Curtis: hippus would happen if instead of this being a percentage controller is an on-off controller

4.2.3 Results

Student explanations for the two feedback examples were coded according to the guidelines described in Section 4.2.1.2, and the results were compiled for each system explanation by pre or posttest and by participant group, FAVL or Non-FAVL.

4.2.3.1 Pre Interview

Home Heating

For the home heating system, I found that many students were able to describe the on-off nature of the home heating system. The results are summarized in Table 4-2.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4-2. Student Models of Home Heat Control (Pre Instruction)

Model	FAVL	Non-FAVL	Total
System as Whole	4 (26.7%)	4 (26.7%)	8 (26.7%)
Boundary	0 (0%)	2 (13.3%)	2 (6.7%)
Internally Connected	3 (20%)	3 (20%)	6 (20%)
Algorithmic	8 (53.3%)	6 (40%)	14 (46.7%)
Total	15 (100%)	15 (100%)	30 (100%)

A Chi-square analysis shows that there is no significant difference between the two groups before instruction: χ^2 (3, N=30)= 2.286, p=0.515>0.05.

Most of the students were able to identify the canonical functional subsystems that make up this regulatory system even though they did not have any detailed knowledge of the physical mechanism that implemented temperature regulation. Only 3 out of 30 students made any specific mention of physical mechanism on the level of detail that Gus did:

> Gus: Well what happens physically it that um you turn on the pilot light and the pilot light turns on the gas and the gas lights the the main burner and when it's hot enough the fan blows it into the rooms.
>
> ...
>
> Well in some models [of thermostats] there is a spring. Others that are electronic there is another sensor. But the main thing is that in the physics uh in the spring model
> the spring either lengthens or shortens which which it
> Well there's a switch that connects the wires which puts on the fan

Instead, there seems to be a focus and ease with the functions that the system needs to perform. One student even uses a placeholder for the sensor function, calling it a 'mechanical dohickey' that senses the temperature, instead of offering a physical description.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Pupillary Control

Table 4-3 tabulates the results of categorizing students' mental models of pupillary control system according to the coding scheme summarized in Table 4-1.

Table 4-3. Student Models of Pupillary Control (Pre-Instruction)

Model	FAVL	Non - FAVL	Total
System as Whole	8 (72.7%)	7 (46.7%)	15 (57.7%)
Boundary	1 (9.1%)	6 (40%)	7 (26.9%)
Internally Connected	2 (18.2%)	1 (6.7%)	3 (11.5%)
Algorithmic	0 (0%)	1 (6.7%)	1 (3.8%)
Total	11 (100%)	15 (100%)	26 (100%)

It is not surprising that few students had any specific descriptions of the inner workings of the eye that went beyond the brain, the nerves and the occasional rods and cones. Most student held a systemic whole or boundary model and described the time-varying behavior of the system as a result of acclimation in which the system 'gets used to' a change in the environment. In most cases, this description of acclimation did not include the idea of continuous adjustment to a changing variable, the light influx. Instead, the focus remained on the outside stimulus of light and 'becoming comfortable' with that light. Only one student was able to explain the continuous and the damped oscillation of the system by describing changes in the level of adjustment in a feedback loop.

A Chi-square test of the two groups of participants show that there is no significant difference between the Non-FAVL and the FAVL group during the pre interview: χ^2 (3,N=26)= 4.462,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$p=0.215 > 0.05$.[4] Note that most of the discrepancy comes from the larger number of students in the Non-FAVL group that had a boundary model. This gives us some confidence that the two groups are equally matched before instruction. There was no significant correlation between the type of mental model that a student described for the home heating system and the pupillary system, Cramer's $V=0.362$, $p=0.334 > 0.05$.

4.2.3.2 Post Interview

The types of models student articulated for the eye pupil system after their respective instructional sequence are tabulated in Table 4-4.

Table 4-4. Student Models of Pupillary Control (Post-Instruction)

Model	FAVL	Non - FAVL	Total
System as Whole	0 (0%)	0 (0%)	0 (0%)
Boundary	2 (13.3%)	1 (6.7%)	3 (10%)
Internally Connected	3 (20%)	11 (73.3%)	14 (46.7%)
Algorithmic	10 (66.7%)	3 (20%)	13 (43.3%)
Total	15 (100%)	15 (100%)	30 (100%)

By the post interview, most students were able to describe the system as an internally connected set of functional subsystems that correspond with those of the canonical model. Correspondingly, their behavioral descriptions are more detailed, and adjustment is no longer a vague acclimation procedure, but more precisely specified as a process involving adjustments based on desired levels, comparisons, and corrections based on that comparison result. However, some of these students still do not see the cyclic nature of the adjustment.

[4] All p values in this study are derived from two-tailed tests.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Specifically, they do not use a cycle-by-cycle account to explain oscillations. Instead, oscillations are left unexplained or explained as an appendage to the feedback system in the form of a separate process that students describe simply and vaguely as the oscillation process. Some students even draw in an 'oscillation part' in their diagrams of the feedback system with no better integration into the system description.

Many of the FAVL students further differentiated the system according to the type of control algorithm and were able to explain the damped oscillation behavior of the pupillary system as a result of a proportional adjustment to an error signal. A comparison of the two groups now show that the FAVL and Non-FAVL groups are no longer equivalent, with many of the FAVL students articulating a more sophisticated model: $\chi^2(3,N=30)= 6.60$, $p=0.037< 0.05$.

4.2.3.3 Pre and Post Results

A within subject comparison of the pre and post results on the human eye pupil interview using the Wilcoxon Signed Ranks test shows that there was a significant difference for students (both the FAVL and the Non-FAVL group) in the positive direction: for the FAVL group, $Z(N=11) =2.836$, $p=0.005$, and for the Non-FAVL group, $Z(N=15)=3.210$, $p=0.001$. That is, students were able to give more detailed descriptions of the functions that make up the feedback systems as well as to explain system behavior such as the adjustment of the system to a desired state. Figure 4-8 shows the change in mental models classes for the FAVL and Non-FAVL students. Note that four of the FAVL students did not answer the pupillary control questions during the pre-instructional interview. These students were not included in the pre-post comparison tests.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

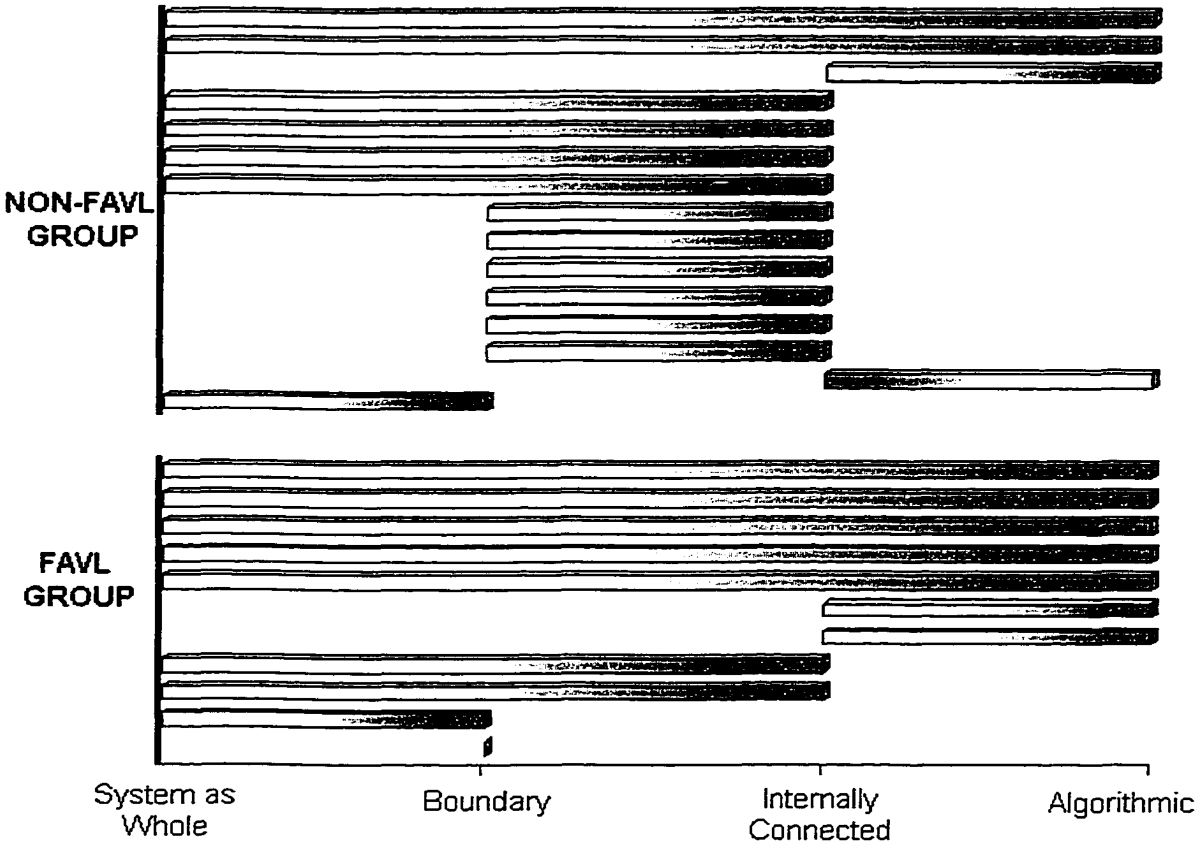


Figure 4-8. Changes in Model Class for FAVL and Non-FAVL Groups. Each bar represents one student. The lighter end denotes the pre-instructional model, and the darker end denotes the post-instructional model.

4.2.4 Discussion

The results of this set of analyses on student models indicate that the sophistication of students' mental model can vary according to the type of system described and that the instructional material described in Chapter 2 can be instrumental in helping students construct a more sophisticated model for systems which were originally difficult for them to explain.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The comparison of the student models from pre-instruction for the home heating and the pupillary control systems suggests that few student explanations seem to derive from the same schema. Even though a student may have a fairly good understanding of how the home heating system regulates the temperature in a house, they do not readily apply the regulatory model to explain how eye pupil size changes. What makes certain systems more easy to explain and others not? There were many more students who had more sophisticated models for home heating than for the pupillary control. Part of the difference may lie in the amount of direct experience and detailed knowledge that students have on the inner workings of each system. Previous studies on people's mental model of biological systems suggest that novices develop misconceptions of the inner workings of the body because the internal details remain hidden from casual observation (Chi, Chiu, & deLeeuw, 1991). A pupillary control system is, after all, difficult to observe even under laboratory situations whereas most students have some experience with thermostats and have likely formed some idea of how they work without formal schooling on the subject (Kempton, 1987). Although slightly more students had more detailed device specific knowledge of the home heating system, this alone, however, does not seem to explain the discrepancy.

When looking over these transcripts, I was struck by the scarcity of examples in which students made specific reference to the details of the physical system. Only 3 out of the 30 students described specific physical instantiations for home heating, and none of the students, not surprisingly, gave any detailed physiological descriptions of the human eye. This, however, did not preclude students from describing the home heating system as composed of functional subsystems which correspond to those found in the canonical model of negative

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

feedback control systems. This may be an indication that functional partitioning does not depend first on a detailed mechanical understanding of the particular physical device. This is consistent with findings from a study by Miyake (1986) on how people construct understanding of complex physical devices. Miyake posits that people come to understand a system through an iterative process of identifying functions and then their corresponding mechanisms (or implementation) at increasing levels of detail. So, although experts and novices differ in the extent of their device knowledge, detailed device knowledge does not seem to be the critical precursor to deriving a general model based on functions.

In fact, a detailed understanding of physical implementation may not necessarily help in understanding the relational structure shared by feedback systems. The contrary may instead be the case: Because novices in a field tend to focus on surface features including physical attributes instead of relationships (Chi et al., 1981; Novick, 1988), a detailed picture of physical implementation may detract from learning about feedback. In fact, during an earlier trial run of the FAVL curriculum, one student who learned the detailed mechanism of the home thermostat had trouble seeing the common pattern of feedback in other physically dissimilar systems and only referred to other functions through specific and tenuous analogical reference to parts in the home heating system (Ma, 1999). The difference between student descriptions of the home heating system and the eye pupillary system does not seem to depend solely on detailed knowledge of the physical instantiation.

Instead, I hypothesize two reasons why students had an easier time with the home heating system. First, the pupillary control system can be roughly modeled as a proportional control

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system where the corrective action changes continuously and proportionally to the discrepancy between the ideal and the current light influx. This is in contrast to the home heating system which is an on-off system with discrete states and clear state transitions between the two. Of the students who described an algorithmic model, only two described a system that did not have an on-off control scheme and these two described multiple, yet discrete levels, or states, of operation, with a high, a medium, and a low rate for heat production from the furnace. Students may find the continuously changing nature of the correction difficult or, at the very least, unfamiliar, to apply to explaining a system. This hypothesis will find additional support in the subsequent analysis of multiple-choice questions. Also, previous research conducted by White and Frederkisen (1990) showed that students found it easier to reason about electrical circuits by first learning a zero-order model where circuit components held discrete states (e.g. the transistor is saturated or unsaturated) and then progressing to higher order models with incremental change.

The second reason why the home heating system was easier to explain than the pupillary system is that part of the feedback loop for thermostatic control (i.e., the relationship between heat produced and the room temperature) is more familiar to students. If nothing else, student always describe the room temperature to be controlled and the heat production that affects the room temperature. Also, students understand the home heating system as a system that is supposed to keep the temperature in the home at or around a desired temperature, which they set with a thermostat. On the other hand, for the eye system, students focus on changes in the ambient light and the resulting change in the pupil size; the controlled variable of the system, the light influx, remains hidden, and encapsulated in the black box if the student had the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

systemic whole model. Furthermore, students have never had the experience of manipulating the pupillary system like they have with the thermostat. Students may be better able to generate an explanation when more of the feedback system relationships are exposed to common inspection and manipulation.

There are few feedback systems for which most interactions are readily available for inspection. The thermostatic control system is likely one of the few that most people have access to even though only a few students interviewed had opened its casing to look inside. When it comes to more complex systems, and especially social or biological systems, it becomes even more challenging to open up the 'black box' to observe an operational system. If students do not spontaneously see similarities between the two systems in the pre-instructional material, then learning and applying the canonical feedback model if only to explore the implications of its applicability to such systems may be an important first step by which students can understand regulatory systems.

The pre-post results indicate that students do learn to apply a more sophisticated model to explain the human eye system after the instructional sequence. These results also suggest that the model instruction portion of the instruction was effective in teaching most students to start to think about these systems in terms of their internal functional makeup and the interactions between those function that give rise to the adjustment behavior they see for feedback system behavior. It is the purpose of the next two chapters to explore how the two primary tools used in our instructions: comparison activities and design work in an articulate virtual laboratory,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

foster learning the more sophisticated models. Before moving on, however, I will take another look at the nature of student reasoning about feedback examples.

4.3 Another Look – Reasoning through the System

The analysis of model classes provides a characterization of student understanding of feedback systems according to the types of parts that students used to construct different explanations for system behavior. This section looks in more detail at the types of relationships that students use to explain system behavior. Whereas the previous protocol did not provide system descriptions, but instead asked students to construct a model of how each system works, the following analysis is focused on how students reason about behavior within a system when they are given a description of the parts and the interactions between those parts that constitute that system. A pre-post comparison is also included to describe changes if any in student reasoning.

4.3.1 Method

I developed a set of multiple-choice questions and analyzed both the scores on these tests and protocols students generated as they talked through their answers. These items were designed to explore student understanding of the relationship between a specific part of the feedback model to other parts or the overall system behavior of a feedback system.

4.3.1.1 Test Design

Because of the highly mathematical treatment given to feedback control systems in textbooks, I could not use test questions typically asked in feedback control classes in my test design. First, high school students would not have the mathematics to solve or even understand these

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

problems. Second, I was more interested in the qualitative relationships students learn than the quantitative relationships emphasized in the traditional class on feedback control. I found limited other sources for questions that would test for a qualitative understanding of feedback systems. With the exception of one question that Kempton (1987) used to ascertain people's mental models of thermostatic control, I designed all the test questions used in this study through a formative approach: The multiple-choice questions were first checked with an expert in control engineering for accuracy and then administered to a small number of graduate students as well as faculty members in Cognitive Science to check for clarity. Pilot studies with high school students in 1997 and 1998 were used to further refine these test items. As a result of this procedure some test items were thrown out, others were reworded, and still others were added to the original set.

In the final sets of questions that were developed, each test item focuses on the relationship between each part of the canonical model to the controlled process of the systems. Each set of questions begins with a description of a specific example of a feedback system followed by questions about that example. I avoided the use of the more general terms that were used in the canonical model, and, therefore, gave students a chance to understand the questions without having to learn the terminology that is associated with the more general model.

I designed isomorphic items between pre and posttests to try to measure changes in how students reasoned about the relationships shared between the physically dissimilar feedback examples. These isomorphic items and the relationships they assessed are listed in Table 4-5.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4-5. List of Isomorphic Multiple-Choice Test Items for Pretest and Posttest.

Relationship	Item	Item
Sensor - controlled process (Sensor misreading leads to shift in the steady state value.)	Home Heating (Version I) Question4a	Light Regulation Question2a
SPU - controlled process (Changing the SPU value changes the steady state value.)	Home Heating (Version I) Question4b	Light Regulation Question2b
Controller gain - controlled process (The system rise time is dependent on the controller gain.)	Marketing Question4b	Light Regulation Question3a
Controller gain - controlled process (The system overshoot is dependent on the controller gain.)	Marketing Question4a	Light Regulation Question3b
Controller type - controlled process (Rise time is not adjustable in an on-off system)	Home Heating (Version I) Question5	Home Heating (Version II) Question3
Comparator - controlled process (Erroneous comparison can lead to self-amplifying behavior)	Home Heating (Version I) Question6	Light Regulation Question4

The questions listed in Table 4-5 were not the only questions used. There were other multiple-choice test items, and the complete sets of questions can be found in Appendix C.

4.3.1.2 Test Administration

There were five sets of multiple-choice questions administered to each student:

1. Marketing/Price Adjustment System,
2. Home Heating System (Version I),
3. Humidity Regulation System,
4. Light Regulation System,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5. and Home Heating System (Version II)

The multiple-choice question sets were administered in the order shown in Table 4-6.

Table 4-6. Test Order.

	Order A	Order B
Pretest	Marketing /Price Adjustment System	Light Regulation System
	Home Heating System (version I)	Home Heating System (version II)
Intermediate Test	Humidity Regulation System	Humidity Regulation System
Posttest	Light Regulation System	Marketing /Price Adjustment System
	Home Heating System (version II)	Home Heating System (version I)

Students in the FAVL and the Non-FAVL group were each assigned to one of two test orders, A or B, with 9/15 students being assigned to A and 6/15 assigned to B.[5] Swapping the test order between pre and post assessment allowed me to detect test bias in the results. Note that the intermediate multiple-choice test was not switched with any other test in the sequence. However, for the purpose of this analysis on overall learning, I look primarily at the results of the pretest and the posttest.

[5] The first 9 students who came to the study in the Summer of 1999 were assigned to order A. The remaining students who came that Summer were assigned to order B. Originally, I had thought more students would volunteer to participate; hence, there is a smaller number of students who received test order B.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

All students were asked to explain their answers as they worked through these tests, and their explanations were video taped and transcribed for later analysis.

4.3.2 Analysis

Students' multiple-choice responses were analyze in two main ways:

1. Correct/incorrect scoring. This offered a rough indication of whether or not students were able to reason about the relationship between certain parts of the feedback model and the overall controlled process.
2. Protocol analysis of students' explanations for each answer. This complemented the first approach by revealing how students reasoned through these questions and not only if they arrived at the right answer. I looked for patterns in their reasoning for each and across different question types and checked to see if there were changes between how students reasoned about these questions before and after the instructional sequence.

4.3.3 Correct/Incorrect Scoring

I analyzed students' overall pre and posttest scores as well as students' per item answers. Students' pretest and posttest scores were calculated as the sum of the number of correct responses for isomorphic test items. The highest that a student can score is 6/6 on the pretest and (obviously) 6/6 on the posttest. Table 4-7 and Figure 4-9 show the results for the Non-FAVL group and FAVL group. An independent samples t-test between the Non-FAVL and FAVL groups for their pretest scores reveal no significant difference between the two groups, $t(28)=1.288$, $p=0.208 > 0.05$, giving us some confidence that the two groups were equivalent before instruction.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4-7. Distribution of Aggregate Scores for the Multiple-Choice Tests.

Test	Group	N	Mean	Standard Deviation
Pretest	FAVL	15	4.6	1.18
	Non-FAVL	15	4.0	1.36
	Total	30	4.3	1.29
Posttest	FAVL	15	5.1	0.99
	Non-FAVL	15	4.6	1.06
	Total	30	4.87	1.04

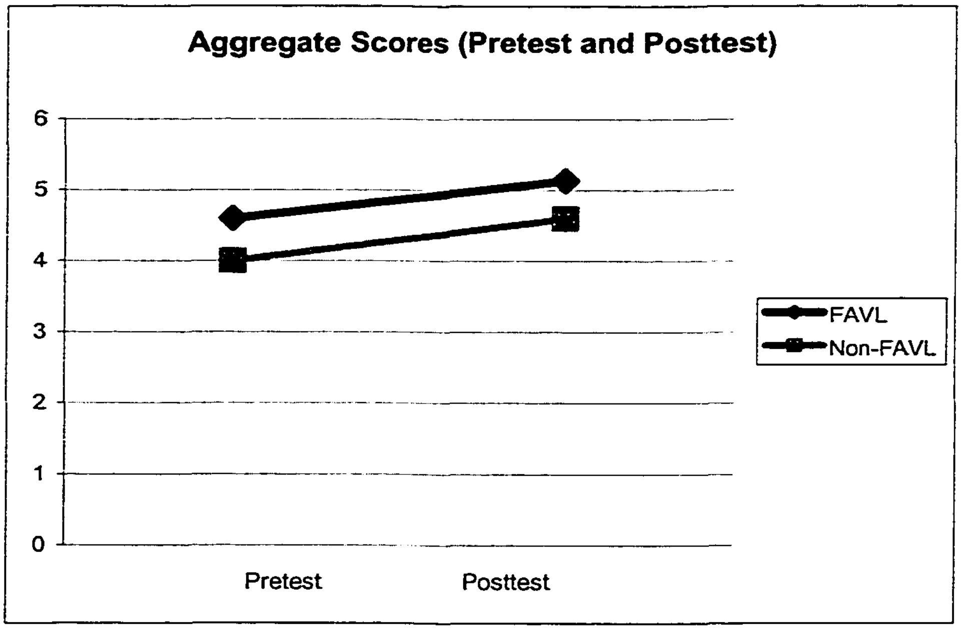


Figure 4-9. Aggregate Scores for FAVL and Non-FAVL Groups on Pretest and Posttest

The aggregate test scores were analyzed using a repeated-measure ANOVA with the Test Scores from the pretest and the posttest as the within-subject factor and the Test Order (i.e., Order A or Order B) and Group (i.e., FAVL or Non-FAVL) as the between subject factor, as shown in Table 4-8. The ANOVA gave a significant pretest-posttest main effect, F(1,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

26)=6.910, p =0.014. There was no significant interaction between the Test Score and the Test Order, $F(1, 26)=0.069$, $p=0.795$, suggesting that the tests were indeed isomorphic. Also, there was no significant interaction between the Test Score and the Group, $F(1,26)=0.155$, $p=0.697$, indicating that the pre-post gain cannot be attributed to work with FAVL. These results seem to indicate that the improvement in reasoning about parts in the feedback model is tied to that part of the instruction (Model Instruction) that precedes FAVL.

Table 4-8. Factors in Repeated-Measure ANOVA

Within-Subject Factor	Between-Subject Factor
Pre-Instruction TEST SCORE vs. Post-Instruction TEST SCORE	FAVL GROUP vs. Non-FAVL GROUP
	TEST ORDER A vs. TEST ORDER B

To see if this is the case, I performed a paired samples t-test for students' aggregate scores from their pretest and their intermediate test. Note that the intermediate test is substantially shorter than either the pretest or the posttest. Consequently, only three items on the intermediate test had matches in the pre-instructional multiple-choice tests, as shown in Table 4-9. The t-test was performed comparing isomorphic items only, with the highest score on the pretest and intermediate test being 3/3. The results did not show any significant difference between the pretest scores ($M = 2.3$, $SD = 0.79$) and the intermediate test scores ($M = 2.2$, $SD = 0.89$), $t(29)=0.551$ $p=0.586 > 0.05$. This may be because the smaller set of items did not measure the change that the larger set of test items used in the pre and posttest comparison captured.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4-9. List of Isomorphic Test Items between Pre-Instruction and Intermediate Interview.

Relationship	Pretest Item	Intermediate Test Item
Sensor - controlled process (Sensor misreading leads to shift in the steady state value.)	Order A - Home Heating (Version I) Question4a or Order B - Light Regulation Question2a	Humidity Regulation Question2a
SPU - controlled process (Changing the SPU value changes the steady state value.)	Order A - Home Heating (Version I) Question4b or Order B - Light Regulation Question2b	Humidity Regulation Question2b
Controller gain - controlled process (The system overshoot is dependent on the controller gain.)	Order A - Marketing Question4a or Order B - Light Regulation Question3b	Humidity Regulation Question3

These are the test items considered in comparing the change in student understanding between pre-instruction and intermediate interview. Note that there are two items listed as the pretest multiple-choice question. Which item is used in the pretest depends on the test order, A or B, to which the student was assigned.

I also looked to see if there were individual items for which students showed marked improvements between pre and post instruction. A Mann-Whitney test shows that there was no difference between the Non-FAVL and FAVL groups per test item. A Sign test, $p=0.012$, indicates that improvements for all students seem to arise primarily from the questions concerning the response time characteristics of proportional control systems.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4.3.4 Protocol Analysis

To understand how students arrived at their multiple-choice answers, I also took a closer look at their talk-aloud protocols. For this analysis, I was specifically concerned with: 1) how students made sense of each of the parts that make up the canonical model, 2) how students related one part to the next, and 3) what other relationships students depended on in answering these questions. In addition, I looked to see if there are any differences in the ways students reasoned about the multiple-choice questions after instruction. The analysis reveals that students draw upon multiple, sometimes inconsistent and sometimes invalid relationships when they reason through a system, and that in most cases, relationships remain stable between pre and posttests on isomorphic test items.

4.3.4.1 Parts Understanding

In the previous analysis, I argued that the behavioral explanations students construct for feedback systems are connected to the types of parts that characterize their mental models. In the following, I will more closely examine students' understanding of the canonical parts in the feedback system.

<u>Sensor.</u> Even though each set of multiple-choice questions was prefaced with a parts description and a set of causal relationships that link part to part for the particular feedback example, a few students (6 in total, 3 from the FAVL group, and 3 from the Non-FAVL group) still struggled to understand what role the sensor had within the system during the pretest. This became clear with a set of questions that asked what would happen if the sensor, whether it be a thermostat, a light meter or an inventory clerk in their respective feedback

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

example, was not working properly and was always reading a higher (or lower) value relative to the actual value of the controlled variable. These students did not see any connection between the sensor reading and the rest of the system. For instance, when asked what would happen to the house temperature if the thermostat always senses 10 degrees higher than actual temperature, one of these students said:

> (*Pretest, Home Heating System Version I, Question 4a*)
> Loni: Well, I don't see how the temperature itself would change. I mean maybe obviously it would read it wrong. But even though they set it to 62, I don't think there's something wrong with the heat that's coming. I just think there's something wrong with the way it's reading it, or sensing it.

Instead, sometimes the sensor reading is described as something intended for a user and not as an input to the rest of the control system:

> *(Pretest, Home Heating System Version 1, Question 4a)*
> Cheryl: Well, the temperature is fine. It's just what it reads, you know. So the thermostat says that it's 70. It's actually 60.
> ...
> Like some people have to have everything just right, I mean,
> but some people
> As long as you [the people in the room] know that it's always going to be 10 degree difference then there's nothing wrong with that.

Of the 6 students who had trouble with this question type during the pretest, 5 of them were also categorized as having the *system as whole* model in describing both the home heating system and the pupillary control systems during their clinical interviews. Furthermore, these 6 students' pretest scores were lower than 50% percentile rank, with 5 students' scores falling below the 20% mark. This suggests that these students also had problems on other question types on the pretest, which rely on constructing relationships between other parts of the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system. I hypothesize that these students had a 'system-as-whole' or perhaps a 'boundary' model of the feedback system and were struggling to make sense of the relationships between the internal parts of the system.

During the posttest, 2 of the original 6 students who did not see the sensor as affecting the rest of the system in their pretest, continued to have similar difficulties in the beginning of their explanations. When asked what would happen to the house temperature if there was a hair dryer blowing hot air on a thermostat, one of these two students responds:

> (*Posttest, Home Heating System Version II, Question 2*)
> Loni: I don't think the average temperature in the house will change, but I think that the temperature that it's reading will change, like the temperature that the thermostat or that the reading that you're getting because you're blowing hot air on it. It's reading hotter than it actually is because you're using it in the bathroom but the whole house is not being affected by the small hair dryer that you're using.

But, then these students would correct themselves halfway through their answers:

> (*Posttest, Home Heating System Version II, Question 2*)
> Loni: Oh no, wait, the thermostat is reading a higher temperature than it should be reading, then it's going to turn off because it's going to think it's too hot when it really isn't that hot. But then again it depends on how hot the air in the hair dryer but I guess it would be hotter than in the house. So I think if you put it on the thermostat and the thermostat reading went up, the heat would turn off. So that would leave the thermostat reading wrong and that would leave the house colder than what you initially, what you wanted to be because the reading is higher.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

By the posttest, therefore, all the students who originally did not understanding that the sensor reading is tied to the rest of the control system, now understood that the sensor reading is more than a display for the user. This supports the previous analysis' findings that show that after instruction, most students developed more sophisticated, internally connected models for explaining feedback adjustment.

SPU. All of the students believed that the SPU in the feedback system examples determines the desired value of the controlled variable and when changed, shifts the equilibrium point of the system. For example, when students were asked to identify the fault in a system that led to self-amplifying, positive feedback behavior, they often eliminated the SPU as the problem because it simply sets the desired value:

> *(Pretest, Light System, Question 4]*
> Peter: I don't think there's anything wrong with the dial [the SPU in this example]. I'm just trying to think about this I mean. I don't really see how if you set it at a certain amount then it'll go up because usually it'll just be set. I mean this [dial] tells that you have to have it here [at set value].

When they were asked how to compensate for an offset in the sensor reading, students reasoned that setting the SPU at a higher (or lower) value would correct the sensor fault by redefining the system's equilibrium value.

This familiarity with the SPU is not too surprising. Previous research (Penner, 1998) suggests that novices are most familiar with parts that they as users can control and change, and the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

SPU in most systems are the most accessible to users; they are manipulated directly whereas most of the other functional subsystems of feedback remain hidden.

Comparator. During the pretest, comparison was often described as part of the control algorithm. This may be because none of the feedback descriptions gave a separate physical part that encompassed only the comparison function without the controller function. This is even though originally, I thought that one of the questions regarding the cause of positive feedback behavior may lead students to identify a comparator reversal; only one student attributed self-amplifying behavior to a problem with the comparison during the pretest.

However, after instruction more students began to differentiate the comparator and the controller portion of the controller/comparator assembly. For example, for the same question which asked for the cause of self-amplifying behavior in a wayward light control system, 33% of the students who answered this question referred to a comparison problem and not just to a problem with the regulation algorithm:

> *(Posttest, Light System, Question 4)*
> Nicole: yeah I think it's the Luster Buster [the comparator/controller assembly] here. It's not taking this number and comparing it to this number correctly.

But, when students tried to be more specific about the problem with the comparator, they became confused and had a difficult time specifying what was reversed. Oftentimes, they thought that the comparator was adding instead of subtracting, which can explain an upward spiral but not a downward spiral:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(Posttest, Light System, Question 3b)

Max: Um there's an error [looking at graph he's drawn that goes up and up] and it tries to correct it and so it gets up here it's still there. It'll overshoot and up here you'll need to compensate by going negative but if it can't do that. If it just keeps adding. It'll just keep going up.
If it goes under, then oh that wouldn't be right then.

Interviewer: Why wouldn't that be right?

Max: because if you're under, if it just gives positive values, it'll go up. It'll keep going up, and so it'll just always grow brighter if that was the problem.
I guess if it um, um
am I missing something?

Nonetheless, the comparator becomes a part within the system that is attributed certain roles within the system and becomes identified with the corrective behavior of the system.

Controller. For each of the feedback system example described, students were told that a plan or device determines the amount of corrective action to take to adjust the controlled process based on the current state and the desired state. Students readily referred to the controller as the part that tells the actuator in the system to take action:

(Pretest, Light System, Question 4)

Anna: cause um it's the thing that regulates the amount of light. If the light is either above of below the setting it has to send a message to deliver light.

(Posttest, Light System, Question 4)

Curtis: like it's [the controller in the light regulation system] supposed to send out a 1 meaning turn on but it sends a 0 so the light doesn't turn on.

However, it was unclear from the protocol if students had a more detailed knowledge of the relationship between the error signal and the action amount beyond the idea that they are connected in some way. In particular, when I analyzed students' pretest responses for

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

questions concerning system rise time and overshoot and their relationship to controller gain, I could not discern if students understood the proportional algorithm described for more than 50% of the protocols analyzed. In a small percentage of the cases (between 3% for rise time and 8% for overshoot questions) it was clear that students assumed that the controller did not make adjustments proportional to the difference between the ideal and the current state but instead increased or decreased the action amount by a constant value depending on whether the controlled variable was above or below the system's setpoint.[6]

The ambiguity may simply reflect student difficulty with understanding the wording within the system description or with the particular feedback examples used. [7] However, note that in the previous work on classifying student explanations of eye pupillary control, there were very few students before instruction who identified and used the proportional relationship between the error signal and the action amount to explain system behavior like oscillation and overshoot, and many of the students in the Non-FAVL group did not identify this relationship even after instruction. This suggests that for many students, the details of how the error signal is related to the action amount remains vaguely defined. This coupled with the observation that more than 90% of the students were able to explain why an on-off controller would change a controlled process at a constant rate, further suggests that students are

---

[6] There were no students who switched from thinking that the action increments by constant step sizes to thinking that the action amount changed proportional to the error signal, regardless of the question type or feedback example.

[7] Note that in these particular examples, the effect on the controlled process is additive. That is, the action dictated is 'in addition' to the action it took with the last cycle. This may have made it a lot easier for students to think in terms of constant increments, whereas if a system whose action is dependent solely on a difference error signal (e.g., a cruise control system) it would have been a lot more difficult to argue for constant increments.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

unfamiliar with thinking about systems where one of the values in that proportional relationship, the discrepancy between ideal and actual, is constantly changing by continuous quantities. On-off systems may be easier to decipher than proportional systems.

There was no significant pre-post difference for either the FAVL and Non-FAVL group (Signed Test, $p=.250$ and $p=.250$ respectively) in using proportional relationship to explain the rise time or overshoot questions. Although when the two groups were combined, there was a significant pre-post difference (Signed Test, $p=0.031$), with more students describing a proportional algorithm for questions concerning system rise time. This hints at some improvement that may be attributed to instruction.

Actuator. Students saw the actuator in the different system descriptions as something within the system that can change the controlled process. Little else can be said of students' definition of this part from the protocol.

4.3.4.2 Stepwise Directed Reasoning

In the framework laid out by Forbus and Gentner (1986) on the role of causal reasoning in learning a physical domain, the authors hypothesize that recognizing causal relationships characterizes one stage in the progression towards expertise; causality "expresses belief in the existence of some mechanism." Causality is typically expressed as a set of directed relationships. The behavior of feedback systems can be explained by the interactions of the parts in a directed manner with one part affecting the next which, in turn, affects the next, and this is one way by which students reason about the behavior of a system, as a step-wise

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

account of the interactions of these parts in time. That is, students use relationships whose directionality is the same as the direction of causation where values or changes are propagated through the parts of the system in time order; within the feedback system, the direction of causation traverses the loop from the controlled variable to the sensor, to the comparator, to the controller, to the actuator, and back to the controlled process. It is one of the assumptions of our instructional design that by giving students a model and a causal chain that links the parts of that model together, students can begin to generate system behavior from the parts. Looking for the use of stepwise directed reasoning, therefore, provides a means of assessing if students use such relationships in their reasoning and if their use changes after instruction.

Stepwise directed reasoning is manifest in student explanations as descriptions where the effect on at least one intermediate part is mentioned with a clear sense of time progression. Note that this does not mean that students always stepped through each and every part of the canonical model propagating changes from part to part. However, as long as there was a propagation of values in the direction of causation, and a description of how an intermediate part is changed, then I considered that an example of stepwise, directed reasoning.

There are different types of directed dependencies, with different orders used in the reasoning and even some instances of numerical value-by-value accounting. In addition, these relationships can be differentiated as one or multi-loop. One-loop directed reasoning span a portion of the feedback loop, usually beginning with the part that had been changed to the controlled process. Multi-loop directed reasoning uses a directed chain of relationships that include multiple iterations through the feedback cycle.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Students' use of directed dependencies varied with the problem type. It was most common for those questions that focused on the effects of a change in one parameter or component on the controlled variable; this include the set of questions regarding a faulty sensor and the rise time and overshoot of a proportional control system, and it is these questions that I will focus on in the following to determine how directed dependencies were used.

Approximately 70% and 60% of the students used directed relationships to reason about the effects of a faulty sensor during the pretest and posttest, respectively.[8] The following excerpts are examples of students reasoning through two different such sensor questions. Notice that in both examples, each student steps through the loop and mentions what happens to the actuator in the problem. The market system question (Marketing, Question 5) asks what would happen to the price of the jeans being sold if the inventory clerk consistently underestimated the number of jeans sold:

> (*Pretest, Marketing System, Question 5*)
> Irene: He underestimated how many are sold then um Karl [the store manager who sets the price] is going to lower the price so more people will buy them.

In a heating system where a hair dryer is directed at the thermostat, students explained:

> (*Pretest, Home Heating System Version II, Question 2)*
> Lee: so if the hair dryer is directed right at the thermostat the thermostat will think that it's higher than it is and it'll turn the furnace off so the average temperature of the house will drop so it'll be lower than before the hair dryer was turned on.

---

[8] This difference is not significant.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For these questions about a faulty sensor, students often reasoned through the loop only once, through the effect on the actuator, and after determining the effects on the controlled variable, few students would continue a loop step-through. For this particular set of questions, this did not present any difficulties in arriving at the correct answer. However, some students who continued to talk about the solution after choosing their answer went on to extrapolate an incorrect, long term behavior:

(Pretest, Marketing System, Question 5)
Phillip: The price will keep on going down because uh
They're not selling enough pairs of jeans so they want to lower the price

This is even when the sensor degradation is a constant offset. That is, the loop continues to change the controlled variable in the same way. This may suggest a tendency on the part of students to step through the loop once, summarize the effects of the loop, and then to add the effects to generate long term behavior.

This is certainly an effective strategy in answering questions regarding rise time. Most students (over 90% for both pretest and posttest responses) explained rise time as the accumulation of action on the controlled variable over time until the desired level was reached. The larger the action amount, the faster the controlled variable will reach its desired state. Directed relationships take a similar form for overshoot questions with the focus turned to what occurs close to the setpoint value.

Looking more closely at the protocols, I found examples that indicate that students may have trouble stepping through the loop multiple times. In the following protocol excerpt, Curtis is

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

trying to answer the sensor question where the sensor, a store inventory clerk in a retail pricing system, is always underestimating how many jeans are sold:

> *(Pretest, Marketing System, Question 5)*
> Curtis: Instead of x minus 6 [Curtis previously assigned x to mean the desired number of jeans sold; the 6 comes from the difference between the starting price of $35 and the ideal price $29. So x minus 6 is a guess as to how many jeans are being sold], you know, when it gets to twenty
> x minus 5 [This is intended to capture the undercount of the number of jeans sold, but actually expresses an overcount.]
> So it just gets to 34 [$34/jeans], and then went down to doubled it [the plan should change the price according to a fraction of the discrepancy between desired and actual count].
> So it went down to x plus 10 [Curtis chooses to double the discrepancy, but is becoming confused between the count of jeans made by the clerk and the resulting price; the price should be $35-10] and then, you know, I think this algorithm is really screwed up.
> I really don't think this is the right way to do it, but you know, whatever.

Notice the problems Curtis has in tracking values as they propagate through the different parts of the system.

A closer examination of the overshoot questions further reveals that students may have more fundamental issues understanding the cyclic nature of these systems beyond difficulties in tracking multiple parameter changes. In particular, some students appear to believe that feedback systems work by making an appropriate one-time adjustment. Consequently, these students are confused by the overshoot questions; there shouldn't even be an overshoot. For instance, when this student was asked if a smaller gain would solve a system overshoot problem, she answered:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(*Posttest, Light System, Question 4b*)
Becky: I don't know if percentage [the gain] is really a problem. Well I guess This all seems like the same thing. It looks like what it was doing before.
Interviewer: What do you mean?
...
Becky: Well I thought before when it was a larger percentage then it would figure out the power needed.
...
I don't see how this could be any different.

There were also similar examples of this in the clinical interviews. When Collins was asked to explain how the eye adjusts to different brightness levels, he answered:

Collins: There's a nerve in the eye that senses it, that senses the condition. And then it compares it to what the brain thinks is comfortable and then the brain compares readings. Then it tells the muscles in the eye to make changes which makes it easier to see.
Interviewer: And so can you use this to explain how the pupil size is changing over time?
Collins: No, not really because usually in feedback systems, in other feedback systems that we looked at, it makes just one precise change.

It is only later in his interview that Collins realizes that the continuous interactions between the parts lead to the oscillations in the system. This may be another problem that students have with multi-loop reasoning: they don't see the constant corrective iteration to a setpoint, but instead see the system as a calculator that determines the precise correction for a change in the system.

Signed tests for change in the use of directed reasoning in the sensor, rise time and overshoot type questions reveal no significant pre-post difference on isomorphic items, $p>0.1$. There was little change in the use of stepwise reasoning in answering these questions. Furthermore,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

there was no significant difference between the Non-FAVL and FAVL groups in their use of directed reasoning; Chi-squared analyses for pre and posttest for each item yielded $p>0.1$.

4.3.4.3 Other Relationships

So far the above protocol analyzes have focused on how students understand the role of the different constituent parts in feedback systems and on how students used stepwise causal reasoning to explain system behavior in a set of multiple-choice questions. This, however, is not to say that these were the only types of relationships students drew upon when they formulated their responses. The above two analyzes are used primarily to capture any change in relationships that are explicitly taught and encouraged within the instructional material. In fact, a quick scan through the protocols reveals that there were a variety of relationships that students used in their reasoning through the multiple-choice questions that went beyond those that fall easily into one of the above analysis categories. These relationships vary from question type to question type, and it is not the purpose of this section to give a complete catalog of these relationships. Instead, what I would like to do in the following is to give a sense of what these relationships and their use might reveal about the way students construct explanations for feedback systems.

Overall system goal as a guiding constraint. While students worked through these questions, it became clear that there were a set of guiding constraints that informed students' answers. Prominent among these is the idea that these systems go towards a steady state value, usually the SPU value. For instance, when we revisit Curtis' attempts to step through the loop, we notice that he makes several remarks that the "algorithm is really screwed up." I conjecture

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

that he became uncomfortable with his results because he knew that the system should not begin to oscillate out of control. Also, when explaining rise time and overshoot, some students made mention of an 'evening out' process in which the system would oscillate around or settles to the setpoint value. Students have this sense without ever stepping through the feedback system more than once. Perhaps the clearest demonstration comes from the nine out of 27 students who believed that replacing a heater with an air-conditioning unit, without changing the controller algorithm, would lead to the same self-regulating behavior during the summertime.[9]

The piecemeal, inconsistent model. Portions of student protocols reveal that students construct and use relationships within the same feedback system that are mutually inconsistent. For example, approximately 30% of the students during the pretest and 25% of the students during the posttest, sought to counterbalance a sensor error with an opposing change in the SPU. That is, if the sensor reading is too high then the SPU should be set lower[10]:

> (*Pretest, Light System, Question 2a*)
> Lee: So if the light meter has degraded, that means that what actually shows is what actually registers on the light meter is less than what's actually in there. So if you want the light level to be at 7, then you should set the dial higher than 7.

---

[9] In actuality, the feedback loop with the air-conditioning system would turn on the air-conditioning when the room temperature fell below the setpoint value and turn off the air-conditioning when the room temperature raised above the setpoint. This has the opposite effect of the original system with the heater.

[10] The SPU, in this case, should be set higher because a high sensor reading would lead to a lower value for the controlled process.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Of the students who used this counterbalance relationship, a little over 70% answered the sensor question correctly and knew the effects of a sensor problem on the controlled variable. In fact, the SPU question always immediately followed the question about the degraded sensor. It seems that these students were not influenced by or were tolerant of within system inconsistencies in their multiple-choice answers.

In addition, students were asked what would happen if the actuator in a feedback system degraded so that it always worked at a percentage of its original capacity. (This question was only posed once during the pre or the posttest depending on which version of the test was given and, therefore, was not included in any of the results that depended on pre-post comparisons.) Approximately 30% of the student responses indicate that students only looked at the local relationship between the actuator and the controlled process without considering what happens within the rest of the system in response to the change in the controlled process. Consequently, these students incorrectly argued that the controlled variable would be lower instead of eventually reaching the same set value because of corrective action taken by the feedback system. Some of these students even made calculations to the effect:

> (*Pretest, Home Heating System Version I, Question 2*)
> Cheryl: Well basically the difference is 33 [between the current and the desired value], and if it can only work half as hard as before and 100 would be the top number
> Then 50 would be, 50% would be ... half of 33 is 16 and a half.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For students, only portions of the system were highlighted and the rest of the system, including the iterations that would correct for defective actuators, was ignored. This points to possibly the piecemeal assembling of relationships to explain system behavior.

Notice that a stepwise sequential explanation to these multiple-choice questions is one way of bringing coherence to the interactions within the feedback system examples. However, students resort to this only sometimes and only when the student already suspects that something is wrong:

> (*Pretest, Light System, Question 2b*)
> (*The student is asked how to compensate for a degraded light sensor.*)
> David: [Set the dial] higher than 7
> Interviewer: Why's that?
> David: because the light meter is degraded and when he wants the level in the bat room to be at 7, the meter's going to be at 5.
> Telling you it's 5 when it's actually 7. So he should set it to a value higher than 7 cause then it'll
> [pause]
> Oh oops. You're right. Wait a second.
> Set the dial
> Oh, wants the bat room
> You should set the dial to the value of 7.
> Wait will it
> The light meter will tell
> [pause]
> Oops. The light meter begins to degrade. So once the light level gets to 7.
> When it's actually at 7 it's at 5, but then if it's at 5 it'll tell the luster buster to give it more. And so he should set it to 5
> Or he should set it to 9 and it'll say
> Just a second.
> It's at 7 and let's say it's at 5 and therefore
> And it's less sensitive to light so
> Ok, it senses at 5
> More watts to get it up to 7.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

> So say it's set to 7, but the things degraded so it won't sense as much light and so degraded and it'll say it's at 5. So it'll tell it to send more watts, and you'll actually be at 9. So send more watts, and if you
> If you set it to 5 blah, it will sense that it's at 3, and it'll send more watts, and 10 more watts and put it at 7.
> Okay.

This piecemeal use of relationships may be a result of the test form; multiple-choice questions are not conducive to constructing coherent explanations of systems. Rather, they focus on different parts of the system. Alternatively, the clinical interviews in which students were asked to construct one model that explains a variety of behaviors may force students to pay more attention to within model coherence. Likewise, design work in FAVL may be fostering the same set of coherence standards that is not enforced in disjoint multiple-choice question/answer forms. Thus, any advantages gained with work in FAVL may not appear at all in these particular multiple-choice test items because they specifically focus on different parts of the system.

System Parameters. One of the characteristics of an expert is the ability to identify key parameter values and relate them to larger patterns of behavior or interaction. There were few examples of this in the multiple-choice protocols. In particular, there was only one example of a student who appears to have established a direct relationship between gain and rise time in a proportional system without resorting to the idea of accumulated action. The following excerpt from this student, Max, is taken from his post interview. Note that Max first identifies the system as a proportional control system and from that identifies the relevant parameter

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

gain and the effects of a large gain on the rise time. He does not argue for increases in action over time like the other students, some of whose excerpts are provided above.

> (*Posttest, Light System, Question 3a*)
> Max: So it's like that proportional controller, I think. The gain
> It'll get it up faster.
> Interviewer: What do you mean proportional controller gain?
> Max: Um a larger percentage of the difference
> Um I'm not sure
> Interviewer: First of all why do you say it's a proportional controller?
> Max: because it's proportional
> to do difference instead of like 5 watts at a time. You adjust it to how much
> error you have. Um so then you have to set the gain
> I'm not sure how to explain it

This may be an example of movement from novice to expert where expertise in a field includes the ability to identify a system and key parameters within the system, such as gain, to reason about another key parameter of the system directly, without regenerating the relationship from a causal step-through of the system. This is only one student out of the 15 who worked with FAVL and, therefore, provides only a plausibility example of the potential learning that students who do design work in FAVL may have.

On the more mundane level, some students also seem to formulate a relationship between gain and overshoot. Without stepping through the system, students will mention that smaller rates of change is associated with increased precision which, in turn, leads to less overshoot.

4.3.5 Discussion

The purpose of this set of analyses was to try to identify how students reason about feedback when they are given the functional subsystem of these systems. The analysis shows that

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

certain parts are more readily understood. That is, students can relate how a change in one part changes the system. However, other parts are harder to grasp. Some of these difficulties seem to be addressed with the instructional material. For example, students who originally had trouble connecting the sensor with the rest of the system were better able to propagate sensor effects after instruction. This supports findings from the clinical pre-post comparison that show that students develop more sophisticated models with internally connected subsystems through instruction. In contrast, students have a harder time understanding the proportional controller presented in these problems. This also finds some support in the model type analysis, which indicates that fewer students, especially from the Non-FAVL group, were able to explain the behaviors that are unique to proportional control systems. Although there is marginally significant improvement in student explanations on items regarding the relationship between proportional gain and rise time, it is unclear if this improvement comes from a clearer understanding of the proportional relationship expressed by the controller.

The protocol analysis also revealed the extent students used step-wise causal reasoning wherein change is propagated around the feedback loop in the direction of causation. Directed relationships were not the only relationships that were used by students, and they did not always lead to correct results. The protocol gives examples of students' losing track of parameters as change is propagated around the system and of students' extrapolating, sometimes incorrectly, based on one iteration through the feedback loop. Consequently, it became clear that step-wise directed relationship was not the only type of relationship that students saw and used to help them reason through these feedback systems. Prominent among

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

these is a sense that these systems are regulatory systems and must move towards an equilibrium or a desired value.

An analysis of the relationships students used to answer questions about a particular feedback system example also shows that these relationships are not necessarily consistent and coherent in student explanations. This points to a piecemeal construction of answers for the question at hand.

4.4 Chapter Summary and Discussion

This chapter established a set of models that correspond to increasingly sophisticated explanations of system behavior and described the nature of the interactions that students use to reason about system behavior. The first analysis of students' clinical interviews described a progression of model types that can be used to assess the depth of knowledge students have regarding the inner interactions between the parts or functional subsystems of a system. This progression was applied to two example systems that students described, a home heating system and a pupillary control system. It appears that student models can fall under different categories for the two system examples. This, I posit, is a result of what is immediately observable within the system, the order of the controller, as well as familiarity with the system. The pre-post comparison of student models also indicates that the instructional activities we designed were instrumental in helping students develop that more sophisticated model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

However, when I looked at student answers to multiple-choice questions which included a description of the functional parts that make up a feedback example, there was only marginal improvement in pre-post score. A subsequent protocol analysis of the relationships students used show little qualitative difference in the way they answer these questions beyond improvements with some students who became aware of the role the sensor played in these systems. What might these results from these two different analytic cuts mean?

The discrepancy can have several explanations. The multiple-choice questions do provide a description of the physical parts and their functions, even though they are described in terms of the specific system used in the example. On the other hand, the clinical interviews ask students to come up with the parts and also to generate explanations for their coordinated interactions. These two types of tests, therefore, do not measure the same knowledge. If student performance on the multiple-choice did not change substantially between pretest and posttest, then the reason may be that once given the parts, students can readily integrate these parts to make predictions for the system. In support, the results are negatively skewed with more students having higher scores for the multiple-choice tests. This conjecture would then suggest that providing students a way of parsing the system into its constituent parts would be the key to learning more powerful models to help students reason about such systems.

This may not be the whole story. A protocol analysis of the multiple-choice response shows that there are some relationships that students repeatedly use to answer these questions, and they are not always used to generate a correct answer. The set of relationships that are used to explain a feedback system can be inconsistent and lack coherence. This too may be the result

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of the multiple-choice test form, which focuses on each isolated part of a system, one question at a time, that may encourage the use of relationships without regard for consistency between relationships. Although the multiple-choice questions were useful in helping to begin to characterize the types of relationships used, these relationships may be further filtered or different relationships may be highlighted or discarded within a more involved explanation task where students are asked to create a coherent set of parts and relationships that give rise to a collection of system behavior.

The model type analysis may, therefore, reflect improvements in student construction of a more coherent set of parts and relationships to explain system behavior. In the following chapters, I will examine the two pedagogical tools that were used within instruction to impart a more sophisticated model to students.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5 The Role of Comparison in Learning the Model

In the previous chapters, I suggested that developing a mental model that enables more detailed explanations and better predictions of feedback system behavior depends on learning the functional parts and internal interactions that constitute a system. Moreover, I posited that the process of comparison could help students re-represent their mental models according to the functional subsystems that make up these systems, and that learning to describe feedback systems according to a uniform set of functional subsystems can facilitate the recognition of the common underlying structure and patterns of behavior across different feedback instantiations. The results presented in Chapter 4 suggest that comparing different feedback systems helped students to see the structure common to these systems and to use more sophisticated models to explain feedback behavior.

The purpose of this chapter is to take a closer look at the role that the comparison activities used in Model Instruction had in helping students come to see the underlying structure shared by feedback systems. In particular, this chapter addresses the following questions:

1. Did comparison help students align feedback systems according to the functional subsystems of the canonical model?
2. Were students better able to see the underlying feedback structure after the comparison activities we used in instruction?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3. What role(s) did uniform relational terms play in helping students notice the similarities between physically dissimilar feedback systems?

More broadly, the analyses presented in this chapter explore the possible pedagogical role that comparison and relational vocabulary can have in helping students learn about systems and phenomena.

5.1 Theoretical Framework – Structure Mapping Theory

I will use the Structure Mapping Theory in order to ground my interpretations of the findings presented in this chapter. The Structure Mapping Theory (Gentner 1983) is a cognitive model of the analogical comparison process. According to the Structure Mapping Theory (SMT), the comparison process involves mapping elements in one example, the base, to another example, the target. Mappings can occur between objects (e.g., *furnace* :: *muscle*), between relationships (e.g., furnace *heats* house :: muscle *heats* body) and between object attributes (e.g., *red* house :: *red* muscles). Mappings between the base and the target are constrained by the following:

1. The one-to-one constraint. An element in the target can map to one and only one element in the base example.
2. The parallel connectivity constraint. If a relationship in the target is mapped to a relationship in the base, then that relationship's arguments must also map to the arguments of its match in the base.
3. The systematicity principle. Determining the best match from among the multitude of possibilities depends on determining which set of one-to-one mappings will give the most

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

matches, with preference given to higher-order[1] relationships (i.e., relationships between relationships).

This process of making one-to-one, parallel connective mappings that favor higher-order relational matches is called the process of alignment. The process of alignment can highlight similarities that previously have gone unnoticed (Gentner, Rattermann, Markman, & Kotovsky, 1995; Kotovsky & Gentner, 1996). It can promote the projection of candidate inferences in one example, the base, to the target. That is, elements are added to the target example in order to try to achieve a better set of matches (Clement & Gentner, 1991; Gentner, 1997). Alignment can also lead to re-representation of the target example (Gentner et al., 1997). For instance, one object or relationship can be 'expanded' into its constituent parts and relationships to allow for better matches. Alternatively, multiple objects and relationships can be collapsed into one object or relationship for better alignment.

The above framework sheds light on how comparisons can help students see underlying similarity (i.e., relational similarity) between surface dissimilar systems (i.e. examples which do not share common objects). Specifically, the process of alignment with preference given to higher-order relationships acts to highlight relational similarities while downplaying less inferentially powerful commonalities. Furthermore, when one of the examples in an analogy is less familiar to the student, the process of alignment can help students see underlying structure through the projection of candidate inferences and re-representation if necessary. Comparison, therefore, is not simply a process of matching what is already known about two

[1] The order of a relationship is defined by the depth of the relationship. For example, a relationship between two objects is a first-order relationship. A relationship between two first-order relationships is a second-order relationship, and so on.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

examples, but allows students to see previously unrecognized relationships between and within examples. The process of alignment is critical in allowing students to apply relationships and principles in a familiar example to understand an unfamiliar problem.

5.2 Analysis I: Can Unaided Comparison Help Students Align Their Feedback System Descriptions with the Canonical Model?

The purpose of this first set of analyses is to examine if comparison alone could help students extract the common functional subsystems that make up the canonical model. This is a particular look at student comparisons *before* these students were formally introduced to the canonical model and the relational terms that denote the functional subsystems. It serves to identify the potential promise and the possible limitations the process of comparing two feedback systems can have on helping students identify the common feedback structure.

I take two analytical slices at this question. First, I coded students' descriptions of the home heating system before comparison and of the home heating and another feedback system during comparison, and I performed a set of statistical analyses to determine if the comparison task helped students to identify feedback functions that went previously unnoticed. The results did not show any significant improvement in function identification. As the second analysis, I took a more detailed, qualitative look for the mechanism of comparison as posited by the Structure Mapping Theory to try to explain why this comparison activity helped some students, but not others, to see the functional subsystems for the two cases used.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.2.1 Activities and Material

To address this first question, I asked students to first describe how they think a home heating system works. I then asked students to compare the home heating system to another feedback system, a water regulation system that is similar to one that they may find in their toilet. As part of this comparison task, students were shown an animation of the water regulation system. (See Figure 5-1.) Students were instructed to look at the animation of the water regulation system and to compare that to the home heating system that they were asked to describe as part of their earlier clinical interview. For their reference, students were given short textual descriptions of each system. (See Appendix G.1.) Then each student was asked to compare the two systems by creating a common representation, using a diagram, a picture, or words that captures the similarities between the two systems, in particular, in how the two systems work. Figure 5-2 shows where the activities used in these analyses fall within the overall study design.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

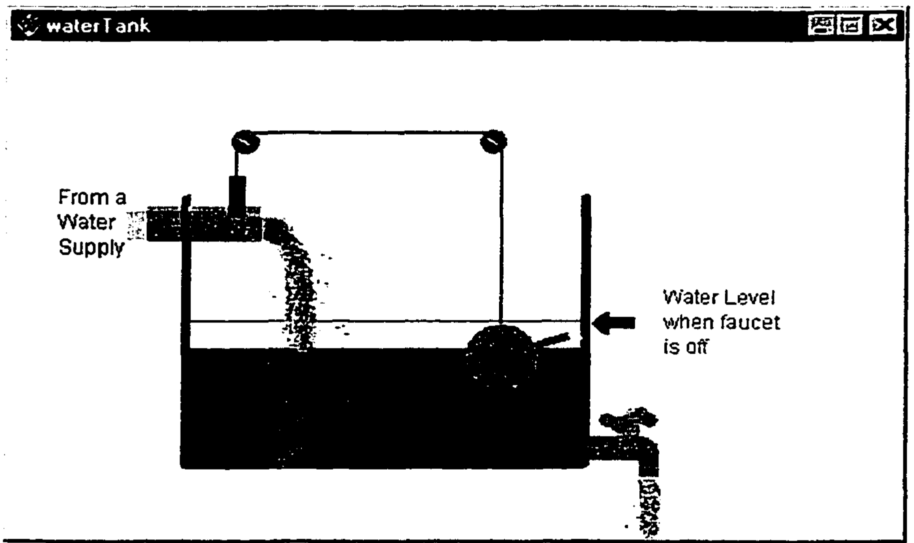


Figure 5-1. Screenshot of the Animation for the Water Regulation System. As the water level drops in the tank, the ball float lowers and lifts and opens the valve of the water supply pipe. This increases the water flow from the water supply into the tank. As the water level rises the ball float rises and lowers and closes the valve, decreasing the flow into the tank.

Pre-Instruction				
Pre-Instruction • **Home Heat Interview** • **Water regulation animation** • **Home Heat vs. Water regulation** • Multiple-choice questions • Pupillary Model • Design flower watering system • Multiple-choice questions	Model Instruction	Intermediate Interview	FAVL Design Project	Post-Instruction

Figure 5-2. Activities used in Analysis I (in bold).

The above student activities were videotaped, student's verbal utterances were transcribed, and accompanying paper artifacts were collected for analysis.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.2.2 Identifying Functions

In the first analysis, I compared the functions that students described during their pre-comparison interview about the home heating system to the functions that students described during the comparison task between the home heating system and the water regulation system. This analysis is targeted specifically at understanding if unaided comparison helped students align their descriptions to the canonical model. Consequently, within the coding scheme, I looked only for those functional subsystems summarized in Table 5-1. Although learning the canonical model also involves articulating the interactions between those functions, for the purpose of this analysis, I focus only on the functional subsystems. This is a first cut at characterizing what can be elicited through comparison; also, noticing interactions between subsystems depends first on an ability to identify those subsystems.[2]

5.2.2.1 Coding Procedure

I analyzed students' initial descriptions of the home heating system and their explanations of how the home heating and the water regulation systems are similar, and looked for mention of the functional parts that make up the canonical feedback model. The coding scheme that I used is summarized in Table 5-1.[3]

---

[2] Students often described these relationships between functions as a narration of events in which one subsystem (or parts that are associated with a certain function) does something and then another subsystem does something. Occasionally, students even described one subsystem passing information to the next. An initial coding for these relationships, however, revealed that these relationships were rarely mentioned during comparison activities. This may be due to the comparison task, which, unlike that specified in the clinical interview, did not ask the students to explain system behavior.

[3] The controlled process is excluded from this list to allow me to focus on the functional parts that implement control.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5-1. Coding Scheme for Canonical Functions.

Functional Part	Description
Sensor	the function of measuring the state of what is being controlled.
Set point	the desired state of the system.
Comparator	the function of comparing the measured to the desired state.
Controller	the functions that manipulate the discrepancy between the measured and the desired state of the system and determine an appropriate action. I also looked for similarities or differences students noticed about the type of controller. The heating system is an on-off system and the water regulation system is a proportional control system.
Actuator	the action that can change the state of what's being controlled.

To identify the functions that students described before comparison, I read through each home interview transcript, segmented the transcript by line[4], and coded for functions listed in Table 5-1. These results were checked against results obtained from the earlier mental model analysis. Recall that part of the coding procedure to characterize students' mental models involved analyzing the transcripts from students' home heating interview for descriptions of the canonical functions. (See Section 4.2.1) There were few discrepancies between the two coding iterations, and these few were resolved by another read-through, which looked in particular for other instances of the function in question.

To identify which functions students described during the comparison activity, I analyzed transcripts of students' verbal descriptions of the similarities and differences between the home heating and the water regulation systems and the representations they were asked to draw to describe the commonalities between the two systems. In this and subsequent

[4] A line roughly corresponds to a sentence or a statement.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

comparison tasks, students could articulate a functional subsystem in two ways. First, they could give a general description of the function:

Ids Sensor	This is the thing that monitors how much there is

Second, they could align objects that serve the same function:

Ids Sensor	I guess like the ball would be like where the temperature is at

Furthermore, some functions such as the comparator function were not reified in student descriptions. That is, students neither identified objects that act as the comparator nor described it with a single word. Instead, the function was embedded in narrative. For instance, the following was coded as a comparator function:

Ids Embedded Comparator	If it's not at the level it's suppose to be

Compare this to a reified comparator:

Ids Comparator	Irene: They both sort of have like a device that keep, that sort of like measures when it's too low or too high

This analysis does not distinguish between the two types of description.

While coding the transcripts, I noticed that although some students did not specifically identify a comparator or a controller function, these students did identify a more general regulator function. A regulator function is similar to the regulator that was described in the internally connected model introduced in Chapter 4. That is, it is a set of parts or events that determines what the actuator should do. Unlike the controller function, the regulator does not

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

determine the action to take based on the discrepancy between the desired and the current situation.

Finally, for the comparison task, I looked to see if students noticed the difference between the on-off control algorithm in the home heating system and the proportional control algorithm in the water regulation system. Students who noted this difference were attuned to not only the parts that make up the model but also distinctions between the control type that lead to different system behaviors. Therefore, noticing this distinction may be a precursor to developing the more sophisticated algorithmic model that was described in Chapter 4.

5.2.2.2 Coded Results

Table 5-2 shows the tally of the number of students who described the canonical functional subsystems in their initial home heating interview before comparison and in their description of the home heating and water regulation systems during comparison.

Table 5-2. Number of Students (N=30) who Identified Similarity before Instruction

	Sensor	**SPU**	**Comparator**	**Controller**	**Actuator**
Before Comparison	21 (70%)	29 (97%)	20 (67%)	20 (67%)	29 (97%)
During Comparison	15 (50%)	25 (83%)	16 (53%)	15 (50%)	29 (97%)

In analyzing these data, I began with a set of correlation analyses to see if groups of functions were typically identified together. There was a significant correlation between the comparator and the controller both before comparison (Spearman's rho = 1.0, $p<0.01$) and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

during comparison (Spearman's rho = 0.935, $p<0.01$). To a large extent, this result should not be too surprising since, according to the coding scheme used, the controller makes a decision based on the discrepancy between the current and the desired state of the system. It, therefore, stands to reason that if a student mentioned a controller that s/he would also mention the comparator function. Nonetheless, this high correlation between functional parts may have implications: First, learning this model may involve learning groups of functions and not one function at a time. So, learning about the controller may require concurrently learning about the comparator. Second, learning the feedback model may involve teasing apart functions that are treated as distinct entities in the canonical model but which are initially strongly linked with each other or simply seen as one entity. Case studies presented in Chapter 6 support this latter observation: Some students, even after they were taught the canonical model, had difficulties distinguishing the comparator and controller functions.

To understand if comparing the heating system to a water tank regulation system helped students extract parts of the canonical model that they did not previously identify in their descriptions of the home heating system, I performed a pre-post comparison. Table 5-2 shows that there was no improvement in identifying any of the functional subsystems through comparison. (Also see Appendix H for the data table for the accompanying McNemar Test for pre-post difference.)

To see if comparison was useful for certain populations, I performed additional tests on two smaller groups from the total 30 students. First, I looked at the transcripts of the nine students who previously described a system-as-whole or a boundary model for the home heating

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system. This is to see if these students were able to identify a comparator or a controller during the comparison task. Recall that students with either model did not articulate the comparator or the controller function in their initial explanations of the home heating system. Four of these nine students saw similarities in the controller and in the comparator subsystems during the comparison task; there was no significant increase in the number of students who noted these similarities (McNemar Test, $p=0.125 > 0.05$ for the comparator, and $p=0.375 > 0.05$ for the controller). However, taking another look at the same group of 9 students, I found that a significant number were able to identify some sort of internal regulator[5] (McNemar Test, $p=0.016 < 0.05$) during comparison. (The data table for each test can be found in Appendix H.) So, although not all these students were able to elicit a comparator and a controller through comparison, there was an improvement in identifying some internal subsystem that connects the sensor to the actuator in the model.

The second group of students I looked at consisted of students who previously held an internally connected model of the home heating system. Students who articulated this model type did not necessarily identify a controller or a comparator in their initial descriptions, and I was interested in seeing if they were better able to identify the comparator and the controller functions during a comparison task. McNemar Tests show no significant difference between the pre-comparison and during-comparison results for identifying either function ($p=0.50$ for

---

[5] The student described a general regulator function that decides how much action to take, a comparator that determines the discrepancy between the current and the desired state, or a controller that determines the action to take based on such a discrepancy.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the controller and p=0.50 for the comparator). (See Appendix H for the data table for each test.)

Finally, I looked to see if the comparison activity helped this same group of student to identify the difference between the on-off control in the home heating system and the proportional control in the water regulation system. Recall that students who held the internally connected model did not describe the control algorithm in any detail. None of these students noted the difference in the control algorithm for the two systems compared. In fact, all of the six students who noticed the difference between on-off and proportional control were students who had also described an on-off algorithm before comparison. That is, these students already had the algorithmic model.

Overall, these results do not indicate that unaided comparison between these two feedback systems significantly helped students to notice the functional subsystems that make up the canonical model. This may be because many students already came to this activity with some knowledge of the internal functional subsystems of the heating system, making it difficult to see any improvements. More specific analyses of the subgroups of students give a mixed picture for the role of comparison for identifying parts previously unseen. Students who originally held less sophisticated models identified the internal regulator functions, the key difference between the less sophisticated models (boundary and the system-as-whole) and the more sophisticated internally regulated model. But, it is unclear if it was the comparison process itself that helped students construct a more sophisticated model or the fact that students learned the internal details of the heating system through the textual description that

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

was provided as a reference to each student. Furthermore, comparison did not necessarily help tease out the comparator or controller functions. Nor did comparison between these two systems help students who held an internally connected model tease out the controller and comparator functions or to become more aware of the difference in the control algorithms. The next section will take a look at student protocols from the unaided comparison task to try to determine why the process of comparing the heating system to the water regulation system elicited some relational similarities but not others. Specifically, I will give examples from the protocol that indicate that unaided comparison can highlight common relationships and promote realignment according to shared relationships. However, because the two systems do not foster one-to-one mapping between physical objects that align according to the canonical functions, comparison between these two examples do not highlight all the shared relationships.

5.2.3 A Look for Mechanism

Nonetheless, the results from Section 5.2.2 do show that some students did see commonalities along some of the functional lines, although the improvement was not always statistically significant. To better understand how unaided comparison helped students see the functional similarities they did and why certain similarities remained hidden during comparison, I took a more detailed, qualitative look at students' talk-aloud protocols. In particular, I looked for the analogical processes that Gentner et al identified as those that can lead to learning and in the more profound cases, conceptual change (Gentner et al., 1997). These processes are: highlighting similarities, projection of candidate inferences, re-representation, and restructuring. Because of the nature of the task, I did not expect to see any examples of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

projecting candidate inferences since both systems mechanisms were made manifest either in text or in animation. Also, I did not expect to see any restructuring since any deep and overarching restructuring is unlikely when comparing just two examples (Gentner et al., 1997). I did, however, see examples in which comparison served to highlight the similarities between the functional subsystems of the two feedback examples and to foster re-representation of the two examples to help alignment according to the shared functional substructures. The following are examples of these processes within this activity and are used within the argument to bolster the role that comparison may have had in helping students see the canonical model. In many cases these examples are not typical of student utterances. Instead, they are intended to give a glimpse of the process of alignment in action.

5.2.3.1 Comparisons Help Highlight Functional Similarities

According to the Structure Mapping Theory, the process of comparison involves aligning two cases to maximize the set of shared relationships. When comparing two physically different examples such as the home heating and the water regulation systems, then the process of alignment should allow students to elicit the underlying similarity between the two that is based on their shared functional subsystems as well as the overall goal of system control. Recall that a function expresses a relationship between component behavior and the overall purpose of the system. Although the components and their specific behavior may differ between the two systems, these two examples share the same feedback functions described in the canonical model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Curtis' protocol provides one example of the potential power of comparison in highlighting functional similarities. Curtis was a student who described most of the feedback functions during his home heating interview. So, the following is not an example of a student using comparison to see the underlying functional structure that he previously did not notice in the home heating system. Instead, the following protocol is meant to illustrate how the process of comparison could highlight relationships shared by two systems, which originally went unseen.

Curtis began the comparison activity by noting that the heating and the water regulation examples are different systems. His evaluation of what makes them different, however, is based on their physical dissimilarity:

> Curtis: I mean looking at it [water regulation system], it doesn't really look like the uh the uh heating system like this.

Although previous research on similarity has shown that people's judgment of similarity depends on both superficial object matches and deeper, relational matches (Gentner, Rattermann, & Forbus, 1993), at first Curtis did not even notice the relational similarities between the two systems. Instead, it was only when he was asked to compare the two systems more closely that Curtis began to notice relational similarities. In the following, Curtis began by noting the similar overall system goal of these two systems and then identified some of the subsystems necessary to meet that goal:

> Curtis: They both kind of do the same thing.

Ids setpoint | I guess they're both adjustable cause you can change that string. You can adjust the length of that whole string there.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

And I guess they're both trying to do very similar things

...

Ids sensor | Depending on what you're doing in this case it's like a ball float and in the other case it's the thermostat.
But, you need something say that represent that monitors what the temperature is

Ids actuator | And you need another thing which gives out adds or adds basically whatever the water or the heat you know

Interviewer: Uh huh

Curtis: And then and then there's something that takes stuff out. In the case of the house, there's like you know a little valve [in water regulation system]

Curtis' protocol also suggests that he did not come to the comparison task with the canonical model in mind, which he then immediately applied to these two examples, individually. Instead, it was the comparison task itself that began to reveal these underlying similarities. This example suggests the power that alignment can have to bring focus to similarities between feedback systems and is in accord with other studies that have shown that comparison can help people see underlying commonalities (Gentner, Rattermann, Markman, & Kotovsky, 1995).

5.2.3.2 Realignment Allows Students to See Feedback Organization

However, comparing these two feedback systems alone did not allow all the students to tease out every function of the model. Why? One explanation is that some students had a different way of viewing these systems. A little less than one-third of the students identified mappings that organized around seeing the home heating and water regulation systems as systems to be used by people, identifying such similarities as "they're both utilities" and "you get bills." In

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

these cases, a common mapping included matching the dial on the thermostat in the home heating system to the faucet in the water regulation system, because both the dial and the faucet are objects that can be directly manipulated by a user to cause their respective system to give the user a desired output, either heat or water. On the other hand, students who organized their mappings around the idea of self-regulation matched the faucet to a window or the doors in the house because these objects are means of disturbing equilibrium that a control system would try to maintain. And, in this latter case, the thermostat dial is matched with the string in the water system's feedback assembly since they both allow a person to adjust the desired temperature or water level, respectively.

The utilities perspective led to different mappings that did not highlight feedback functions. Some of these students were able to realign their mappings to bring out some feedback functions during the comparison process. That is, in order to facilitate a better map, students re-represented the system from one in which the internals of the system were left vague and unspecified to one that was more detailed and included descriptions of the internal subsystems. For example, at the beginning of the comparison interview, Becky saw both systems as utilities that someone can turn on and off:

70° = Faucet	Becky: Okay, so if someone wants it to be at 70° or if someone wanted to turn on the faucet, then both of them would have something that turns on.

Part way through the comparison interview, Becky began to focus on what would happen when both systems are on.

Ids Embedded	Becky: So, it'll give off heat until it gets too hot and then it'll turn off.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Comparator and Controller	And then the water the valve will let out water until there's too much water and so it stops.

Finally, towards the end of the comparison task, Becky realigned her original mapping so that the faucet was no longer just something that is turned on and off by a person and, therefore, similar to the dial on the thermostat. Instead, the faucet was matched with something that cools the room since it disturbs the equilibrium of the system.

Faucet = room getting cooler	Interviewer: Is there something like the faucet for the room heating system? Becky: mmm I guess when it turns off it gets a little cooler

Nancy's protocol gives another example of the realignment that occurred during comparison that revealed the common mechanisms of regulation. At the beginning of the comparison task, Nancy matched the faucet to the dial:

Faucet = dial	Nancy: Well, there's some kind of regulator like the faucet or the dial that tells what you want the system to be at.

Part way through the comparison interview, Nancy began to draw a diagram (Figure 5-3) to explain how the two systems are similar:

	Nancy: That's [points to regulator box in diagram] tied to the kind of gauge that that
Ids Sensor and Comparator	that tells you where you're at and it's not quite where you want it to be
Ids Controller	like and this [*points to gauge in her diagram*] turns on
Ids Actuator	some sort of outside source like the water supply or the fire

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Ids Embedded Comparator and Controller	And if if it's not at the level it's suppose to be at, then this [points to outside source in her diagram] either turns on or turns off

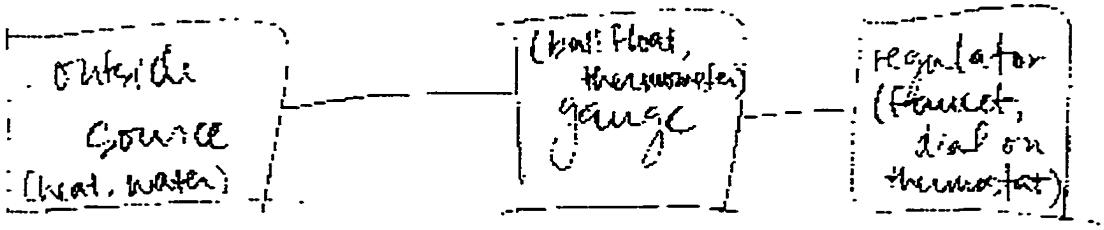


Figure 5-3. Nancy's Diagram that Illustrates the Similarities between the Home Heating and the Water Regulation Systems.

At the end of the comparison task, Nancy pointed out that the faucet should not correspond to the dial:

Faucet shifts equilibrium	Nancy: It [faucet] doesn't really like if if its goal is to maintain. It [faucet] shifts like, I don't know, the equilibrium or whatever. So, it's not helping it maintain anything.

5.2.3.3 Comparison Alone is Not Enough

However, for one student, the utilities perspective allowed the feedback functions to remain encapsulated in a 'black box' throughout most of the comparison activity.

> Yvette: One provides water, one provides heat
> Interviewer: Okay
> Yvette: They're both providing things with natural resources
>
> Interviewer: Is there anything similar about the way they work?
> Yvette: Yeah it's never like

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

No mention of feedback functions	It's never going to be like empty. And there's like a device there. Like there's like the supply like a natural supply that keeps the device always full.
	. . .
Temperature = Water out	Yvette: The home heating system is regulating the temperature in the house. And this system is regulating the water that you want to take out of it.
	. . .
	Yvette: You have a main supply and it's going to be huge relative to the [output]. And it's going to keep refilling.
Possibly the feedback device?	And it goes through a device, and the device is regulated by some human action to produce a certain amount . . .
	Interviewer: You started to say a little bit about the regulation thing. You said that it's something that a human does? Yvette: Well, the human would set it at something
Ids setpoint?	Like the machine is engineered to do what the humans have set it to.
	Interviewer: Where is that setting here [*point to water tank animation*?
Faucet = Temperature setting	Yvette: Here [point to faucet knob in animation] the knob in the faucet. Interviewer: Okay, and where is the setting for home heating? Yvette: um where? That would be the setting of a certain temperature.

It was only after the interviewer refocused this student on the overall regulation purpose of both systems that she began to address the internal functions of the system:

Interviewer redirects according to	Interviewer: I'm going to try to kind of suggest another way of looking at this, okay? Think about the system

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

overall goal of regulating levels	The purpose of this system [point to water regulation system] as trying to maintain the water level inside the tank. If you think about it that way, is it similar to the home heating system or does it just become something completely different?
	...
	The way this [water level regulation system] tries to keep this water level at a constant value and the way the home heating system is trying to keep the temperature in the room at a constant level.
	Yvette: Yeah, because the
	The that thing is going up and down and that is where it should be [point to water level].
Ids Embedded Comparator Controller	And, here if the room temperature is too low, this will turn on and supply more. And, if it's too much higher, then it's turn off.
	So it'll readjust it, and the same thing here.
Ids Embedded Comparator	If the water level is too high, then it goes back and then it gets readjusted.

The preceding indicates one of the difficulties in using unguided comparisons to help students see the underlying structure inherent in feedback systems: Systems can invite multiple, legitimate mappings. Students can assign different overall purposes to a system and may not recognize its self-regulatory goal. Students can also analyze the systems according to different levels of resolution; they can focus on different levels of explanation. So, although a student may note that two systems regulate themselves, s/he may not necessarily focus on the details of its mechanism.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Moreover, recall that according to the Structure Mapping Theory, the process of comparison depends on one-to-one mappings between elements in the target and the base. However, within these two examples as well as in most other practical implementations of feedback systems, multiple functions are often encompassed in one physical object[6] or one function can be implemented with many objects. This can potentially make it difficult for students to notice the shared functional subsystems. That is, if students focus on the physical objects in the system, then certain functions will be encapsulated within an object, and comparison between these systems may not promote differentiation between or identification of certain functions in the feedback system model since alignment would be based on one-to-one physical object matches. For instance, notice how in the above examples none of the students separated and reified the comparator and controller functions during this comparison task. Drawing out these functions through comparison depends on re-representations that cut across physical object boundaries. For students unfamiliar with functional partitioning, this may be difficult and can make the comparison between these systems along feedback lines seem weak.

Using comparison activities to help students see the common functional substructure of feedback system, therefore, needs to be better guided. Some of this guidance can come from the context of their work. According to SMT, judgment of similarity depends on the number, type (higher-order vs. lower-order), and interconnectedness of the mapping between target and base, but other cognitive processes including evaluating the appropriateness of the map and

---

[6] For example, the thermostat is the sensor, the comparator and the controller in the home heating system, and the ball float assembly is the sensor, the comparator and the controller in the water regulation system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the applicability to the problem at hand are also important in ultimately deciding which mapping to use in analogical reasoning. For example, asking students to design and build systems would require a more detailed component level view and may encourage students to look for internal functional similarities across designs. (I explore this pedagogical strategy in the next chapter.)

Students could also be given a set of vocabulary terms that denote the shared relationships in order to promote alignment according to a certain set of similarities. This is the approach we took when we designed the material that was used as part of the Model Instruction portion of our instructional sequence. (This material is described in Section 2.3.1.) Recall that this portion of instruction introduced students to the canonical model of feedback systems and the terms that denote the shared functional subsystems, through a set of comparison activities to a base example. In the following section, I will investigate the effects of teaching students the canonical model through comparison with relational terms as realized in this material.

5.3 Analysis II: Were Students Better Able to See the Underlying Structure of Feedback Systems after Instruction?

This section takes a targeted look at the effectiveness of the instructional material described in Chapter 3, which was designed to help students learn the canonical model for feedback systems including its functional subsystems and the relationships between these subsystems. More broadly, the analyses in this section explore the possible advantages of using comparison with relational labels in teaching students to see a system according to functional

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

subsystems. In the following set of analyses, I look in particular at student's ability to partition feedback systems into its constituent parts and to reintegrate them according to the canonical model. The hypothesis is that the instructional material facilitated student construction of a relational abstraction, or schema, of feedback systems that captures the common structure of these systems without specification of physical implementation. This, in turn, is applied in the identification of feedback systems and is used to align systems according to the parts and their interactions.

Three different analyses were performed to test the hypothesis: 1) I looked at the correspondences students articulated when they compared feedback systems after instruction, and I compared these mappings to the ones students made before instruction to see if there were improvements in identifying the functional parts. 2) To assess if students applied the model to identifying feedback systems, I looked to see if students were able to identify feedback systems from a set of systems and what criteria they used in their judgment. 3) Finally, I analyzed if and how students were able to partition feedback systems according to the canonical model and to articulate the relationships between these functional subsystems.

5.3.1 Activities and Material

During Model Instruction, students were introduced to the canonical model for feedback systems through a set of comparison activities. Now, to see if students were able to identify the canonical model that underlying all feedback systems after Model Instruction, I asked students to work through three activities as part of their intermediate interview. (Recall that the intermediate interview immediately followed Model Instruction.) First, I asked students to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

compare three systems, one pair at a time and to point out similarities and differences between each pair. Two of these examples were feedback control systems, a depth control and a volume control system; the third was a positive feedback system consisting of a speaker and an amplifier and served as the distracter in the triad. For each of these examples, students were given a short textual description of these systems, which gave a causal story of how the different objects in each system affect one another. (Note that the purpose of this comparison activity is to assess student understanding, and specifically, to determine if students represent the feedback systems that are presented to them according to the parts experts use to describe feedback systems. This is in contrast to the comparison activities used during Model Instruction, which served an instructional purpose.)

Second, I then asked each student to identify the feedback systems from the set. Third, I asked each student to use the template, shown in Figure 5-5, to partition each system that s/he thinks is a feedback system into its canonical subsystems and to specify the information that is passed from one component to the next. Recall that the signal flow through a system is used to characterize the interactions between the components in the canonical model. For any system that a student thinks is not a feedback system, I instructed the student to cross out those parts or those signal paths that do not seem to apply. Copies of the material that was used, including a description of the three system examples can be found in Appendix G.2.

These three activities were repeated during the post-instruction interview with another triad, two of which described feedback systems, a human thermoregulation and a eye pupil control system, and one, a feed-forward system, that served as a distracter (a camera's light exposure

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system). These system descriptions are included in Appendix G.3. Recall that the post-instruction interview for FAVL students occurred after their work with FAVL whereas the post-instruction interview for Non-FAVL students occurred approximately 6 days after their intermediate interview. Figure 5-4 highlights in bold the activities used in this set of analyses and places them within the context of the larger study.

Pre-Instruction		Intermediate Interview		Post-Instruction
• Home Heat Interview • Water regulation animation • **Home Heat vs. Water regulation** • Multiple-choice test • Explain Pupillary Model • Design flower watering system • Multiple-choice test	Model Instruction	• Multiple-choice test • Design washing machine • **Compare 3 Systems** • **Id Feedback Systems** • **Map Example to Model**	FAVL Design Project	• Multiple-choice test • Explain Pupillary Model • Design toaster • **Compare 3 Systems** • **Id Feedback Systems** • **Map Example to Model**

Figure 5-4. Activities used in Analysis II (in bold).

5.3.2 Parts Identified during Comparison Task

This section looks at changes in student mappings when they compared feedback systems before and after the instruction. The prediction is that if students learned to see the underlying structure of feedback systems, then they should align the feedback examples according to the canonical parts of the expert model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.3.2.1 Analysis

Student interviews during the intermediate and post-instruction activities were video taped and then transcribed for analysis. I then coded the similarities they describe when they were asked to compare the two feedback systems from the intermediate interview (the depth control and the volume control systems) and the two feedback systems from the post interview (human thermoregulation and the eye pupillary control system). I used the same coding scheme that I used in the pre-interview comparison activity described in Section 5.2.2.

5.3.2.2 Results

A count of students who identified the functional subsystems during the intermediate and post-instruction comparison assessment activities is shown in Table 5-3.

Table 5-3. Number of Students (N=30) who Identified Functional Similarities during Comparison

	Sensor	SPU	Comparator	Controller	Actuator
Pre-Instruction Interview (home heating system vs. water regulation system)	15 (50%)	25 (83%)	16 (53%)	15 (50%)	29 (97%)
Intermediate Interview (depth control system vs. volume control system)	13 (43%)	19 (63%)	10 (33%)	9 (30%)	16 (53%)
Post-Instruction Interview (human thermoregulation vs. eye pupillary control)	15 (50%)	19 (63%)	15 (50%)	13 (43%)	17 (57%)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In addition, the results of the intermediate interview show that three out of the thirty students were able to identify all the functional relationships in the feedback model, but the rest did not even after model instruction. In fact, one of the students did not see any similarity between the two feedback systems, while another five students identified no similarity along functional lines. For the post-instruction interview, six students identified all the functional parts in the post interview. All but three students saw similarities with one or more functional part associated with the expert model of feedback.

A set of McNemar Tests was performed to see if there was any improvement in students' ability to see commonality in the functional subsystems during these comparison activities. Table 5-4 shows the change in students' identification of the canonical parts between the pre-instructional comparison and the intermediate comparison activities, and Table 5-5 shows the change between the pre-instructional comparison and the post-instructional comparison. There were no improvements in students' identification of any of the canonical subsystems. In fact, students did significantly better at identifying the actuator function during the pre-instructional comparison activity than during either the intermediate or the post-instructional activity.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5-4. McNemar Tests Showing Changes (Pre-Instruction vs. Intermediate Interview) in Students' Identification of the Functional Subsystems during Comparison Activities.

Pre-Instruction vs. Intermediate Comparison (n=30)

Sensor (Intermediate)	**Sensor (Pre)**		
	Not Identified	Identified	
Not Identified	10	7	Binomial distribution
Identified	5	8	p=0.774

SPU (Intermediate)	**SPU (Pre)**		
	Not Identified	Identified	
Not Identified	3	8	Binomial distribution
Identified	2	17	p=0.109

Comparator (Intermediate)	**Comparator (Pre)**		
	Not Identified	Identified	
Not Identified	7	13	Binomial distribution
Identified	7	3	p=0.263

Controller (Intermediate)	**Controller (Pre)**		
	Not Identified	Identified	
Not Identified	9	12	Binomial distribution
Identified	6	3	p=0.238

Actuator (Intermediate)	**Actuator (Pre)**		
	Not Identified	Identified	
Not Identified	0	14	Binomial distribution
Identified	1	15	p=0.001

For those cases where $p<0.05$, students were better at identifying the functions during pre-instruction.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5-5. McNemar Tests Showing Changes (Pre-Instruction vs. Post-Instruction) in Students' Identification of the Functional Subsystems during Comparison Activities

Pre-Instruction vs. Post-Instruction Comparison (n=30)

Sensor (Intermediate)	**Sensor (Pre)**		
	Not Identified	Identified	
Not Identified	9	6	Binomial distribution
Identified	6	9	p=1.00

SPU (Intermediate)	**SPU (Pre)**		
	Not Identified	Identified	
Not Identified	3	8	Binomial distribution
Identified	2	17	p=0.109

Comparator (Intermediate)	**Comparator (Pre)**		
	Not Identified	Identified	
Not Identified	6	9	Binomial distribution
Identified	8	7	p=1.00

Controller (Intermediate)	**Controller (Pre)**		
	Not Identified	Identified	
Not Identified	7	10	Binomial distribution
Identified	8	5	p=0.815

Actuator (Intermediate)	**Actuator (Pre)**		
	Not Identified	Identified	
Not Identified	1	12	Binomial distribution
Identified	0	17	p=0.000

For those cases where $p<0.05$, students were better at identifying the functions during pre-instruction.

Running the same test on subgroups of students gave a similar set of results:

- For students who originally held the boundary or the system-as-whole models for home heating, there was no significant improvement in the functions they identified (McNemar

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Test, $p>0.05$ for the sensor, SPU, comparator, controller, and actuator). Likewise, there was no significant increase in the number of students who were able to identify these functions between the pre and the post-instruction comparison activities. (See Table 5-6 for the accompanying data tables.)

- For students who originally described an internally connected model for home heating, there were no significant differences between the pre-instruction and intermediate comparison activity (McNemar Tests, $p>0.05$) or between the pre-instruction and the post-instruction comparison activities (McNemar Tests, $p>0.05$). (See Table 5-7.)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5-6. McNemar Tests Showing Changes in Identification of the Functional Subsystems during Comparison Activities for Students who Initially Held The System-As-Whole or Boundary Model.

Pre-Instruction vs. Intermediate Comparison (n=9)

Comparator (Intermediate)	**Comparator (Pre)**		
	Not Identified	Identified	
Not Identified	3	4	Binomial distribution
Identified	1	1	p=0.375

Controller (Intermediate)	**Controller (Pre)**		
	Not Identified	Identified	
Not Identified	4	3	Binomial distribution
Identified	1	1	p=0.625

Pre-Instruction vs. Post-Instruction Comparison (n=9)

Comparator (Post)	**Comparator (Pre)**		
	Not Identified	Identified	
Not Identified	2	5	Binomial distribution
Identified	2	0	p=0.453

Controller (Post)	**Controller (Pre)**		
	Not Identified	Identified	
Not Identified	3	4	Binomial distribution
Identified	2	0	p=0.688

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5-7. McNemar Tests Showing Changes in Identification of the Functional Subsystems during Comparison Activities for Students Initially Held the Internally Connected Model.

Pre-Instruction vs. Intermediate Interview (n=6)

Comparator (Intermediate)	Comparator (Pre)		
	Not Identified	Identified	
Not Identified	1	1	Binomial distribution
Identified	2	2	p=1.0

Controller (Intermediate)	Controller (Pre)		
	Not Identified	Identified	
Not Identified	2	2	Binomial distribution
Identified	0	2	p=0.5

Pre-Instruction vs. Post-Instruction (n=6)

Comparator (Post)	Comparator (Pre)		
	Not Identified	Identified	
Not Identified	1	2	Binomial distribution
Identified	1	2	p=1.0

Controller (Post)	Controller (Pre)		
	Not Identified	Identified	
Not Identified	2	2	Binomial distribution
Identified	0	2	p=0.5

Finally, I compared the FAVL and the Non-FAVL groups in identifying each of the functional subsystems during the pre-instruction, intermediate, and post-instruction comparison activities. Since the only difference between the two groups is that one worked with FAVL

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

after the intermediate interview, I expected to see a difference, if there is one, only in the post-instruction data. A set of Fisher's Exact Tests comparing the FAVL and Non-FAVL group show no significant difference in identifying any of the functional subsystem during the pre or intermediate comparison activity, as anticipated. There was also no significant difference in identifying the functional subsystems during post-instruction, with one notable exception: FAVL students made specific mention of the similarities and differences between the type of control, whether it was a proportional or an on-off control system, Fisher's Exact Test, p=0.042, as shown in Table 5-8. (See Appendix H for the complete set of data tables for these tests.) This result is consistent with the findings reported in the previous chapter that show that significantly more FAVL students described an algorithmic model during their post-instruction interview.

Table 5-8. Fisher's Exact Test Showing Difference in the Identification of Controller Type during Post-Instruction.

Control Type	**Group**		
	Non-FAVL	FAVL	
Not Identified	15	10	n=30
Identified	0	5	p=0.042

Together these results indicate that students were no better at aligning feedback systems to the canonical model after instruction than before instruction. This may be because students did not learn the canonical model from the instructional material. That is, they did not know how to partition these systems according to the canonical model. Alternatively, students may simply not notice these particular relational similarities during comparison for the feedback examples used in the test sets. The feedback system examples used in the comparison task in the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

intermediate interview and in post-instructional interview may be more difficult to align according to the canonical parts because multiple functions are encapsulated in one physical object. In the remaining analyses in this chapter, I will show that students did learn the functions that make up the canonical model. Specifically, they were able to identify the functions when they were given a template that explicitly guides alignment according to the canonical parts. However, students did not spontaneously represent the systems according to the canonical model during the comparison tasks that were used to assess learning in the intermediate and the post-instruction interviews.

5.3.3 Identifying Feedback Systems

The purpose of this analysis is to assess if students used the structures described in the canonical model to help them determine if a system is a feedback system or not. As such, this analysis tries to determine if students did learn the canonical model even though they did not highlight these relationships during the preceding comparison task. Furthermore, learning to classify systems according to common structures is also an important part of developing expertise. This analysis, therefore, also serves to identify what relationships constitute the criteria for categorizing a system as a feedback system.

5.3.3.1 Analysis

During both the intermediate and the post-instruction interviews, I asked each student to consider the three systems, which they had just compared, and to identify which systems from the three are feedback systems. Recall that one of the triad in both the intermediate and the post interview was a distracter. Students were then scored on whether or not they correctly identified the feedback control systems.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.3.3.2 Results

Table 5-9 presents a tally of the number of students who identified the example listed as a feedback system. Not all the students were able to decide which systems were feedback systems until they had used a template that listed the parts and interactions of the canonical model.[7] These numbers are also provided in Table 5-9.

Table 5-9. Number of Students (N=30) who Identified Example as a Feedback System

Intermediate Interview	**Depth Regulation System**	**TV Volume Control System**	**Speaker -Microphone System (distracter)**
Before filling out template	28 (93%)	28 (93%)	9 (30%)
Only after filling out a template	2 (7%)	2 (7%)	-2 (eliminated as feedback system)
Post-Instruction Interview	**Eye Pupillary System**	**Human Thermoregulation**	**Aperture System (distracter)**
Before filling out template	29 (97%)	26 (87%)	26 (87%)
Only after filling out a template	1 (3%)	4 (13%)	3 (10%)

What is interesting about this data is not that most students were able to identify the feedback systems from the triad but that some students were fooled by the distracter in each set of three. During the intermediate interview, 30% of the students identified a positive feedback system as a negative feedback control system, and during post instruction, 87% of the students identified a feed-forward system as a feedback control system. It seems that students were

---

[7] I provided these templates as part of the activity, labeled "Map Example to Model" in Figure 5-4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

able then to identify feedback systems based on some set of system criteria. However, the criteria may not just be based on the identification of the canonical subsystems. This is most evident in students who identified the speaker and microphone assembly as a negative feedback system even though it is difficult to argue for a system partitioning that aligns with the negative feedback model.

On the other hand, the aperture system in a camera, which was the distracter system in the post-interview, can be partitioned into the functional subsystems found in feedback control systems. Instead, it is the nature of the relationships between the parts that distinguishes it as a feed-forward system. Specifically, the camera aperture control system that is described makes a one-time calculation of the aperture setting before film exposure; the cyclic nature of the feedback loop is missing from this and other feed-forward systems. Some students argued that if the controlled variable is the light entering the camera and not the light hitting the film, then the system could be correctly construed as a feedback system, provided that constant adjustments are being made by the system. This may explain why most students identified the camera system as a feedback system.

To see if students considered functional structure in their evaluation, I looked at student transcripts to determine what criteria they used to determine if a system was a feedback system. The top four types of relationships that students used in their judgment are shown in Table 5-10. Note that these criteria are not mutually exclusive. These are:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- Functional Parts. Students tried to identify some of the functional subsystems that characterize the canonical model. A feedback system, therefore, is partially defined as consisting of certain required functional parts.
- Adjustment/Reaction. A feedback system is any system that reacts to its surroundings. All the mental model types described earlier in Chapter 4 include this basic relationship.
- Control/Maintenance. Students described the overall goal of the system. A feedback system is a system that tries to maintain an equilibrium or steady state value.
- Cycle. Students pointed out the cyclic nature of the system and mentioned that information is passed back and forth between parts of the system.

Table 5-10. Relationships Used to Judge if a System is a Feedback System.

	Functional Parts	**Adjustment/ Reaction**	**Control/ Maintenance**	**Cycle**
Intermediate Interview (N=24)	13 (54%)	9 (38%)	7 (29%)	6 (25%)
Post-Interview (N=23)	13 (57%)	10 (43%)	8 (35%)	7 (30%)

Only the top four relationship types are shown. Students who did not articulate any criterion were not considered in the total N.

Looking in particular at the nine students who misidentified the positive feedback system as a feedback control system, I found that six of these students did not try to identify the functional subsystems. Instead, a system was a feedback system if there was a cycle or if the system reacts, in any way, to its environment. Given these loose criteria, a positive feedback system would be considered in the same class as a negative feedback system. What was surprising, however, was that 3 of these 9 students who believed that the speaker-microphone system was

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

a feedback control system did try to identify functional parts; nonetheless, they failed to eliminate the positive feedback system as a feedback control system. This suggests that at least some students had difficulty applying the canonical model to different systems.

5.3.4 Mapping the System to the Canonical Model

Were students able to apply the canonical model to different system instantiations? To answer this question, I looked to see 1) if students were able to partition these systems when they are given the part names in a template and 2) if they were able to describe how these parts were linked to each other. Note that the template is diagrammatically similar to the base example (described in Section 2.3.1) and to the general model of feedback systems that students were taught as part of their Model Instruction. Therefore, the template provides additional supports, or reminders that may help students fill in the blanks. A copy of the template is shown in Figure 5-5.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

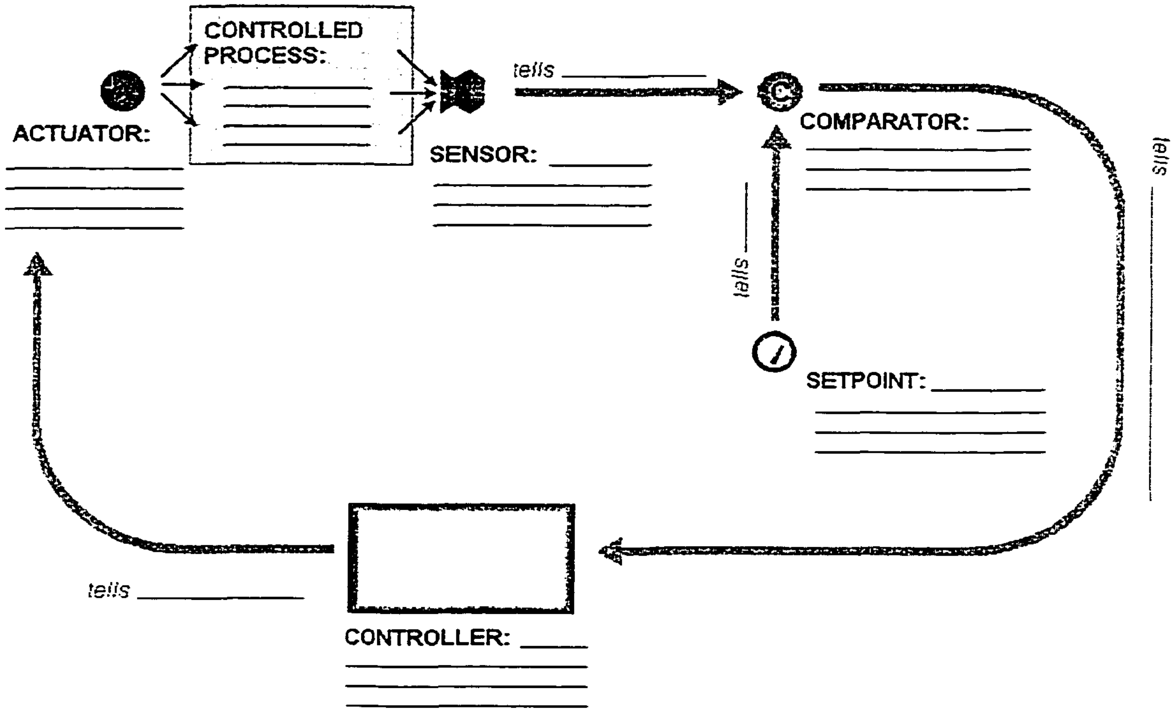


Figure 5-5. Template of the Canonical Feedback System with Relational Terms

5.3.4.1 Analysis

I scored students' completed templates to see if they had correctly identified each part. Students varied in the level of detail of their partitioning. For example, in identifying the actuator for the human pupillary system, some students identified the actuator as the specific muscle that moves the iris (this information was provided in the text), while other students identified the iris with no further details. I did not distinguish between different levels of granularity within their responses. All responses that identified a part that performs the said function were scored as being correct. I only scored the templates that students filled out for those examples that were feedback systems. Some students did fill out templates for the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

distracters; these are not included here but instead will be addressed in a qualitative analysis in the subsequent section.

5.3.4.2 Results

The results of this analysis are tabulated in Table 5-11 and Table 5-12.

Table 5-11. Number of Students who Correctly Identified the Functions Using the Template.

Intermediate Interview	**Sensor**	**SPU**	**Comparator**	**Controller**	**Actuator**
Depth Control System	30 (100%)	29 (97%)	29 (97%)	27 (90%)	30 (100%)
Volume Control System	30 (100%)	30 (100%)	28 (93%)	29 (97%)	30 (100%)
Post- Interview	**Sensor**	**SPU**	**Comparator**	**Controller**	**Actuator**
Pupillary Control System	26 (87%)	26 (87%)	28 (93%)	29 (97%)	30 (100%)
Thermoregulation System	28 (93%)	29 (97%)	27 (90%)	29 (97%)	30 (100%)

The results in Table 5-11 indicate that most students, although they may not have been able to identify these subsystems in the preceding comparison task, could identify them when given the template with the relational terms. This suggests that students did learn the functional subsystems of the model enough to allow them to partition a set of physically diverse systems according to the same functional lines.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5-12. Number of Students who Correctly Identified the Type of Information Passed Between Components

Intermediate Interview	**Sensor-Comparator**	**SPU-Comparator**	**Comparator-Controller**	**Controller-Actuator**
Depth Control System	30 (100%)	23 (77%)	25 (83%)	26 (87%)
Volume Control System	28 (93%)	19 (63%)	24 (80%)	26 (87%)
Post- Interview	**Sensor-Comparator**	**SPU-Comparator**	**Comparator-Controller**	**Controller-Actuator**
Pupillary Control System	29 (97%)	16 (53%)	25 (83%)	28 (93%)
Thermoregulation System	29 (97%)	20 (67%)	25 (83%)	23 (77%)

However, students had a slightly more difficult time specifying the information that was passed between the different functional parts. It is difficult to tell from this data if students simply did not attend to the information that is passed. For example, the number of students who did not correctly identify the information that is communicated on the SPU-Comparator link simply did not specify anything for that item. On the other hand, it is possible that the information communicated on some links were not well understood at this point. This may be the case especially for the relationship between the comparator and the controller; most students who were wrong on this item specified an action that should be taken to compensate for a discrepancy instead of the results of the comparison. This observation concurs with earlier analyses that show that identifying the comparator and the controller functions during the earlier pre-instruction comparison activity is highly correlated. This may also indicate a difficulty in reifying and separating the two into distinct functions. Furthermore, one of the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

case studies in Chapter 6 will also indicate that the student had trouble separating these two functions within her design work. (See Section 6.2.2.1.)

5.3.5 Discussion

The results of these three analyses suggest that most students learned the parts of the general model and that when they were provided with an external aid, a template, they could apply this model to partition various feedback systems. However, without the external aid, students did not necessarily recognize these feedback systems according to canonical lines; there were no improvements in students' ability to align feedback systems according to the shared functional structure during the intermediate or the post-instruction comparison tasks after model instruction.

I had originally suspected that because the feedback system model was the only model they were taught, students would try to identify the subsystems of the feedback model during these comparison activities. That is, students would try to 'game' the test. On the contrary, students did not do better in identifying the functional parts in comparison even after instruction. On possible explanation may be that different pairs of systems highlight different similarities; some functions can be obscured within a particular system; that is, they are not substantiated with a tangible object or set of objects. For example, neither the thermoregulation nor the eye pupil control systems has a physical entity that can be clearly identified as providing the setpoint value whereas in the depth control system, a diving chart indicates the appropriate depth level. Consequently, when students compared the thermoregulation system to the eye

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

pupil system, it was more difficult to extract the SPU function than when students compared the depth control system to a volume regulation system.

Also functional matches may have been difficult because the examples that were used did not always have a one-to-one relationship between a physical object and a canonical function. For instance, in the volume control system, the TV watcher is the sensor and the comparator and the setpoint. As I pointed out earlier, the Structure Mapping Theory posits one-to-one mappings between objects and relationships, but if students were initially focused on relationships between discrete objects or could not decompose the objects into its constituent objects, then comparison will not draw out the functional similarities.

Finally, considering that each system encompasses a number of possible relationships and possible partitioning of parts, it is not too surprising that students would not originally align these examples according to the canonical model. Even work with FAVL did not change the manner by which students encoded these examples and the similarities they saw. Research in child development indicates that similarity judgments are initially conservative based on object and lower-level relational matches. Relational matches increase with domain knowledge (Gentner, & Rattermann, 1991). To jump to seeing similarities that cut across object boundaries may not be immediate and may, in fact, require additional effort with material aids to help re-represent those examples.

The results of these analyses suggest that students were able to re-represent the feedback systems according to the canonical model once they were given a template. In fact, a few

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

students needed to look at the template with the names of the parts before they were able to determine if a system was a feedback system or not. And, almost all the students were able to perform a functional partitioning once they are given the relational labels and the abstract structure whereas they were not able during preceding the comparison task. This suggests that students were constructing a representation of these systems that was different from the one they used in comparison. The template was, therefore, an external aid that was facilitating system re-representation.

5.4 Analysis III: The Role of Vocabulary

One of the original premise of our instructional design was that by giving students the terms that denote the functional relationships in feedback systems, students would focus on this particular functional partitioning and encode feedback systems according to these parts as well as according to object features and other relationships that they notice. Encoding these examples according to this particular partitioning is important to allow future retrieval according to relational similarities and not according to surface similarities. That way, students could use a previous feedback case when they encounter another feedback system even of a different physical configuration. However, the results from the previous analysis suggest that students did not readily apply the general model in their comparisons. What's more, the instructional material, which relied on comparisons using relational terms, may not have been enough to help students encode other feedback examples according to the general expert model. Instead, it was the act of mapping the system into a template using relational labels that allowed students to re-represent the systems according to the expert partitioning.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The purpose of this last set of analyses is to take a closer look at the role that vocabulary may play when students compare and then re-represent these systems. I will analyze if relational labels were used during comparison and how the labels were used when the students were asked to partition the feedback system according to their functional parts.

5.4.1 Were Relational Labels Used in Comparison?

To determine if relational labels were used during the comparison activity, I searched through each student's transcript from their intermediate and post-instruction comparison tasks for mention of the terms: sensor, SPU, comparator, controller, and actuator. Recall that during these comparison tasks, students were first asked to read through textual descriptions of three systems and to then to compare these systems, two at a time. They did not have the template with the relational terms available to them during this comparison.

Table 5-13 shows the tally of the number of students who used these terms during the intermediate and the post-interview comparison activities.

Table 5-13. Number of Students who used Relational Term in Comparison.

	Sensor	**SPU**	**Comparator**	**Controller**	**Actuator**
Intermediate comparison	1 out of 12 (8%)	2 out of 19 (11%)	2 out of 7 (29%)	3 out of 10 (30%)	2 out of 16 (13%)
Post-Instruction comparison	7 out of 15 (47%)	7 out of 19 (37%)	5 out of 15 (33%)	6 out of 13 (46%)	5 out of 30 (17%)

This count is the number of students who used relational term out of the total number of students who identified that functional similarity during the comparison task.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

During the intermediate comparison, few students used the relational terms to describe the functional similarities they noted. Slightly more students used the terms in their post-interview comparison. There were no significant difference between the FAVL and Non-FAVL groups in the use of the relational terms with two exceptions: FAVL students used the term actuator and controller more often during the post-instruction comparison, Fisher's Exact Test p=0.042 for the actuator and p=0.017 for the controller. (See Table 5-14 and Table 5-15. The complete set of data tables for these tests can be found in Appendix H.)

Table 5-14. Fisher's Exact Test Showing Difference in Use of the Relational Term "Controller' during the Post-Instructional Comparison Task.

Controller	**Group**		
	Non-FAVL	FAVL	
Not Used	15	9	
Used	0	6	p=0.017

Table 5-15. Fisher's Exact Test Showing Difference in Use of the Relational Term "Actuator" during the Post-Instructional Comparison Task.

Actuator	**Group**		
	Non-FAVL	FAVL	
Not Used	15	10	
Used	0	5	P=0.042

These results do not indicate that the labels, or at least the articulation of the labels, were necessary in allowing students to identify the functional similarities between two feedback systems. Otherwise, it is difficult to determine the role that the vocabulary had in helping

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

students compare feedback pairs with the above count. I can, however, offer some speculations based on a closer look at the students' talk-aloud protocols.

There are some indications that these labels may be instrumental in helping students determine the underlying similarities. For example, when David first compared the human thermoregulation system to the eye pupillary control system, he could not see any similarities between these two apparently different systems, but he then reconsidered and identified them as both being feedback systems. To do so, he began by calling out the names of the functional parts that make up the canonical systems and only then identified the similar entities from each example that implement these functions:

	Interviewer: Um, so when you look at these two [thermoregulation system and eye pupil control system], anything similar?
Ids feedback system	David: I want to say no but They're both feedback systems.
	Interviewer: Okay.
Ids sensor	David: These are the sensors.
Ids comparator	These are the comparators.
	...
Ids sensors and comparators	The eye where The retina's the sensor and the retina's the comparator. The thermoreceptors are the sensors and the comparators

The above excerpt seems to indicate that the relational terms may serve to remind students of the functional subsystems that make up the canonical model and guide the identification of components that implement those functions in each system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

On the other hand, there were many more students who did not use the relational labels during the intermediate and post-instruction comparison tasks. Some of these students may have chosen not to use these words in their descriptions, but many students also simply did not notice these functional similarities at all. It is possible, therefore, that the relational terms that students learned during Model Instruction did not affect the way students initially see the examples used in the intermediate and post-instructional interviews. That is, they did not encode these examples according to the relational terms. However, students were able to successfully map the feedback systems to the template, and these terms may have been useful in helping students re-represent these systems into their canonical parts. In the following section, I will consider how the relational vocabulary is used to help students carve up their feedback system examples. In particular, I will give examples that show that students used these terms to help them focus on the functions and to determine whether or not a specific object in an example did or did not perform the function within the larger system.

5.4.2 How were Relational Labels Used?

In the following analysis, I take a qualitative look at how students used the relational labels to re-represent a system according to its canonical parts. I look specifically at students' talk-loud protocols when they were trying to map the parts of a system to the canonical parts using the template that I provided. The talk-aloud protocols of students mapping the negative feedback systems to the template showed that these mappings were fairly straightforward with most students simply identifying the correct functional subsystems without further explanation. Although many of the students also tried to map the feed-forward system, which

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

is the distracter in the triad used in the post-interview, the protocols from that segment do not shed light in particular on the use of relational terms. Instead, the most revealing data on how students used or misused the relational terms came from the intermediate interview when nine of the thirty students tried to fit the positive feedback system into the template for the negative feedback system. The following are observations on these students' attempts to apply the template and the relational terms to the microphone and amplifier system.

5.4.2.1 Relational Terms Help Focus on Functions

Some students used the terms to focus on the relationships that exist in the example. For instance, Alice began the interview by identifying the distracter as a feedback system. But, when she began to map the parts of the system to the template according to the relational terms, she became more focused on incongruous functions (e.g., the comparator) as well as a difference in the overall system purpose:

> Alice: I changed my mind [the distracter is a feedback system]
> Interviewer: You changed your mind?
> Alice: Yeah, for this one [the distracter]
> ... I usually start with the controlled process

Overall system purpose	It was kind of hard to figure out what's the control What it's trying to control.
	How.
No comparator	I don't know how there could even be a comparator or anything.

> Interviewer: Is there anything about this [feedback control] model that applies?
> Alice: Well, there are like sound waves that are changed to electric waves.
> Electric waveforms. So, I guess one part would tell like the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

microphone to send the sound waves to the speaker. [Traces the line from the comparator to the controller on the template]

And the speaker would take that and kind of

I guess

I guess it would send this as an electric wave and the speaker change it into a sound wave.

No setpoint or comparator | But there's really no set point and no comparator.

Likewise, Irene was a student who originally identified the microphone and speaker assembly as a feedback system. When she was asked to mapped the system parts to the canonical model represented in the template, she realized that the model did not apply:

Irene: I mean like sort of without this [points to comparator and SPU]

Identifies sensor | There's something like

The microphone is the sensor that senses the sound waves, but isn't it like

And it changes it to something, but it doesn't really. It's not

It's not

It's sort of not really changing

. . .

Interviewer: Okay. What if you could change this?

Irene: Uh huh

Interviewer: What would you change so that this can describe what goes on here [points to microphone]?

Irene: Um I guess

No comparator | I really don't know what it's comparing it to again.

Interviewer: Okay

No SPU | Irene: So, I don't know if there's like a set point

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Six students out of the nine who initially identified this example as a feedback control system eliminated the microphone and amplifier system as an example of a feedback control system when they began to apply the template. That is, the template with the relational terms encouraged students to reconsider their initial assessment of the microphone-speaker system as a negative feedback system. Although it is unclear if the terms alone fostered this re-representation, the above examples give some indication that the labels, or at least the template, helped students focus on and consider each functional part. In this particular case, most of the students eliminated the positive feedback example because it lacked an identifiable setpoint and a comparator.

5.4.2.2 Relational Terms can be Vague and Powerless

Alternatively, there were a few students who were convinced throughout most of this exercise that the positive feedback system fits with the canonical model and persisted in trying to map the distracter to the feedback template. When I looked at how the vocabulary was used, I found that the labels provided little help in guiding the students' parts identification because the terms were applied loosely with little of the specificity that gives them their power. Curtis was one of these students. For Curtis, 'sense' was used to mean 'pick up' or 'detect' and not 'measure', and 'compare' was used to mean 'change' or 'match':

Sensor = microphone	Curtis: okay the microphone picks it up, right. And, it sends electric sound waves to
Comparator = microphone	This [points to comparator and sensor on template] is all part of the microphone and the comparator takes the
	It [sensor] sends the electric sound waves to the comparator [points to setpoint]
Setpoint =	which has the electric waveform

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

electric waves	
Comparator 'changes' sound to electric wave	which [points to comparator on template] says to change the sound wave to electric waveform with the same pattern, which I thought was a key kind of thing as the incoming sound wave.
Comparator combines sound and electricity	It [comparator] kind of pairs the two ... and makes this one [comparator output] out of them both
Controller = amplifier	sends it to the amplifier which gives an electric signal to the speaker which put it back into the room

The above excerpt shows that Curtis knew that the comparator combines two signals, but he was unclear as to how exactly the two should be combined. He did not realize that the combination should be a comparison.

Instead, Curtis relied on physical placement to identify functional parts. For example, once Curtis convinced himself that the comparator was the microphone, he reasoned that the setpoint should be the electrical outlet for the microphone; the setpoint became something, anything that physically feeds into the comparator:

	And, this [points to sensor and comparator on template] would be the plain old microphone.
Setpoint = electrical outlet	And, this would be just like the electricity from the wall or something.

There were no indications that at this point in his explanation, Curtis was using the meaning of the relational terms to help him understand the appropriateness of this model to this example. This example also gives further support to the power of surface similarities to (mis)lead

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

students in learning. For some students, the relational terms were not enough to redirect them to the relationships encompassed in the canonical model.

5.5 Summary

The set of analyses presented in this chapter explored the possible role that analogical comparison aided by relational vocabulary could play in helping students learn an expert model of feedback systems. The study focused primarily on one aspect of learning feedback systems: the parsing of feedback systems into its functional parts according to a common underlying structure.

To some extent asking students to see feedback systems according to the specific set of relationships described in the canonical model was difficult to effect through unaided comparison. Functional partitioning does not organize along physical lines making it difficult to extract these functional similarities based on comparison alone. This is especially the case for 'real-life' feedback systems in which one physical component may serve multiple functions. So, when I compared the functions that students identified for the home heating system, before they looked at another feedback system, to the functions that they identified when they were asked to align the home heating system with another feedback system, I found no general improvement. However, students who initially had a system-as-whole or boundary model noted a regulator function within their comparisons. So, the process of comparison may help some students draw out some functions that define the canonical feedback system. But, this comparison task was not enough to elicit all the functional components for all the students. This result could be a consequence of the examples I used; some functions such as

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the controller are less prominent (i.e., are not associated with a concrete and discrete physical object) in home heating than in a human thermoregulation system. However, the examples I used in the pre, as well as the intermediate and post, interview were based on real world feedback examples, and these results may indicate how difficult it would be for students to learn this model based only on comparisons between everyday, familiar systems. The process of comparison, therefore, is not an all-powerful force that allows students to extract the canonical model from any two feedback system examples.

Even after Model Instruction, students did not show a significant improvement in identifying the functional subsystems during the comparison tasks used in the intermediate and the post-interview. (Recall that during Model Instruction students were taught the canonical model and the relational labels for each of the functional subsystems.) This result suggests that students did not always `represent, or encode, these feedback examples according to the canonical model. (This is assuming that the similarities students noted during these comparison tasks are indications of how they internally represented these systems.) This, in turn, has implications on students' ability to retrieve these feedback cases based on their shared functional structure.

This was not a result of students failing to learn the parts of the canonical model; a subsequent activity showed that most students were able to partition these same feedback systems according to the canonical parts. Instead, students did not spontaneous apply the canonical model to system description. Systems are rich in relationships, and students seem to be conservative in the application of this functional partitioning during these comparison tasks.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In fact, a subsequent analysis indicates that students may be using criteria other than shared functional structure to determine whether or not a system is a feedback system. Instead, most of the students were re-representing the systems according to the expert partitioning only when they tried to map the feedback examples into a template with the relational labels.

One of the assumptions that guided our instructional design is that giving students the relational labels that denote the functions shared by all feedback control systems would help students recognize their common structure. At the end of these sets of analyses, it is still not clear what role, if any, these relational terms played; the study design makes it difficult to tease apart the role that relational terms played in student learning. The intermediate and post interviews show that a majority of the students did not use these terms spontaneously to guide their comparison, although all the students were able to use the terms and its associate model to identify the functional parts of the feedback system examples later during the interviews. Again, this latter result demonstrates that students understood how to apply these terms on some level. There is some evidence from a protocol analysis that indicates that the relational terms seem to help some students focus on the type of functions they should look for in a feedback system and to determine which systems are not feedback systems. On the other hand, there were other students who did not seem to benefit from the relational terms; the relational terms lacked specificity and were loosely applied to system descriptions. Instead, physical placement seemed to play a larger role in (mis)guiding these students in parsing systems.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In general, the intermediate and the post interviews reveal that providing a canonical model and a set of relational terms that denote its parts can be beneficial in helping students parse systems into key functional parts and in revealing the underlying relational structure. Students were able to parse the feedback examples into its constituent canonical functions once they were given a template. However, students do not spontaneously apply the canonical model and must be asked to do so in order to facilitate representation along functional lines. These data also suggest that students need some guidance in applying the terms of the model. For example, they need help to focus on functional relationships and not physical placement and to develop a more specific meaning of the parts that make up this model. In short, comparisons aided by relational terms may be useful tools in instruction, but may not be enough in and of themselves in helping students arrive at an understanding of the underlying structure of feedback system. In the following chapter, I will elaborate on what I mean by developing a richer understanding of the parts of feedback systems and will describe design as a complementary activity that can facilitate students' understanding of feedback systems.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6 Learning through Design with FAVL – A Set of Case Studies

The purpose of this chapter is to take a closer look at how students developed their understanding of feedback systems through design work in the FAVL computer-based learning environment. Using a set of case studies, I will illustrate how students' understanding changed and discuss why certain changes occurred while others did not. These case studies serve to complement the findings reported in the previous two chapters by providing a more detailed look at the process of change and not just the consequences of working in FAVL. In particular, this chapter will look at three aspects of students' evolving understanding of feedback systems in the course of their design projects:

- *Refinement* of the components and signal flow that make up the canonical model. The analysis in Chapter 5 indicates that students who worked with FAVL were able to explain feedback system behavior in greater detail compared to their Non-FAVL counterparts. This implies that students were learning more sophisticated models for understanding feedback behavior as they worked on design projects in FAVL. This chapter looks at how the FAVL students learned these more sophisticated models during their design work on the computer. Specifically, I provide a set of examples to show how students refined the meanings they gave to the different functional subsystems that make up the canonical model, differentiated previously confounded parts, reified the functional partitioning, and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

defined and used the information that flows through a feedback system. I will propose a framework for understanding these changes and argue that refinement occurred as students tried to coordinate three different perspectives in describing their feedback designs.

- *Redefinition* of the components and information in the canonical model. Students did not merely refine but also redefined the roles that components had, using familiar components in novel ways, for example, to accomplish a different function in their designs and placing components in configurations different from the canonical feedback loop. In addition, students began to create new information types by combining components and signals as they worked through their design projects. This chapter gives examples from students' work in FAVL to illustrate the nature of these redefinitions.

- *Reuse* of common patterns of feedback interactions across different control system designs. Results from Chapter 6 show that students learned to apply the canonical model to describe different feedback systems according to a common set of functional subsystems. Furthermore, some of the protocol data from Chapter 6 suggest that uniform relational terms may promote recognition of these similarities between physically dissimilar systems. This chapter examines students' design work to see if students recognized common patterns of feedback interaction across different FAVL projects and how they used the similarities they noticed within design work. These case studies indicate that students often made use of the shared canonical model as a basis from which they could begin their redesign. Design work also afforded students an opportunity to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

learn other patterns of feedback behavior and to associate those behaviors to specific classes of feedback design (e.g., a proportional from an on-off feedback system).

Each case described in this chapter includes very detailed descriptions of portions of students' design work. To help the reader, a summary of the main points of each case follows each description.

6.1 Data Corpus

These case studies are based on the design experiences of three students as they each worked through four design projects in FAVL: a room temperature control, an object tracking, a cruise control, and a collision avoidance system. The students worked alone on these design projects at their own pace for approximately 1.5 hours each day over 3 consecutive days. They worked in an undergraduate computer laboratory that was largely unoccupied except for the one occasional programmer and myself.

I videotaped the students' work on FAVL, documenting the series of steps that they took to build each design and the sequence of redesigns they created as they moved toward the final solution. The videotapes also captured any comments the students made, discussions they had with me, and questions they asked along the way. These videotapes were transcribed for analysis. In addition, I saved each of the designs they created in FAVL in computer files for analysis.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.1.1 The Students

The three students chosen for these cases studies were selected from the 15 FAVL participants based on their pre and post interview results and the completeness of their protocols. Becky was a student who had difficulties describing and reasoning about the internal functional subsystems and their interactions during her pre-instruction interview. An analysis of her experiences, therefore, is useful in characterizing how students who come to FAVL with little prior knowledge learn with FAVL. On the other hand, David and Curtis were students who had already begun to describe the internal subsystems that constitute feedback control during their pre-instruction interview. An analysis of their work reveals how two students who have more sophisticated mental models negotiate the design projects in FAVL and the similarities and differences in the approach of two equally matched students. Figure 6-1 and Figure 6-2 summarize the three students' pre and post-instruction results in relation to the larger FAVL group.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

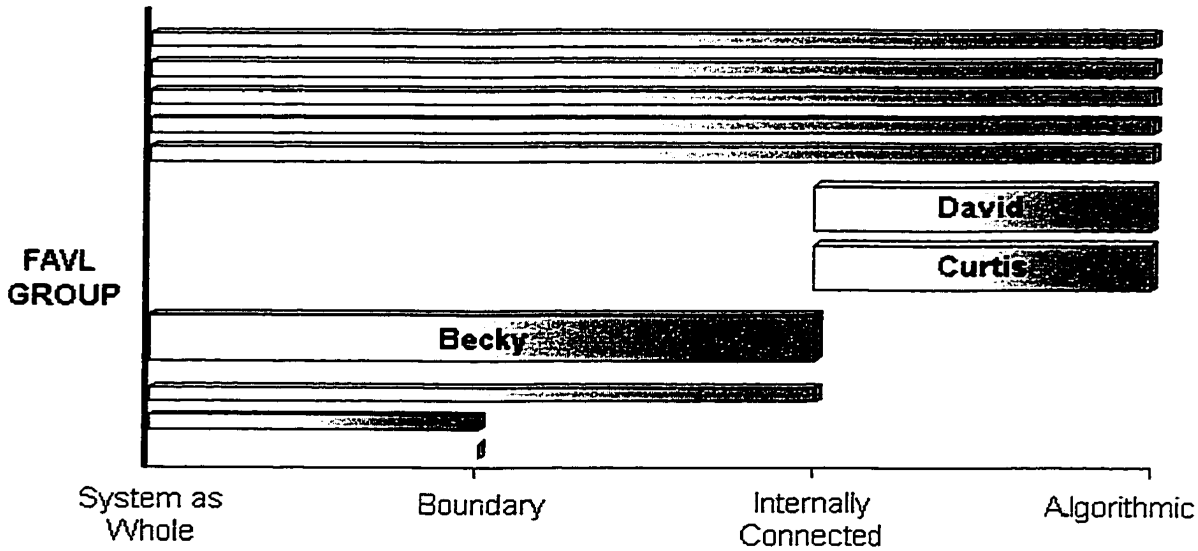


Figure 6-1. Summary of Pre and Post-Instruction Assessment of Mental Models for the Three Case Subjects. The lighter end denotes the pre-instructional model, and the darker end denotes the post-instructional model.

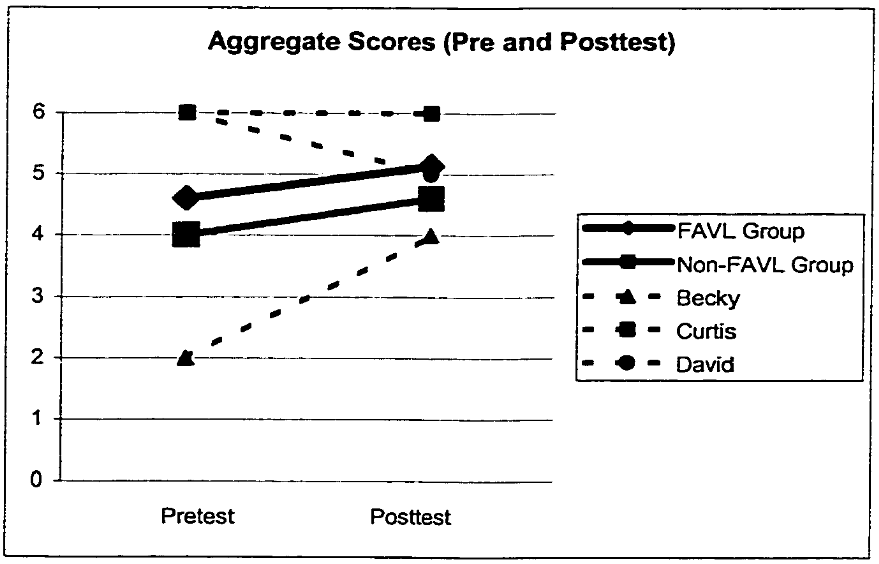


Figure 6-2. Multiple Choice Test Scores for the Three Case Subjects

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.1.2 Overviews of the Design Projects

This section gives a short description of each project along with tables that summarize the sequence of redesigns for each student. This presentation is intended to give the reader a sense for each design project as a whole. Thereafter, relevant segments of each student's experience will be used to illustrate the nature and process of refinement, redefinition and reuse that took place during design work within FAVL.

6.1.2.1 Room Temperature Control Project

In their first design project, students were asked to create a room temperature regulation system that would keep the temperature in a room between 60°F and 80°F at all times. The successful design should be able to maintain room temperature within the acceptable range for a cold winter day, for a hot summer day, and for a day where the temperature outside varies drastically from 50° in the morning to 95° in the afternoon and back to 50° at night.

All the students were first asked to run simulations of the controlled process, a simulated room, to become more familiar with making simulation runs in FAVL and also to begin to explore how the system would work without feedback loops in place. Then, because this was their first design project in FAVL, I provided students with a partially completed FAVL design (shown in Figure 6-3) and asked them to make predictions and then simulate how this original design worked. This original design consisted of a home heating control system that could keep the temperature inside the simulated room above 60° in wintertime. However, it did not include the air-conditioning unit or its control loop. So, after making a simulation run for summertime, students were asked to fix the original design so that their redesign would

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

work for summer as well as for winter. This essentially meant that students would need to replicate the heating control loop and change some parameters to implement a cooling system as well.

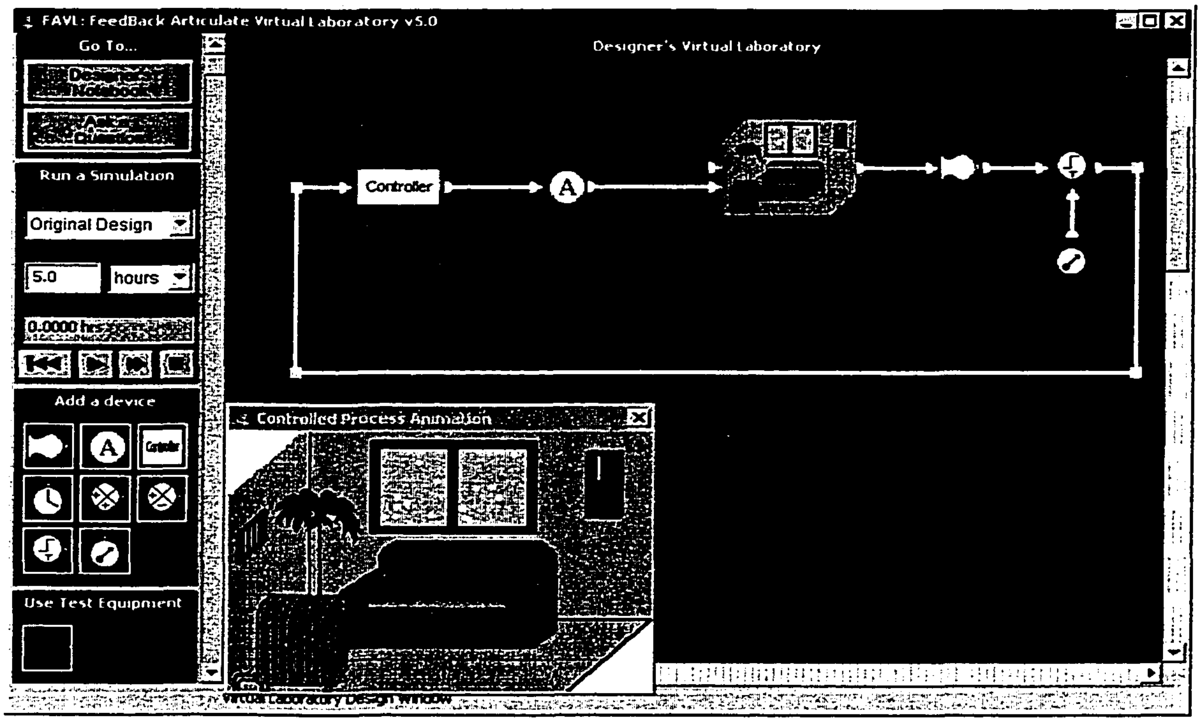


Figure 6-3. The Original Design for the Room Temperature Regulation Project. This design regulates the heating system only. The student must add another feedback loop to this design to allow the system to keep the room below a set temperature as well as above a set temperature.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6-1. Case Subjects' Sequence of Redesigns for the Room Temperature Control Project
(continued on next page)

General Description of the Designs and Activities	**Name of the Specific Design** (in time order)		
	Becky	**Curtis**	**David**
Just the Controlled Process. Students run simulations on the room without any feedback loops in place.	Feb	Feb	DESIGN1882
Original Design. Students run simulations with the original design, a feedback system that controls the heating for the room.	Original Design DESIGN1442	Original Design Summer w/ Original Design	Original Design
One Common Actuator. Students create a design in which one actuator is used as both the air-conditioner and the heater.		DESIGN1403 DESIGN1412 DESIGN1423	
Two Actuators, a Shared Controller, Comparator, SPU and Sensor. Students use two actuators, one for the air-conditioner and the other for the heater.	DESIGN1451	DESIGN1433	
Two Actuators, 2 Controllers with Shared SPU, Comparator and Sensor. Students create a dedicated controller for each actuator. Note that this design is inefficient because the heater and the air-conditioner have the same setpoint value.	DESIGN1466 DESIGN1479	DESIGN1444 DESIGN1464 DESIGN1475 DESIGN1486 DESIGN1497 DESIGN1508 DESIGN1519 DESIGN1540	DESIGN1893

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6-1. Case Subjects' Sequence of Redesigns for the Room Temperature Control Project

General Description of the Designs and Activities	Name of the Specific Design (in time order)		
	Becky	**Curtis**	**David**
Two Actuators, 2 Controllers, 2 Comparators, and 2 SPUs. One set is used to control the heater and the other to control the air-conditioner.	DESIGN1491 DESIGN1734 DESIGN1746 DESIGN1758 DESIGN1770	DESIGN1561 DESIGN1595	DESIGN1910 DESIGN1923 DESIGN1936 DESIGN1951 DESIGN1966 DESIGN1983 DESIGN2004

6.1.2.2 Object Tracking System

In the second design project, students were asked to design a feedback system that would be able to seek and track both stationary and moving objects. As such, this project was a departure from many of the other systems students saw during their pre and intermediate interviews as well as from their first design project in FAVL; instead of a system that uses feedback to maintain a certain, fixed level, a tracking system uses feedback to follow a changing value.

More specifically, in this particular design project, students were asked to design a simple model of a frog that would rotate on a lily pad to catch its surrounding prey. There was only one variable to control, the angular direction which the frog could change by kicking to the right or to the left; student were not responsible for designing a control system to track the elevation of the prey nor were they responsible for designing the 'firing' system that would catch the targeted prey. However, students were told that the frog needed to be facing its prey within a small margin of error for at least 3 seconds before its firing system engaged and its

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

tongue shot out to strike the prey. There were only two flies, the frog's intended prey, that appeared on the screen at one time. Once a fly had been eaten, another fly appeared in a different position as its replacement. Thus, there were always two potential prey available to the frog at any one time.

For a design to be deemed successful, the frog modeled must be able to catch 10 flies within 10 minutes. This held for stationary as well as for moving prey. I asked students to begin with stationary prey and to try to have the frog catch a fly by manually controlling the amount and direction of force in its kicks. A positive kick rotates the frog a certain amount clockwise and a negative kick rotates the frog an equal magnitude counterclockwise. I hoped that experimenting with manual control would help students begin to tie together the relationships between the magnitude and sign of the applied force with the frog's movement and orientation and to articulate the control algorithm that they, the students themselves, used in order to position the frog to face its prey.

After experimenting with manual control, the students were asked to try to implement the control algorithm with the parts available in FAVL. This essentially meant that students would need to create a proportional feedback loop that would allow the frog to track each prey and a means of deciding which of the two flies to track. The latter required students to use new components, to disconnect feedback loops, and to reconnect them in different ways. Students went on to apply their designs to moving targets only after they had successfully caught stationary prey. Introducing moving prey gave students an opportunity to explore the trade-off between gain, response time, and settling time in a proportional control system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6-2. Case Subjects' Design Sequence for the Object Tracking Project

General Description of the Design	Name of the Specific Design (in time order)		
	Becky	Curtis	David
Manual Control. Students try to manually control the frog's position.	Manual control		Manual control
SPU set to Fixed Prey Position. Students set their SPU value to the position of one of the two prey.	Froggie		DESIGN1224
Changing On-Off to Proportional Control. Students change components in their on-off control design to create a proportional control system.	DESIGN1815	Froggie DESIGN1330 DESIGN1347 DESIGN1385 DESIGN1394 DESIGN1403 DESIGN1412	DESIGN1358 DESIGN1416 DESIGN1425 DESIGN1435
SPU set to Changing Prey Position. Students try various ways of designing a setpoint value that can update itself.	DESIGN1822 DESIGN1831 DESIGN1414		DESIGN1444 DESIGN1458 DESIGN1466 DESIGN1474 DESIGN1490
Choosing between Prey. Students build another feedback loop for the second fly and try to combine the two loops so that the frog can choose which fly to track.	DESIGN1425	DESIGN1421 DESIGN1432 DESIGN1443 DESIGN1459 DESIGN1472	DESIGN1498 DESIGN1507 DESIGN1518 DESIGN1528
Experimenting with Moving Prey. Students try different gain values for the proportional control system to catch moving prey.	DESIGN1444	DESIGN1485 DESIGN1495 DESIGN1505 DESIGN1515 DESIGN1525	DESIGN1539 DESIGN1549

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.1.2.3 Cruise Control System

In the third design project, students were asked to design a cruise control system for a car in FAVL. The requirements are much tighter than the previous two projects, specifying the maximum oscillations, the minimum rise time, and the maximum overshoot allowable within the design. To meet all of these specifications, students had to create a proportional control system and to optimize the controller gain, a process that I hoped would help students realize the relationships between gain and oscillation, gain and rise time, and gain and overshoot.

As with the object-tracking project, I gave students an opportunity to manually control the velocity of the simulated car so that they could begin to think about the algorithm that underlie the control system before implementing a design with the components available to them in FAVL. I also provided students with a partially completed design as shown in Figure 6-4. Some students chose to work from this design while others began construction anew, building from the controlled process only.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

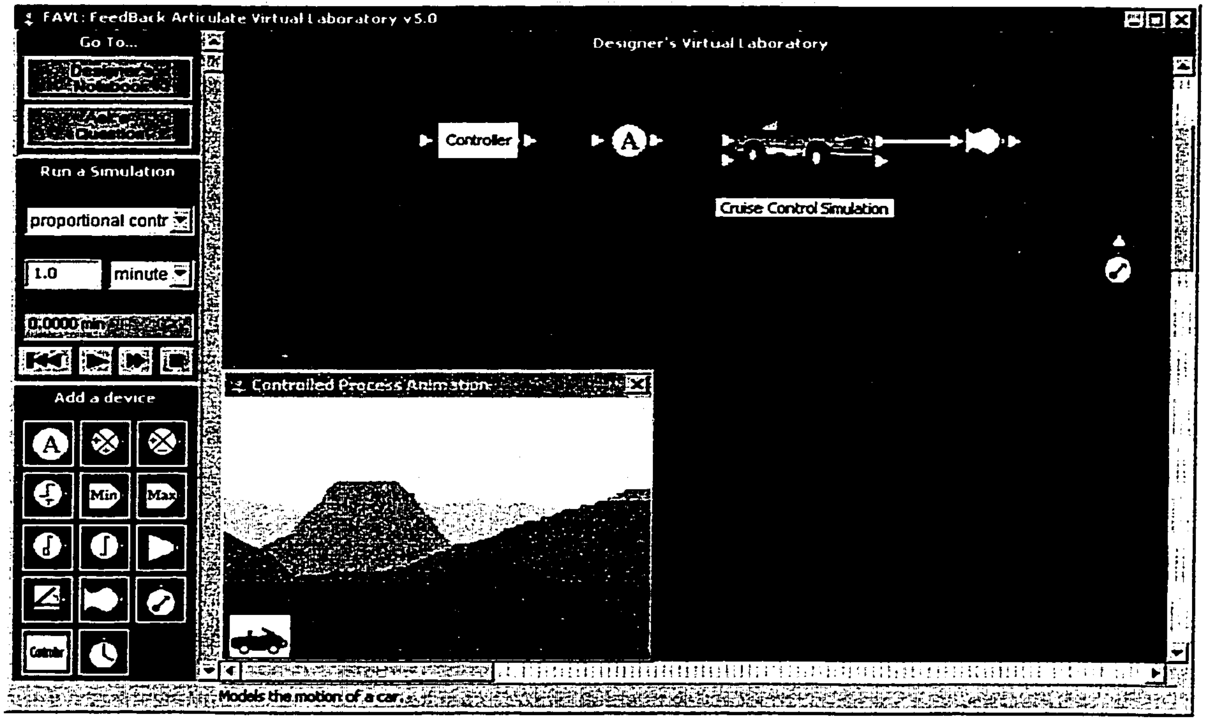


Figure 6-4. A Partially Completed Design for the Cruise Control System. In order to create a successful design from what is given, a student needs to add a difference component to compare the setpoint value to the current speed of the car as measured by the sensor, to connect the components together, and to set the parameter values for the setpoint and the controller.

Table 6-3. Case Subjects' Design Sequence for the Cruise Control Project (continued on next page)

General Description of the Design	Name of the Specific Design (in time order)		
	Becky	Curtis	David
Manual Control. Students try to manually control the car's velocity.	Manual control		Manual control

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6-3. Case Subjects' Design Sequence for the Cruise Control Project

<u>Choosing Proportional Control</u>. Students add and change components to create a proportional control system.	DESIGN1967 DESIGN1984 DESIGN1993	DESIGN2085 DESIGN2094 DESIGN2103 DESIGN2120 DESIGN2133 DESIGN2146 DESIGN2157 DESIGN2168 DESIGN2168 DESIGN2168 DESIGN1897 DESIGN1921 DESIGN1930	On-Off control DESIGN2083
<u>Experimenting with Gain.</u> Students change the gain of the proportional control system to try to meet the system requirements for rise time, oscillation, and settling time.	DESIGN2002 DESIGN2011 DESIGN2020 DESIGN2029 DESIGN2038	DESIGN1939 DESIGN1948 DESIGN1957 DESIGN1966 DESIGN1975 DESIGN1984 DESIGN1993 DESIGN2002 DESIGN2011 DESIGN2020 DESIGN2029 DESIGN2038 DESIGN2047 DESIGN2056 DESIGN2065 DESIGN2074	DESIGN2094 DESIGN2148 DESIGN2157 DESIGN2166 DESIGN2175 DESIGN2184 DESIGN2193 DESIGN2202 DESIGN2211 DESIGN2220

6.1.2.4 Collision Avoidance System

In the collision avoidance project, students were asked to build on top of their successful cruise control system from the previous project. The collision avoidance system should allow their simulated car to drive safely through traffic without colliding into the cars in front of it.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Students were told that they only needed to worry about the obstacles in front of the car and that the car would be tested on a single lane road; that is, the car could not switch lanes to avoid rear-ending the obstacle in front.

In order to meet this project's requirements, students needed to create a design that would disable the cruise control system when necessary and that would control how and when the brakes should be applied. Unlike the cruise control project, which was essentially a controller optimization problem, this project required students to create another feedback loop to control vehicle braking and to somehow integrate that with the cruise control system. As such, it presented a challenge similar to the object-tracking project and revealed how students decided to disconnect and recombine feedback loops into an integrated whole.

The collision avoidance project was the fourth in the series of design projects that students were asked to work on in FAVL. Both Curtis and David completed this project, but because of time constraints, Becky did not.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6-4. Case Subjects' Design Sequence for the Automatic Collision Avoidance Project

General Description of the Design	Name of the Specific Design (in time order)		
	Becky	**Curtis**	**David**
Start with Cruise Control Design.	DESIGN2038 DESIGN2053 DESIGN2061		DESIGN2220 DESIGN1740
Two Separate Loops. Students build two unconnected loops; one implements the cruise control system, and the other controls the braking system.	- END of FAVL Project Work -	DESIGN2097 DESIGN2109 DESIGN2123 DESIGN2138 DESIGN2152 DESIGN2166 DESIGN2180 DESIGN2194 DESIGN2216	DESIGN1756 DESIGN1786 DESIGN1800
Two Connected Loops. Students try various means to connect the braking system to the cruise control system.		DESIGN2230 DESIGN2245 DESIGN2260 DESIGN2276	DESIGN1821 DESIGN1836 DESIGN1851 DESIGN1866 DESIGN1881
Two loops connected with a controller and switch. Students use a switch to disable the cruise control system. The controller opens the switch when the braking system is engaged.		DESIGN2291 DESIGN2307 DESIGN2323 DESIGN2239 DESIGN2355 DESIGN2373 DESIGN2391 DESIGN2409 DESIGN2427	DESIGN1896 DESIGN1914 DESIGN1932

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.2 Refining the Model

The pre-post results described in Chapter 5 indicate that students who worked with FAVL were able to explain feedback system behavior in more detail than their Non-FAVL counterparts, suggesting that students were refining their understanding of these systems as they worked on design projects in FAVL. The purpose of this section is to illustrate the nature of these changes, particularly in students' understanding and use of the functional parts and signal flow, during the course of their design work. Some of these changes are changes towards understanding how to use the canonical model. For instance, students who previously confounded functions learned to separate and reify the functions of the canonical model. Other refinements include developing a more detailed description of how information is transformed and transferred from part to part, and differentiating parts which belong to the same functional category (e.g., distinguishing between an on-off and a proportional controller) to explore different feedback behavior. The following gives examples from the three students' work that illustrate the nature of these changes and highlight the learning strategies and resources that these students used to understand and to create their feedback designs.

6.2.1 A Framework for Understanding Change

First, I will begin by proposing a descriptive framework for understanding how students made sense of their designs in FAVL: Students interpreted their designs according to three perspectives, the functional view, the signal perspective, and the system narrative. Each of these three views highlight different aspects of a feedback system by focusing on different types of entities and different types of relationships between those entities in system

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

description, in its composition and its behavior. Many of the design decisions that students made seem to be informed by coordinating these three perspectives in their work with FAVL.

I have argued earlier in Chapter 2 that part of learning about feedback systems includes learning about the functional subsystems that underlie all feedback systems. To review, in the functional view, a feedback system is partitioned into its functional subsystems, each of which plays a role in the system's self-regulation and control. According to the canonical model, a feedback system is partitioned into the functions shared by all example feedback systems: sensors, comparators, SPUs, controllers, and actuators as described earlier in Chapter 2. These functions express the relationships between physical parts to the system's overall goal and abstract the specific implementation to the more general roles physical parts play in the overall system. The Model Instruction portion of our instructional sequence is intended to teach students to recognize and partition feedback systems according to these canonical functional parts.

Part of developing expertise also includes learning a signal perspective. In the signal perspective, a system is defined by the flow of *quantifiable* information with one component receiving, transforming, and passing information to the next component along a directed path. There is little emphasis on the physical nature of the signals or the physical parts that generate the signals. Instead, the components that make up the system are defined according to how they change the information, or signal, that traverses the system. The change in the signal value as it loops around the feedback system is used to describe the system's behavior in pseudo-time. As I described earlier in Section 2.1.2, this perspective, therefore, provides a

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

way of characterizing change within a system as well as a way of connecting parts of the system together according to the sequential flow of information that implies causality. The signal view is the predominant view used in college textbooks on control theory and is the precursor to mathematical modeling of not only feedback, but all types of systems. FAVL, as well as other modeling and simulation tools in which variables of one 'part' propagate and change variables of another 'part', uses this perspective as a way of describing system interaction.

In addition, students told narratives of what happened or should happen within their designs. A narrative is a time order account of the system's behavior that includes the episodes and events that happen to objects[1] within the system. Of the three perspectives, the narrative is the most context bound since it includes specific reference to physical, not necessarily functional, objects in the system and their interactions with one another. This narrative perspective ties the more abstract functional and signal perspective to the particular design problem by giving a time order account of changes to specific objects (e.g., a furnace in home heating) in the design.

Let me further delineate these views with a specific example of the now familiar home heating system. According to the functional view (also shown in Figure 6-5), the system can be described thus:

> A home heating system works to maintain the temperature in a house at a particular set value. In order to do this, the system must have a sensor

[1] Note, that an object does not necessarily correspond to a functional object delineated in the functional view.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(implemented in the thermostat) that can measure the current temperature (around the thermostat), a comparator (also implemented in the thermostat) that can determine if the temperature is at the right value, a controller that decides what to do in the current condition to move the temperature towards the set value, and an actuator (in this case, a furnace and radiator) that can change the temperature in the house.

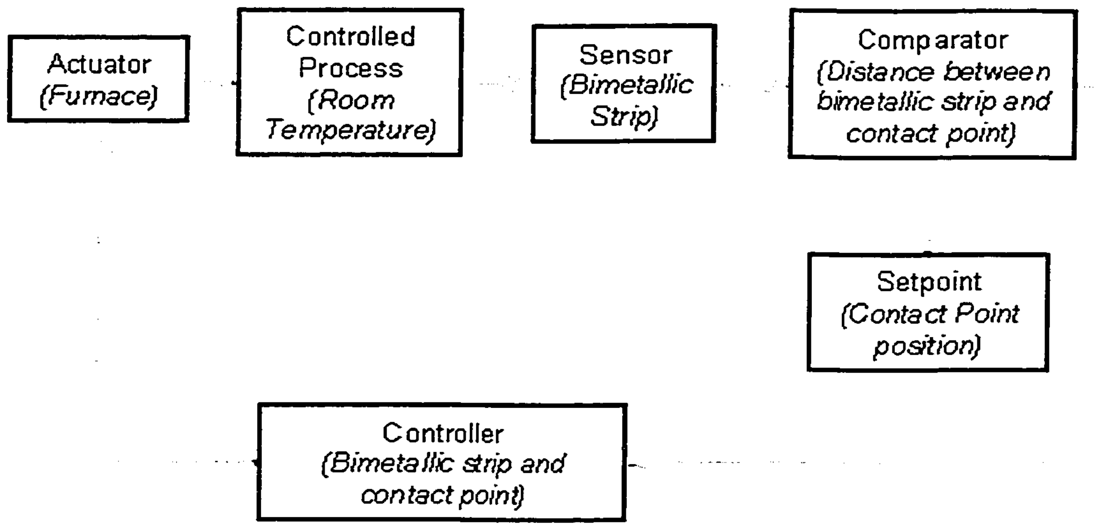


Figure 6-5. Feedback System as a Set of Functional Components

According to the signal perspective, the home heating system is described as a directed signal that is transformed by the parts as described in Figure 6-6.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

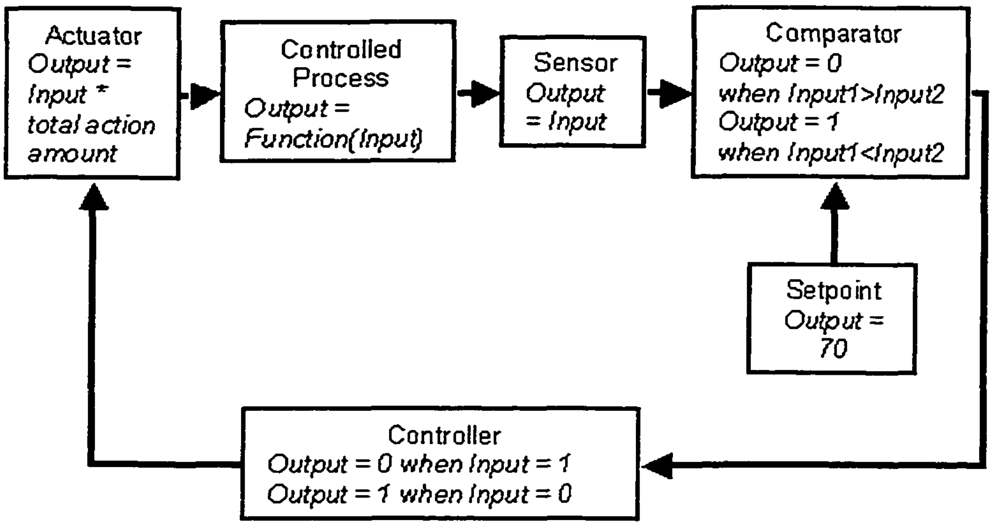


Figure 6-6. Feedback System as a Flow of Information

Finally, according to the narrative view, the heating system can be described as such:

> When the room temperature falls below a set value, the heater turns on and the room temperature increases. When the room temperature goes above a set value, the heater turns off. When the heater is off and it is cold outside, the room temperature decreases.

Students drew upon all three perspectives to inform their design work in FAVL. For example, the functional view was used when students were trying to first identify the appropriate component to add to their designs. The signal view provided topological information about what was connected to what and allowed students to trace a faulty signal to its roots as well as to propagate values to explain certain system behavior like the steady-state error in a proportional control system. The narrative helped students to make sense of the design in the context of the particular design challenge, and students often resorted to telling a story of what should happen in time order to figure out how what might be wrong with their designs.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

These three perspectives evolved together as students worked on their FAVL designs, and it appears that part of developing a richer understanding of feedback systems through design work in FAVL depended on coordinating these three perspectives. For example, components that represent the different functions in a feedback system were also defined as signal transformers that changed input values to output values. Also, different signal values became associated with different states in the particular feedback system. For example an input value of 0 to an actuator that represented the heater in a room temperature control design meant that the heater was off. Changes in signal values were then interpreted as changes in states that corresponded to key events in the system's narrative.

Interpreting their designs within these three views and coordinating these views were not always straightforward for the three students. To varying extents, their design experiences with FAVL was a process of learning to use and concurrently coordinate the functional, the signal and the narrative descriptions of their systems. In the following, I will give examples of how the three students learned to apply the three descriptions of feedback systems and to integrate their use in design work.

6.2.2 Refining the Model - Examples

This section presents a set of examples to illustrate how students refined their understanding of feedback systems during their work in FAVL. At times within this section, I will refer to specific designs or sequence of redesigns. A summary of each student's design sequence for each of the four design projects can be found in Table 6-1, Table 6-2, Table 6-3, and Table

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6-4. These tables serve to help orient the reader and to place the work described within the larger sequence of design decisions.

6.2.2.1 From a System-as-Whole to a System of Parts

By the time they started work in FAVL, both Curtis and David had demonstrated some knowledge of the different functional subsystems that make up a feedback system. Even within their pre-instructional interviews, these two students were able to describe some of the functions shared by all feedback control systems. Becky, however, was not as familiar with the functional composition of feedback systems. Becky's explanations of the different feedback examples in the pre-instruction interviews lacked any description of how these systems regulate themselves. Furthermore, on her multiple-choice tests, Becky had a harder time tying together the parts of a system. When Becky began working in FAVL she was still struggling to make sense of the different functions that make up a feedback system.

Much of Becky's experience with the first design project can be described as a movement from characterizing the feedback system as a black box, or system-as-whole, to a system of functions. This involved learning to define and use the functional components she encountered earlier in the instructional sequence within the design context of FAVL and, concurrently, to coordinate the functional view with a less familiar signal view. In the following case, I will describe how Becky began to learn what each component represent and to separate previously conflated functions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The System-as-Whole Model in FAVL

At the start of the first design project, Becky was confused about what the components in FAVL represent. For example, she was surprised that a design that did not include any feedback components could not regulate itself:

> *(for a design that included only the simulated room and no feedback control loops)*
> Interviewer: Is that what you expected it to be?
> Becky: Yeah, uh, yeah
> Well, no not really.
> Interviewer: No, not really?
> Becky: Well, I thought it said it should stay. It started out at 60 degrees. So, I thought it would stay the same.
> ...
> Interviewer: Why did you think it would stay the same?
> Becky: cause if I just left it at 62 it should just stay there.
> Interviewer: Why do you think this went down like that?
> Becky: Um, I don't know.

One design later, I asked Becky to look at and explain how a design with a feedback loop would work; Becky was unable to give any details about the interactions of the parts that led to self-regulation:

> Becky: Okay, so it works better when it has everything working together
> Interviewer: Uh huh.
> Becky: and otherwise it just doesn't.

Compare Becky to Curtis' explanation for the same design. Curtis' description is much more detailed and includes an enumeration of the parts that make up his design, some description of the information that is passed from part to part, and an interpretation of the resulting graph that explained the system's behavior:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Curtis: That's the sensor [points to sensor icon]. And, that's the comparator [points to comparator icon] and the set thing [points to SPU icon]. And, I guess that [points to comparator icon] finds the difference, which travels along this line [points to connection between comparator icon and controller icon], which goes to the controller [points to controller icon], which tells the actuator [points to actuator icon] in order to turn on the heat.
Interviewer: Okay, and why would this design give you a graph like that?
Curtis: um because the setpoint [looks at graph but not at SPU value]
And then
You had it set at 62 degrees. So it didn't turn on for this period of time [pointing to start of graph which drops down because the starting room temperature was higher than 62°]

Furthermore, Becky seemed confused as to why the room temperature would steadily rise to the outside temperature during the summertime for a design that had only a feedback loop to control heating and nothing to control home cooling. She asked, "How come it didn't stay under 80 degrees ... wasn't it doing the same thing that the cold day was?"

Neither Curtis nor David had similar difficulties interpreting these same designs. At the very least, Becky was more confused about what was represented in these FAVL designs and what she was expected to do. Moreover, this may reflect not just unfamiliarity with the FAVL interface but confusion about how the room temperature control system can be partitioned into its functional subsystems and the internal interactions that lead to system behavior. This latter conjecture concurs with pre-instruction observations that indicate that Becky held a system-as-whole model for explaining feedback phenomena. Design work, however, forces students to articulate the internal relationships that give rise to self-regulating behavior, and a large part of Becky's work in the first project involved opening her system-as-whole model to explore the internal workings of her feedback designs.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Articulating The Parts Of The Feedback Design Within FAVL

To create a room temperature control system in FAVL, Becky would need to select the parts for her design as well as define the connections between those parts and the information that flows from one component to the next. Becky began her redesign by adding an actuator component that would represent the air-conditioner in her design. This may be because the actuator component is one of the easier functions to identify within control systems. Recall from Chapter 6 that most students readily identified the actuator function in the home heating system. Furthermore, in this design project, the actuator maps to a physical object, an air-conditioning unit, which is familiar to most students. With successive designs Becky would add successive upstream components,[2] but adding the other components would not be as straightforward.

Part of the reason is because Becky at first was not attuned to the interactions between the different parts of her design. For example, when she first added the actuator to her design, Becky didn't connect either its input or its output to any of the other parts. This is even though I had earlier told Becky that in order for one component to affect the next component in FAVL, they must be connected to each other. It was only after two failed simulation runs that Becky realized that she must not only explicitly identify the parts of her design but the connections between the parts. Notice that making these connections coincided with recognizing that one part must pass information to the next:

> Becky: It [the graph of the room temperature] looks the same.
> Interviewer: Okay, why do you think that is?

[2] Both Curtis and David followed the same design sequence: They began by adding an actuator and then added successive upstream components with subsequent designs.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Becky: Oh, that's right. Do I have to change everything?
Interviewer: What do you mean?
Becky: I don't see why I have to change everything. Why isn't it working?
Should I take this [actuator representing the heater] out?
Interviewer: So, what do you think is happening here [points to actuator representing the air-conditioner]?
Becky: I guess the controller is telling the
Well, [points to controller] the controller is not part of this. Should I connect it? [Connects air-conditioner to the common controller]

Disambiguating the Parts

As Becky continued to work through this project, she sought to define the appropriate functional role for the remaining components in the design and the information that connects one component to the next. Becky seems to have the most trouble with the comparator and the controller. For instance, in the early part of this project (during DESIGN1466), Becky did not understand why the controller would have the comparison result as its input; she also misidentified the comparator as the sensor. Part of her difficulties appears to lie in problems partitioning the two into separate functions. She often placed the comparator in the role of the controller; the comparator tells the actuator the amount of action that should be taken, and it is not clear what role the controller has in Becky's model:

Becky: So, the comparison person is like 'put on everything' and it's not doing anything because
And when the person says don't do anything, then it does something.
...
Interviewer: The comparator there [points to comparator]
Becky: Um yeah. It's just telling it what to do.
Interviewer: What exactly is that comparator telling?
Becky: Um, it's telling him
Well, there it's telling to put on all the heat.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Why was it hard to differentiate the comparator from the controller or to even determine the controller's role? The answer may lie in the obscure role that the controller plays within this design. When it is too hot (or cold), the air-conditioner (or heater) turns on. It is the comparator that determines if it is too hot or too cold in the room, and it is the actuator that turns on or off. Nothing comparable to a controller is ever mentioned in a narrative description of events. This may have made it difficult for Becky to elicit the controller function and promoted the conflation of the controller with the comparator.

Another reason may be because the controller within this and other designs can be described as a component that transforms the signal from the comparator to the actuator. To understand this component in this manner requires some familiarity with seeing parts as signal transformers. But, up to this point in her work with FAVL, Becky rarely talked about signals or the information that is passed from part to part. It was only after I described the controller as a translator that converts the signal from the comparator to a signal for the actuator that Becky began to disambiguate the controller function and gave the controller component a role within her design. In this particular case, it transforms the 1 from the comparator to a 0 and a 1 for the heater and air-conditioner actuator, respectively:

> Becky: Okay, so if this guy [sensor] says it's like 95 degrees in here and this guy [SPU] is like I want it to be 60 degrees then this guy [comparator] will be like we need to turn on the air conditioner
> So, 1 [as the output]
> Interviewer: right.
> Becky: so it's zero to here [point to controller - heater actuator link]
> Interviewer: zero to the heater
> Becky: but it should be 1 to the [point to air-conditioner actuator]

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

However, an analysis of her protocol from the later part of this project and the beginning of the second design project indicate that this signal transformation definition was precarious. For example, at the end of this design project when I asked Becky how the controller for the air-conditioner is different from the controller for the heater, Becky answered that she did not know.[3] Instead, as Becky continued to work through this design, the controller became defined as the component that could turn the heater or the air-conditioner on and off. For example, during DESIGN1734 and at other points in her design project, Becky repeatedly referred to the connected controller to determine if the actuator was on or off and tried to change the controller settings in order to control the actuator's actions.

At the end of this project, Becky seemed to have a better grasp for the parts that make up her feedback designs:

> Becky: Okay, on this one it just runs itself through and then it tries to keep itself at 62 degrees here [point to threshold comparator and SPU]. And then it goes here [controller] and then it goes to the heater and it heats up everything. And this one it just goes around and it cools everything off.
>
> Interviewer: Can you tell me more about what's going on in here [point to threshold comparator and SPU]? What's that thing [point to threshold comparator] doing?
>
> Becky: That thing is the thing that decides what like if the room is like comfortable or uncomfortable. Like the ... the room is too cold or the room is too hot. And then it tells the controller to tell the actuator to fix it.

---

[3] The controller for the heater has a different algorithm from the controller for the air-conditioner. Specifically, it turns on the heater when the temperature in the room drops *below* a certain value. Alternatively, the other controller turns on its actuator when the temperature in the room rises *above* a certain value.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

However, Becky continued to conflate the controller and the comparator functions in the earlier portion of the subsequent design project. That is, she did not readily transfer the definitions she assigned to the controller and comparator parts in her first design to the next project, although there was no example of this conflation in the last two projects. These observations point to the unstable or perhaps the non-generalized nature of the definitions that Becky assigned to the parts in this first design project and suggests that learning to associate the function to the component need to occur over different systems. Furthermore, notice the lack of details in Becky's description of the signal flow; she does not describe what type of information is carried between the components of her design. I speculate that learning to understand each part of a design is tied to constructing a concurrent understanding of the nature of the signal and its transformation in the system, a view that Becky struggled with in her early design projects.

Case Summary

Becky's case provides an example of how a student who initially held a system-as-whole model could begin to articulate the internal components and interactions by designing a feedback system. Some parts and interactions were more difficult to define than others. And, at the end of her first project, it is not clear if what Becky learned about the parts and interactions was easily transferred to her next project. Observations on Becky's progress and difficulties suggest that understanding the functions of the components is only one part of understanding how to design a successful system in FAVL. In particular, design work requires a coordinated understanding of signal propagation, a perspective that Becky was only starting to develop in her first FAVL project. In the next case, I will describe what coming to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

view a system according to the signal perspective looks like with an examination of Curtis' design experience with the room temperature control project.

6.2.2.2 Refining the Idea of the Signal

Compared to Becky, Curtis was more familiar with describing feedback systems as an interaction of the canonical functional parts. Instead, much of Curtis' first experience within FAVL can be characterized as a refinement of the signal perspective. He began with a nascent and unspecific idea of information being passed on the lines between the parts in FAVL; his first descriptions consisted of little more than specifying the type of information sent by the comparator and the controller. All the other signals were ignored:

> Curtis: And, I guess that finds the difference [points to comparator], which travels along this line [points to connection between comparator icon and controller icon], which goes to the controller [points to controller icon], which tells the actuator [points to actuator icon] in order to turn on the heat

However, by the end of his first design project, Curtis had a much more detailed understanding of the signal; parts were defined according to how they transformed signals as well as by their function, and signals took on different values that were given meaning tied to events in the narration. This allowed Curtis to isolate faulty parts and otherwise inform his design. In the following case, I will give examples from the data for these manifestations of understanding and I will identify the key aspects of Curtis' learning.

Parts As Signal Transformers

When Curtis first began working on his first FAVL design project, he brought with him some understanding that each component would tell the next component some information, for

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

example a difference or a command of what to do. However, there were no quantifiable values given to the signals or any description of how those values would be changed. For example, early in the project (DESIGN1394), Curtis explained, "Well I think it's [the controller mapping] the, you know, it's what the comparator says and what it [actuator?] should do;" Curtis did not describe how the controller would map the different incoming values to outgoing values. Also, in the same design, Curtis claimed that the comparator would sense when it was too cool and, without looking at the comparator properties or description, concluded that when it was too cool it must send a 1; it's not clear if or how the 1 was derived from the comparator inputs. (As it happens, the comparator should output a 0 when it's too cool.)

Curtis' design progression was marked by a more detailed exploration of the idea of parts as signal transformers. An analysis of his protocol shows that Curtis was beginning to describe the parts of his design, especially the comparator and controller, according to how they change the incoming to the outgoing signal values:

> Curtis: [describing the comparator] if the input, if it's larger it gives a 1 and if it's smaller it gives a 0 so
> ...
> [describing the controller] so when it gets a 0 it sends out a 0, which, I guess, turns on the heater.
> It tells the actuator [traces line to actuator representing the heater] to go that that little
> which turns on the heater

However, determining how a component transforms its incoming signal was not always straightforward. Even though FAVL includes descriptions of how components convert their

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

incoming to outgoing signal values, these descriptions were sometimes hard to understand. According to Curtis, "it's just worded oddly." I suspect that this is because they are not context specific. That is, the descriptions are not tied to the particular system design or the system narrative, forcing the students themselves to make those connections[4]. (See Figure 6-7 for an example.)

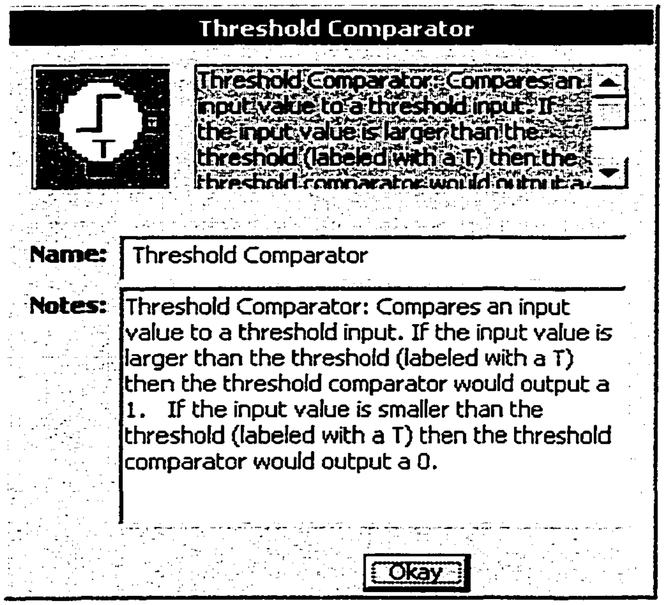


Figure 6-7. Description for the Threshold Comparator. (Note that the description is typically found only in the uppermost gray box. In this figure, however, the description of the threshold comparator is also placed in the notes area so that the reader can see the entire textual description.)

Moreover, learning how a component changes its incoming signal(s) and using this knowledge during design work require that students focus on each component and predict how the signal

[4] One student even wrote a 'crib' sheet that mapped the outputs of the threshold comparator to conditions in the simulated room for the temperature control project to remind him that when the room was too hot, the threshold comparator would output a 1 and when the room was too cold, the threshold comparator would output a 0.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

will be transformed from part to part and to check each intermediary signals to see if it meets predictions. This is something that I had to teach Curtis to do as he struggled to specify the controller mapping in his design. Before this tutorial, Curtis would rarely trace the signal past one part and would not make predictions about any intermediate signal. For instance in DESIGN1394, Curtis decided that because the room was not cooling down on a hot day, the actuator must be faulty; consequently, Curtis changed the initial value of the actuator output even though this parameter value would be changed by the signal from the upstream controller. This is a mistake that students often made in the first two design projects, altering values that would be updated by other values during a simulation because they did not focus on how signals can be changed by upstream components. Even later in his project work (during DESIGN 1540), I had to repeatedly focus Curtis on tracing the entire signal instead of just attributing the problem to one component and then changing a parameter within that component.

Signals Are Given Semantic Meaning Tied To Events

Learning about signal transformation seems to be closely tied to an ability to assign signal values to object states and changes in signal values to events in the system's narrative. There are examples throughout Curtis' protocol that indicate that different signal values came to represent different states and events in the system's narrative. Making this connection was not always straightforward even with an on-off control system design where there are essentially two states (on or off) and two state transitions to worry about for each feedback loop. One reason for this is that, in the beginning of his design sequence, Curtis assigned meaning to signals without a valid anchor. He did not know where to start with the signal assignment.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

As an example, early on in his design sequence (DESIGN 1403), Curtis tried to define what a 1 coming from the comparator could mean. However, instead of tracing the signal forward from the controlled process and checking the output of each part for consistency with predicted states and events, Curtis traced backwards from the actuator beginning with an incorrect assignment, that an input of 0 to the actuator turned the air-conditioner off.

After I modeled how to trace a signal as it propagates and is changed by the system parts, Curtis was better able to assign signal values a meaning within the narrative. For example, in DESIGN1561, Curtis used signals, in this case the controller output to the actuator, to identify the problem with his design; both the air-conditioner and the furnace are turning on at the same time:

> Curtis: I do that by looking at the actuator or is it the controller?
> Interviewer: You could [interrupted before finishing]
> Curtis: graph [opens up the graph for the heater controller]
> Interviewer: You could do it either way.
> Curtis: Also, I need the graph for this one at the same time [Opens the graph for the air-conditioner controller]
> [Runs simulation]
> [Graphs oscillate]
> Curtis: Yes, they're both going on.

Not only did this signal fluency give Curtis the ability to debug his design, but Curtis could also make more informed decisions about the parts used in his design by identifying what they did to the signal. For instance, at one point during DESIGN1561, Curtis was trying to determine if a proportional controller was an appropriate part to use. Coupled with the understanding that the controller translates the input signal to an outgoing signal, Curtis was able to determine that the proportional controller was inappropriate for the task of turning the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

heater off when the room is too hot. He did so by assigning signal values the following meaning within the narrative: 1) an incoming value of 1 means that the room is too hot, and 2) an output value of 1 means that the heater turns on:

> Curtis: Should it be a proportional?
> Interviewer: Okay, what do you think that might mean?
> Curtis: Uh, I would guess that it would give out a certain amount of something. You know, it gives out a certain amount of signal.
> [Opens the mapping for the proportional controller]
> Oh it looks a little more complicated, but if it gets a one it should not do. This is the heater so when it gets a one it means that the room gets too hot. It should not do anything. When it gets a zero it should do something.

Specifying a Signal

Making these assignments between signal value and events, Curtis also had to grapple with some subtle distinctions between information and signal value. That is, one signal value can only carry one piece of information to the next part. From DESIGN1403 to DESIGN1561, Curtis repeatedly tried to create a design in which two values, 1 and 0, could be used to convey more than two pieces of information: to turn the air-conditioner on, to turn the heater on, to turn the air-conditioner off and to turn the heater off. More specifically, when I asked Curtis during DESIGN1412 (Figure 6-8) to explain what he thought would happen if the output from the common controller was 1[5], Curtis replied, "it'll probably turn on the air-conditioner." There was no mention of what would happen to the heater when the controller output is 1.

---

[5] This design has only one actuator that acts as both the heater and the air-conditioner and a common controller attached to that one actuator.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

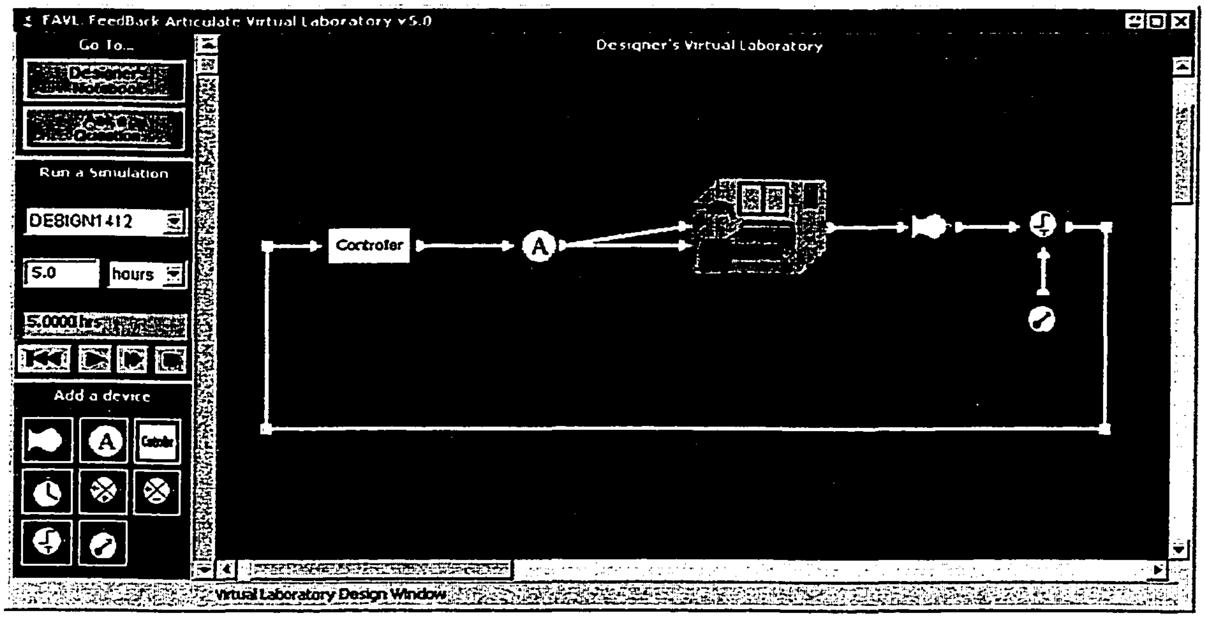


Figure 6-8. DESIGN1412: One of Curtis' Intermediate Design for the Room Temperature Control Project. Note that one actuator is used to represent both the air-conditioner and the heater.

With successive designs, Curtis re-encountered this problem in different manifestations and what eventually convinced Curtis that he would need two actuator-controller pairs was this need to have different independent signals controlling when each actuator should turn on and off.[6] This happened during DESIGN1423 when he assigned three distinct commands to three distinct signal values:

> Interviewer: Remember that the controller is the thing that basically converts the results of the comparison to the action, how much action should be taken. So a 0 means no action. Don't take any action whatsoever, and a 1 means take all the action you can.
> Curtis: So, I really need 3 numbers like a 1, 2 or 3
> or a 0, a -1 a 0 and a 1

[6] The algorithms used to control the heater and the cooler are different. Therefore, from the control design perspective, cooling and heating should be modeled with two, not one, actuators and there should be a dedicated controller for each of these two actuators.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

cause I need to turn on the heater, to leave it neutral, and to turn on the ac.

After he realized that the on-off controller could not be redefined to accommodate three signals, Curtis added a dedicated controller for each actuator. Again, towards the end of his design sequence during DESIGN1561, Curtis tried to assign multiple meaning to one signal value and asked if a signal could be 'nothing' to try to give additional states to a binary signal:

> Curtis: [talking about the output value for the comparator] like when it starts out the room is like just right. It doesn't need to be raised or lowered any. So the initial value should be something. You know what I'm saying?
> Interviewer: Okay, what would it be?
> Curtis: See one
> No. That would turn the ac on.
> [Opens comparator description]
> Curtis: It turns on the ac and I don't want it to turn on the ac. So the initial value shouldn't be anything. Can it be nothing?
> Interviewer: It's either zero or one. It can't just hang out.
>
> Curtis: There's no way that it can't send any information?
> ...
> Interviewer: There's no null signal that everything sort of stops at.

However, the information flow model does not allow for ambiguous signals. It is the specificity required from working with signals that forced Curtis to consider other alternatives in his designs.

<u>Case Summary</u>

Curtis' case helps identify how a student can develop and use the signal perspective in his design work in FAVL. In FAVL, a signal takes on values that can be used to help students debug their design as well as determine how to set component variables. Learning this signal

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

perspective, depends on two interrelated activities: learning how the signal is propagated and changed in a design and connecting key values or value changes to object states and events in the history of the system. Assigning a value and a particular meaning to a signal also forces a level of specificity in the design work that was not found in any of the other activities in our instructional design. This can prompt students to give more careful consideration to what can be conveyed with a signal. Many of these observations would also likely apply for other computer-based modeling tools (e.g., STELLA) that propagate values between component parts to simulate dynamic system behavior.

6.2.2.3 Differentiating control systems

In the previous two cases, I looked at how Becky and Curtis' work in FAVL refined their understanding of functional partitioning and signal flow. In the following example, I will illustrate how students were also refining their understanding of the feedback model through a process of differentiation in which a component type (e.g. a comparator) is separated into subtypes (e.g., a difference comparator and a threshold comparator) and a canonical feedback model is differentiated into its subtypes (e.g., on-off and proportional control systems) each with its distinct set of behaviors. More specifically, I will describe how David came to differentiate the parts and behavior of a proportional control from an on-off control system during his second design project, the strategies and resources he used to do so, and the obstacles he encountered on the way, some of which could be explained as difficulties in coordinating the three perspectives described in Section 6.2.1.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

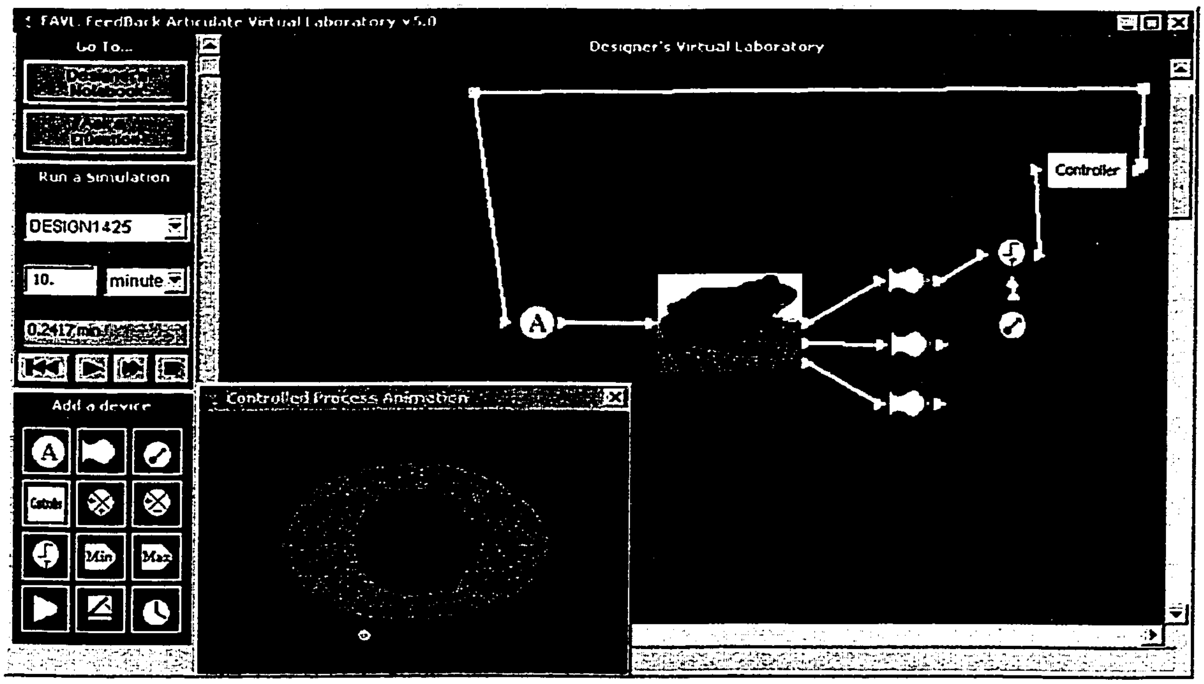


Figure 6-9. DESIGN1425: David's On-Off Control Design for Object-Tracking.

Starting With The On-Off System

David's design progression towards building a proportional control system was in many ways similar to Becky and Curtis'. (See Table 6-2 for all three students' design sequences.) Like Curtis and Becky, David began with an on-off feedback design as shown in DESIGN1358, Figure 6-9. The on-off control system provided a starting point for his redesign efforts. Even though David had already begun to articulate an algorithm for proportional control and to identify the type of information that he would need while he was experimenting with manual control, David started by replicating an on-off design. He even deleted the difference component that he had added while articulating the proportional control algorithm in order to restart work from the on-off design.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

This on-off design served as a template from which to build a feedback system more appropriate for the design problem. Its collection of sensor, SPU, threshold comparator, controller, and actuator, seems to be have been used as placeholders for the basic types of parts that may be needed for a design, and it may represent not an on-off system but a more general feedback system. Alternatively, he may have chosen to start with and modify an on-off system because it was a more familiar design. In either case, it was from this design that David decided if each component should be used or changed. For example, in the beginning of the project (during DESIGN1358), David first replicated the loop and only afterwards paused to reconsider the individual components that made up his on-off design. Again, later in his work (during DESIGN1444) David replicated a completely separate feedback loop for the fly before evaluating each of its components and determining that none of these components were necessary in order to move the frog to the position of the fly.

Changing the On-Off Design

To create a proportional control system from the on-off template, David began by noting a relationship that he recognized while experimenting with manual control:

> David: Like when it's farther away from the flies
> And I told the frog to kick softly when it was really close and I wanted to get it to the spot where it would snag it

To implement this relationship, David identified the type of information that would be needed. As David explained, "I need to know where the frog was in relationship to the fly." But, that required specifying the difference between the position of the fly to the frog so that the appropriate *amount* of action would be taken. This informed his decision to use a difference

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

component instead of a threshold comparator, one of the differences between a proportional and an on-off system:

> David: But I was thinking, use a difference unit to uh
> So it can calculate how far it is from
> So it'll slow down the kicks

Choosing a proportional controller was less straightforward. When he first selected a proportional controller, David was not sure how it would work but guessed that the proportional controller would be associated with an ability to cause the frog to go faster or slower. This hunch preceded any detailed understanding of the proportional control as a signal transformer. According to David, "I'm still thinking that this should be proportional, but I'm still fuzzy on how to work this thing." David used the proportional controller, nonetheless, to see what would happen.

Part of the difficulty with interpreting the proportional controller as a signal transformer may to be tied to the difficulty by which its outputs can be mapped to an event in the narrative. As one of his first explanations of how the controller might work, David interpreted an output of 1 and 0 as meaning that the frog should and should not zap the fly in front of it, respectively. It is, however, unclear how strongly David believed in this interpretation since this relationship was never mentioned again in this design project. Note, however, that Becky and Curtis' protocols also show an initial inclination to assign these two discrete values to discrete states and events in the narrative. For example, both Becky and Curtis assumed that a 1 and a 0 would, respectively, cause the frog to move and to stop moving. In fact, one of the reasons why Curtis at one point reverted back to an on-off controller was because he erroneously

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

believed that the off state of the on-off controller could correspond to stopping the frog from rotating past the fly.

Because the error signal and the controller output change smoothly in a proportional design, it is difficult to associate one discrete event to one discrete change in the signal value.[7] This may be why David's description of the proportional control system lacked any step-by-step account of value changes that leads to self-adjusting behavior or any narrative account of how the adjustment is made. This could also be the reason why David was not initially sure what the proportional controller does.

Experimenting With Different Gain Values

Instead, a part of learning the interactions of a proportional control system may depend on learning how key parameters affect system behavior. Much of David's understanding of the relationship between the controller and the behavior of the system grew from experimenting with different values for the controller gain in his designs. From DESIGN1458 to DESIGN1490, David was essentially changing the controller gain to see the effects on the system, and it is from these simulation runs that David began to formulate the following relationships: 1) the smaller the gain, the more precise the frog seemed to be in its movements,[8] and 2) the higher the gain, the faster the frog would move. Previously, in Chapter 5, I noted an example of a FAVL student who was able to identify and relate key

---

[7] The only exception might be a change in the sign of the controller output, which is indirectly related to the direction of rotation.

[8] Precision is defined by how well the frog could seek its target with minimum overshoot.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system parameters (e.g., gain) to larger systemic patterns of behavior. David's case provides some insight on how these relationships are forged within design work.

Case Summary

David's case provides an illustration of how a student can begin to differentiate a more specific class of feedback systems from the more general canonical model and how that student can begin to distinguish between the types of comparator and controller used in an on-off from those used in a proportional control system. This case also suggests that students may have trouble with describing proportional control systems because of difficulties in identifying key events in its narrative and in articulating how signals are changing. In this case, the computational environment itself was helpful in allowing David to establish relationships between the key parameters of the design and the resulting system behavior.

6.3 Redefining the Model

Beyond constructing more detailed understanding of the parts and the signal that describe a feedback system, there were also examples of students using familiar parts and signals in novel ways. The following set of examples is meant to illustrate the nature of these departures from the parts and information flow taught in the canonical model and to show that within a design context, change did not come only in terms of refinement but at times included constructing different definitions for and from the parts and signals at hand.

6.3.1 Redefining a Canonical Part

The first example is taken from David's first design project and shows how a student can assign a functional role to a part that is different from its role in the canonical model and how

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

that student eventually reconciled the two definitions. Specifically, in this case the SPU no longer determined what the desired value of the system should be but instead was used with the threshold comparator as an on-off switch for the connected actuator.

The SPU as a Switch

Like Curtis and Becky, halfway through the first design project, David had created a design with two actuators, one to represent the air-conditioner and the other to represent the heater, a dedicated controller for each actuator, and a shared threshold comparator and SPU. This design, DESIGN1893, is shown in Figure 6-10. Because both the heater and the air-conditioner are tied to a common SPU, the heater and the air-conditioner alternatively go on and off despite the outside conditions. This made for an inefficient design where the air-conditioner would go on (and off) in the winter and the heater would go on (and off) in the summer.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

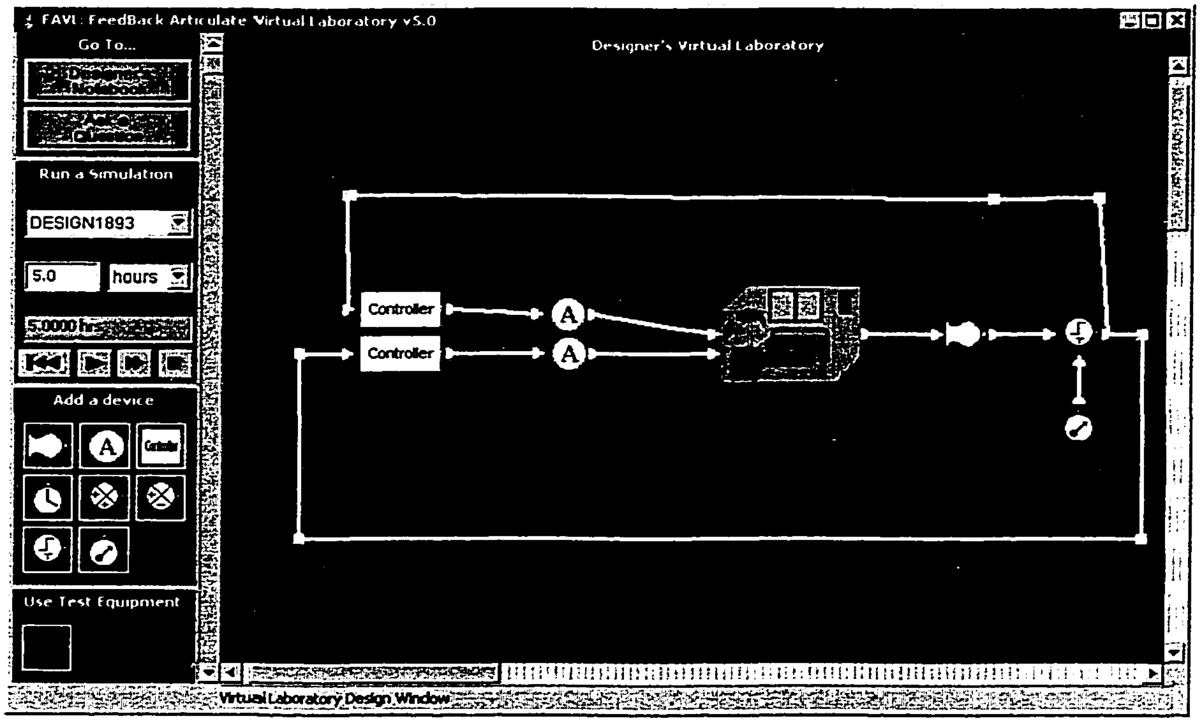


Figure 6-10. DESIGN1893: David's Room Temperature Control Design with Shared SPU. David's design turns on the heater even on a hot day and turns on the air-conditioner even on a cold day because both control loops share the same setpoint. That is, as soon as the heater raises the room temperature past the setpoint, the air-conditioner will turn on. Alternatively, as soon as the air-conditioner lowers the temperature below that same setpoint, the heater will turn on.

At the beginning of this sequence of redesigns, David's design was modeling a hot day in summer, and a simulation run had indicated that the heater was turning on. David proposed a direct fix to the problem of the heater turning on in the summer; David wanted to, "unplug the heater" but was reluctant to disconnect anything. He explained his problem:

David: What's happening is that the heater is turning on when it's hot and I don't
want that to happen.
I just want the room heating up by itself.
Interviewer: Why is the heater turning on at all?
David: because as soon as it gets too cold in there the heater turns on
and I want

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

I want the heater to actually be disconnected.
But there should be some way that I can do it better. Maybe if I made my own comparator um.
Interviewer: How would that help?
David: I don't know if that would really help at all. You need a sensor and a threshold comparator for both. And there's a setpoint here
It wouldn't help because then they'd both turn on. You need some way of making it so that this stays off when this is on when it's hot out.
and I'm just thinking
I don't know what to do here.

Notice that although David had the idea of using a pair of threshold comparator and SPU for each actuator, he did not realize that if he had two SPUs he would be able to set different values for each of the SPUs to effectively create an acceptable range with the air-conditioner turning on and off when a maximum temperature was reached and the heater turning on and off when a minimum temperature was reached. Despite my efforts to draw attention to when each actuator should be turned on and off, David continued to think of the SPU value as one value, 62°. I speculate that this is because he did not see the SPU as anything other than the desired value, the one value that the room should eventually reach or oscillate around.

However, when David identified the subgoal, to turn off the heater, he began to reconceptualize the role of the SPU. Specifically, the SPU and the threshold comparator could act as a switch, or a means of connecting and disconnecting an actuator:

David: I want the air-conditioner to turn on when it get above 62, and I want the heater to turn on when it gets below 62.
Interviewer: Is that possible?
David: Yeah sure.
Interviewer: without they're coming on and competing with each other, fighting with each other?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

David: That's why I have to disconnect it.

...

David: I mean I was thinking if I made a whole new comparator for this then
and a set point
and I set the point [SPU], this thing is
Set this to some outrageous temperature. So it would turn on when it was like
90 degrees in the room.

That is, by setting the SPU for the heater at a very low temperature for a summertime simulation, then the heater would never turn on. Alternatively for a simulation of wintertime, David would change the SPU for the air-conditioner to 95°, a high enough value to insure that the air-conditioner would never turn on and would also change the SPU for the heater to 62°F. (See DESIGN1910 shown in Figure 6-11.)

Reconciling the Two 'Different' SPUs

However, when asked to create one design for both the winter and summer time, instead of using the two SPUs to define the upper and lower limits of the acceptable room temperature range, David changed both SPU values back to 62°, reverting to thinking about the SPU as the one (and only) desired value. Only after another simulation run (during DESIGN1983) did David set the SPU value for the air-conditioner to a higher value than that for the heater thereby creating a successful design.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

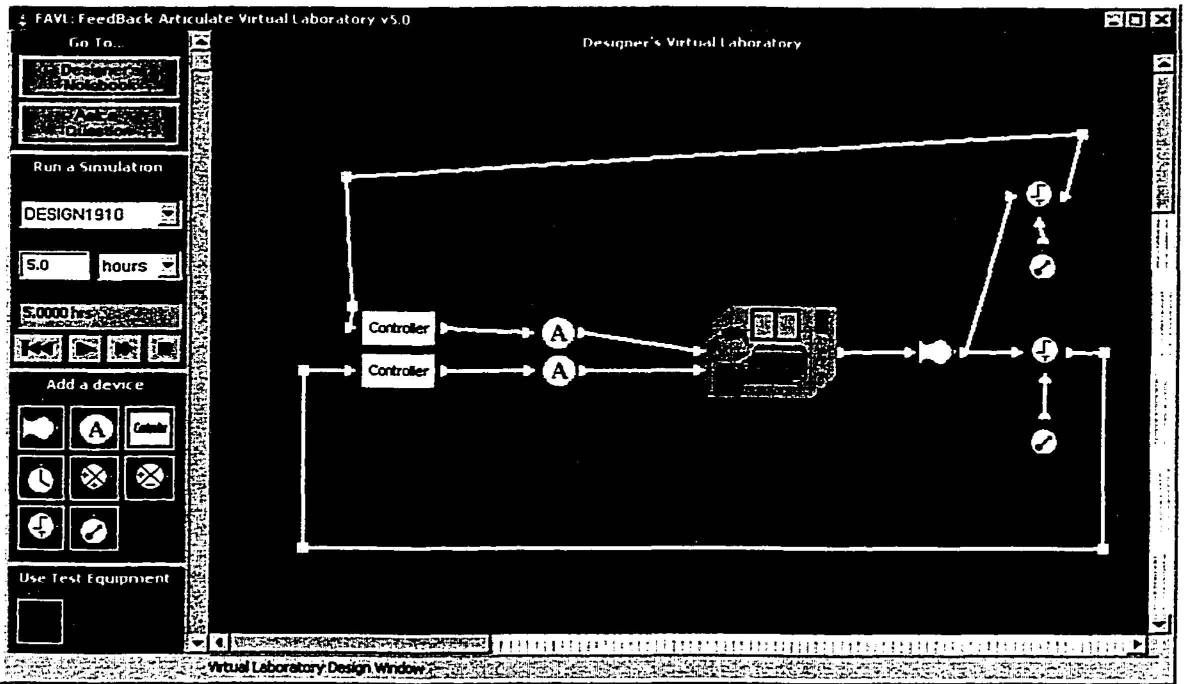


Figure 6-11. DESIGN1910: David's Design with Two SPUs. This design allows him to set two different setpoint values for the heater and for the air-conditioner.

Although David assigned two different roles to the same component within the same design, it was difficult for David to see a relationship between these two roles, the SPU as the setpoint value that determines the equilibrium point of the system, and the SPU as the trigger for turning an actuator on and off. In fact, both Curtis and Becky had the same difficulty in thinking about the SPU in this design as a 'trigger' point. This lends some support to the conjecture that students saw the SPU as having two distinct roles within this design. I speculate that this may be because the SPU resides on two levels of system description. The SPU as a setpoint value describes its function within the overall system goal, and this is the definition that students were more familiar with when they first started this design project. Alternatively, the SPU used as a 'trigger' point describes its function within a set of the internal interactions that leads to the overall system goal of maintaining the temperature at the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

desired value. The latter role seems more strongly linked with a narrative account of when the actuator turns on and when it turns off or even with a signal perspective, which can be used to generate a cycle-by-cycle account of the behavior. This conjecture concurs with the observation that David formulated the idea of using the SPU as part of a switch while he was thinking about *when* the heater should be turned off completely and while he was trying to *disconnect* the heater from the rest of the system.

Case Summary

The two roles that students gave to the SPU in this design and their eventual reconciliation have several implications. The design context, which can force a focus on subgoals, can lead students to formulate new functional roles for familiar components as they move towards a successful design. Reconciling the different roles in which a component can play in a design may depend on using another perspective to forge an appropriate link between the two. Furthermore, the initial difficulty in reconciling the two roles brings to question the usefulness of the uniform vocabulary. This is because students can potentially assign different functions to the same part in different designs and not see that the uniform terms denote uniform functions across designs.

6.3.2 From Component to Signal

As the three students continued their work in FAVL, the definitions they gave to the parts of their designs continued to change. One key aspect of this change is that students began to disassociate the information provided by a part from the part itself. The signal becomes an entity that could be created and manipulated. Some students seemed more fluent with using and defining signals to inform their design while others had a harder time with this transition.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In the following, I will describe the first time Becky began to experiment with creating a signal during the object-tracking project to examine what may be difficult with this transition and how it could be negotiated.

Recall that the object-tracking project asked students to design a frog that could track flies, which could be either stationary or moving. Once the frog had caught one fly, it would need to move on to catch another. Within the feedback design, this meant that the SPU value must change. That is, when the flies are stationary, the SPU value must change whenever a fly was caught so that the frog could target the next fly. Alternatively, when the flies are moving, the SPU value must follow the changing position of the targeted fly. Up to this point, the FAVL project had involved using one set value for the SPU. With this project, the students needed to determine how to design a changing SPU. The easiest solution is to replace the SPU with the output from a sensor that detects the position of one of the flies. But, this exchange was not immediately apparent to Becky.

The Setpoint as a Component

With DESIGN1815 (Figure 6-12), Becky had constructed a control system to try to catch one of the flies. This first design had all the requisite parts of the canonical feedback model, and it was from this model that Becky first began to try to understand what the SPU value should be. Becky's explanation indicates that she knew that the sensor could tell the position of the purple fly, the prey that Becky wanted to catch first. Becky also knew that the setpoint value should be the position of the purple fly:

> Becky: So this [sensor that tells where the purple fly is] will measure the degree from that one

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Interviewer: Right

...

Becky: And, so this [sensor that tells where the purple fly is] tells what angle I need it to be at

Interviewer: That tells you where this fly is.

Becky: So, I don't get what this thing is going to do [moves mouse over the feedback loop in her design]

Interviewer: What do you think it's going to do?

Becky: Well, the setpoint would be where the fly is
And so
This [SPU] should be what this [points to sensor for purple fly] and would tell how to get there

Yet, Becky did not immediately replace the SPU component with the output from the sensor. Instead, Becky looked up the position of the purple fly and then set the output of the SPU component to that one value. This, however, only allowed her to catch one fly.

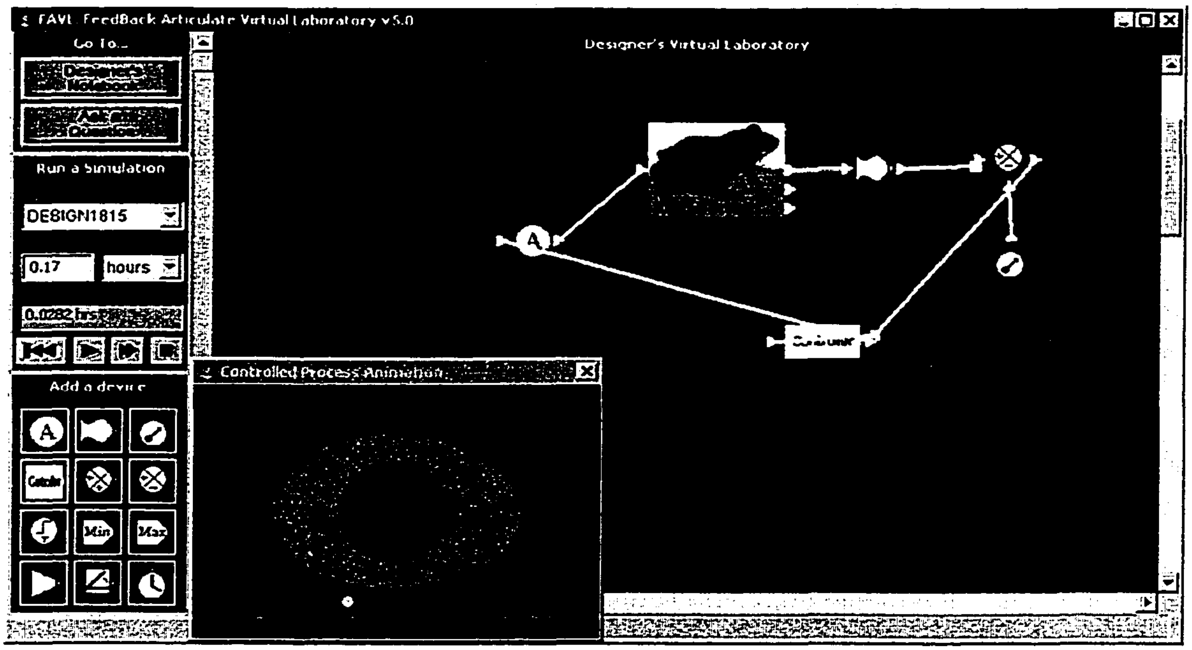


Figure 6-12. DESIGN1815: Becky's On-Off Design for the Object-Tracking Project.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

After catching that fly, Becky began to wonder how she could redesign the frog to catch more than one fly, and she reformulated the control strategy so that her frog would essentially sweep the entire area searching for flies without regard for the positions of the flies. Although Becky would not need a feedback system at all to implement this control algorithm, a simple change to the existing SPU component provided the same effect:

> Becky: All right we did it. Is it going to try to get all of them?
> Interviewer: He should try to get 10 of them in 10 minutes.
> Becky: Well, if he were like rotating slowly like all the way around, then he can just catch all the flies.
> Interviewer: That's probably true. That's one way you can make the design.
> ...
> Becky: Wait. So I have to catch all the flies?
> Interviewer: You have to catch at least 10 flies.
> Becky: Out of one thing?
> Interviewer: Out of one thing.
> Becky: How? Okay, so I'll make him do a 360, but wait, but there's a set point.
> How do you make it?
> Well but then I can just make him end up at [points to 360]
> [opens SPU properties]
> So I can make him want to go like to um like
> So if he's at 1 now so I want him at 360
> So he's going to spin around slowly
> [changes SPU to 360]

Becky implemented this new algorithm by resetting the SPU value of her feedback design to 360°. Notice that in doing so, Becky was using the SPU component in a familiar way; it serves as the long-term, targeted value of the system, the place where the frog should eventually end up. So far, however, there had been no movement in disassociating the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

setpoint value from the SPU component. On the contrary, the setpoint value seems strongly tied to its corresponding component.

Focusing On Value

But, Becky was beginning to question if she really needed a setpoint at all in this design or if she could just let the frog spin. Consequently, she began to consider replacing the SPU component with another component:

> Becky: So, the counter
> So, what would it count? Degrees?
> Interviewer: It just counts numbers 1, 2, 3, 4
> ...
> Becky: Could I have something so where one would roll and then it would stop
> and then it could have a different one that would go?
> ...
> And then after that one, then the first one will stop
> Uh
> I mean you can't just see the same by just having
> Like setting it every time and then stopping the clock

As she became more focused on the setpoint *value*, Becky finally decided to connect the output of the fly sensor to the comparator, effectively making it the setpoint value within her design:

> Interviewer: So, what do you want to do with that setpoint?
> Becky: Well, I want to be able to change it every time
> Interviewer: Okay, how
> What would you change it to?
> Becky: the degree where the fly is
> Interviewer: Can you get that information?
> Becky: Yeah, from this [points to prey2 output]

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Experimenting with different components that generate different setpoint values seemed to help Becky focus on the signal itself and may be the first step in replacing a rigid association between a particular component and the information that it provides to allow for more flexibility associations between parts and signals. In this design, this, in turn, allowed Becky to use information that had been associated with another familiar part, the sensor, in a new configuration.

Case Summary

Part of learning to work in this particular design space involves learning to construct with signals, and this involves paying attention to the information and not just to the components of the design. This short episode from Becky's second design project suggests that when students begin their design work, certain types of information may be strongly tied to a particular function, and students do not immediately see the information apart from the familiar functional component.[9] This is not necessarily a disadvantage when a student is just learning to use the components. However, to gain added flexibility in design work, students through experimentation with different components may break these associations and learn to generate a familiar signal type by using other combination of parts.

6.3.3 Creating New Information Types

The previous case provided a short description of a student who was just beginning to become more flexible in her design configurations. In the following, I will describe another example in which a student combines components and signals in novel ways to create a new information

---

[9] Becky's case was not unique; David's design decisions also followed a similar path.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

type for his design. In particular, I will highlight the strategies he used in creating these new combinations.

Focusing On Component Ports and Constituent Signals

As part of the second FAVL project, students needed to figure out a way to merge two feedback loops in order to determine which of the two flies the frog should track at any one time. The most straightforward solution was to use a minimum component to determine which fly is closer to the frog, but it took Curtis several attempts at redesign before he came to this solution. From the outset, Curtis knew that he needed to somehow combine the information about the two preys' positions. Even before he decided to first focus on one fly, Curtis had begun to identify ways of combining information and suggested using a minimum or a maximum component. Part of what guided his decisions on how to combine information initially seemed to lie in identifying components that would allow for multiple inputs and one output. It is not at all clear if Curtis was as concerned initially with how the inputs would be transformed into the outputs. For example, one of the first components he added to his redesign was a threshold comparator. According to Curtis a threshold comparator has two inputs: the bottom port is the setpoint value, and the left port is the value that is to be compared to the setpoint value. When he began to make the connections to the other parts, Curtis noted, "I don't know which is the setpoint." That is to say, in combining the two signals, one which is the difference between one fly and the frog's position and the other which is the difference between the other fly and the frog's position, Curtis could not make this distinction between the bottom and the left ports of the threshold comparator. This, however, did not stop him from making the connections as shown in Figure 6-13 and running

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

a simulation. And, when this design failed, Curtis replaced the threshold comparator with an adder, another component that has two inputs and one output. He just knows he wants something with two inputs and a single output.

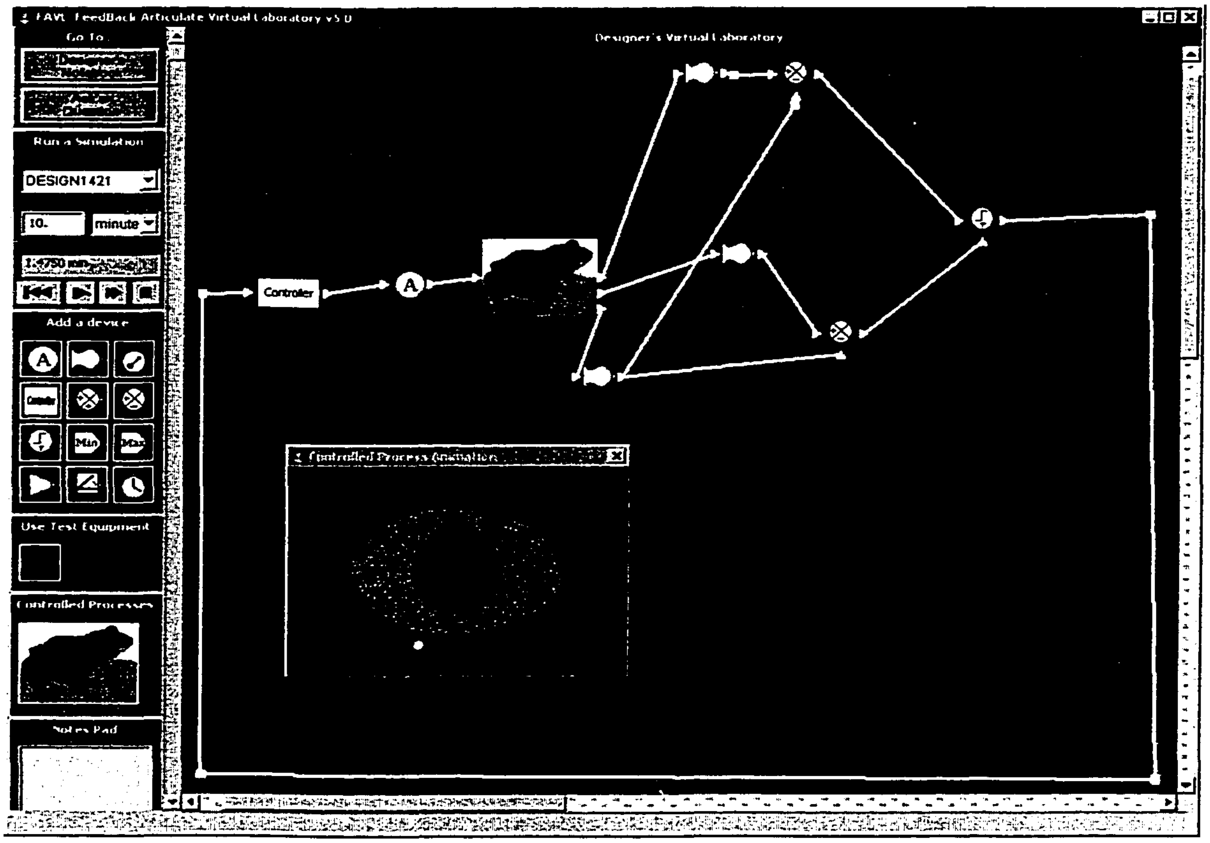


Figure 6-13. DESIGN 1421: One of Curtis' First Attempts to Create a Design That Can Choose between the Two Flies.

Furthermore, in Curtis accompanying descriptions, he could not articulate how to combine the signals although he was fairly clear about the information path that should exist between the components:

> Curtis: These two have to somehow be combined but they just can't be mixed.
> Interviewer: No?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Curtis: And I don't really know how I can do that. I tried using the comparator but I didn't know which one would be the set point. So I just tried the bottom one and nothing really worked

Interviewer: Okay, what would you like to do?

If you can say it in English, what would you like to do with those signals?

Curtis: I would like them to be combined but then sorted.

Interviewer: Combined in what way?

Curtis: So that

Sort of like some device that takes both signals in and tells the controller to do and then, you know, this

Or, tell the actuator to do this and then do that.

Interviewer: Okay.

Curtis: These can both [points to the two difference components] can't both be connected to the controller

The preceding indicates that Curtis' initial understanding of how the two signals should be combined lacked specificity and that defining a new signal type may begin with a general notion of what information should be used and then increasing specification on the nature of the transformation. Furthermore, that specification may not be well reasoned but may depend on experimenting with components based on their physical attributes, such as the number of ports available on a component.

Using a Familiar Part to Define a Signal

Later during the project, Curtis suggested two possible implementations for choosing between the two flies. In the first, he would create a design in which the frog would try to catch one fly then the next after a fixed time; in this plan, the SPU value would change every *x* seconds. For the second proposal, he would design an SPU value that would switch from one fly's position to the next after the frog has caught the previous fly. Curtis explained:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Curtis: So what I would need is I would need the original purple fly to become the setpoint. That could be the set point, and then I would need another difference thing or something to find which one is less.
Interviewer: Yeah that would be one way of doing it.
Curtis: So how how would I do that exactly per se?
And but then how is it going to catch the yellow fly?
Interviewer: okay so let's say you catch the 2nd purple fly, and the 3rd purple fly appears and it's pretty far away. Would you rather go for the purple fly or the yellow fly?
Curtis: the yellow fly
So the purple fly would need to be the setpoint. Er, no the purple fly needs to be the original point and then the yellow fly needs to be the setpoint.

In both proposals, Curtis was trying to construct a setpoint value. Note that the setpoint value is seen as information that is not necessarily associated with a certain component but could be created by a combination of components. Although Curtis eventually would abandon these two solutions, and work towards a design (shown in Figure 6-14) that would compare which fly is closest to the frog's position, these two proposals revealed which part of the system students found to be more easily manipulated. I speculate that change centered on the setpoint unit because of two reasons: The signal was formerly associated with a single part, and this facilitated the partitioning of the design problem along familiar lines of the canonical model. It's easier to change one part of a familiar model then to change combinations of parts. Second, notice that Curtis described what should happen when in order to inform how the setpoint signal should be formed. That is, a narration of events seems to be instrumental in defining the setpoint value. Becky, like Curtis, also had the same redesign proposals, to create a changing setpoint value, when addressing the same design problem in her project work.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

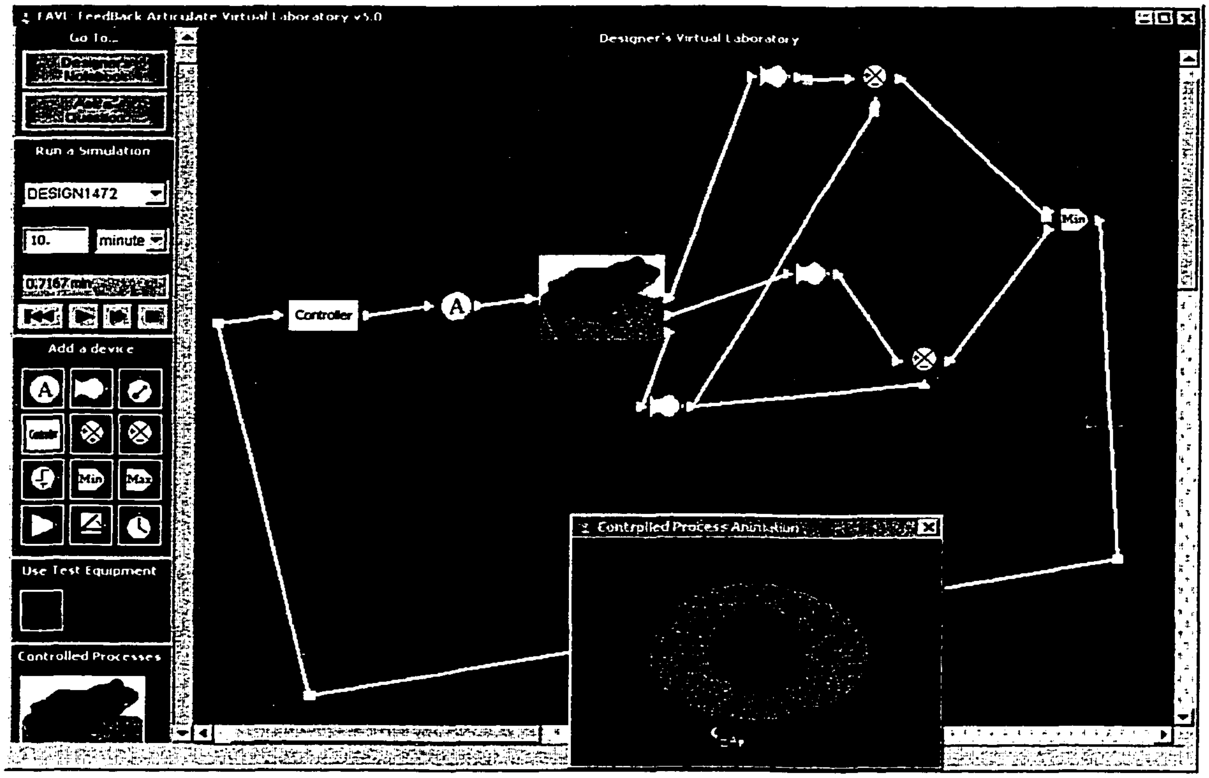


Figure 6-14. DESIGN1472: Curtis' Final Design for the Second FAVL Project. In this design, the minimum component finds which fly is closer to the frog.

Case Summary

This case provides an example of how a student can assemble a signal value from components and other signals available in FAVL and identifies some of the resources that a student may use. In this particular case, Curtis considered component features such as the number of incoming and outgoing ports for each component in selecting his parts. In addition, Curtis also tried to determine what type of information needed to be combined to form his signal, but his verbal descriptions regarding how the signals should be combined were vague and not specific enough to help him narrow his selection. His narration of what should happen in his design, however, did seem to play a role in his design work (i.e., the design he created seems

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

to be informed by an account of what should happen *when*), as did the canonical model, which suggested what could and could not be readily modified.

6.4 Reuse of Feedback Patterns

Earlier in Chapter 5, I argued that the ability to see the underlying structure common to different systems is a critical part of expertise. FAVL was designed with a uniform set of icons that represent the shared functional components in feedback systems in order to help students see the underlying patterns of feedback. However, the examples described in Section 6.3 revealed that students used familiar components in novel ways in their designs and suggest that students may not interpret and apply a FAVL component in a consistent manner across projects in the creative context of design work. Did students, then, still see similarities between the different feedback systems they built in FAVL? What commonalities did and didn't they see in design work? The purpose of this section is to examine if students noticed and made use of common relationships across different design projects in FAVL.

6.4.1 Analysis

I looked through the three students' talk-aloud protocol for two types of data for all four FAVL projects. First, I looked for these students' descriptions of similarities and differences that they noted across design projects. Some of these were observations that student made while the they were trying to redesign their systems; each student was also asked at the end of the second and third design projects if the project which they've just completed was similar to previous project(s) they've already designed. Second, I looked for recurring patterns in their designs; a pattern is a set of components that was used for the same purpose (i.e. they act as a unit) across different designs and across different projects. From these two types of data, I

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

tried to determine not only what similarities students noted but also if those similarities were used to inform other designs. The following describes the findings of the analysis.

6.4.2 Judgments of Similarity – A Few Observations

FAVL was built on the conjecture that an interface that provides students with a uniform set of icons to represent functional components would help students see the structural similarity between feedback systems. That is, the icons allowed for superficial matching that should correspond to functional matches. Did students see commonalities in their design work across different FAVL projects?

The answer to this question is unclear, but I can make the following observations: First, students saw the similarity in the overall purpose between design projects even though they did not always articulate any internal structural similarities. In other words, they matched the system-as-whole models of these systems:

> (*comparing the temperature control to the object-tracking project*)
> Interviewer: Did you feel this was very similar to the home heating or did it have a completely different feel to it?
> David: Um it had a
> It was a little bit
> Because the frog kept on going back and forth and you had to right it, and the temperature keeps going back and forth and you had to right it.

> (*comparing the temperature control to the object-tracking project*)
> Curtis: Well, they both have uh control. Other than that, there's very little similar between them.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Second, their judgment of what makes two designs similar did seem to depend on the types of parts that were used. That is, students pointed out similarities and differences according to which components were and were not shared across projects. For example, when Curtis was asked if the object tracking and room temperature control systems were similar, he noted differences according to the number of actuators and sensors used in each of the designs:

> Curtis: For one the
> There's only one action that the frog can do whereas there's all sorts of, you know
> He's got to look at all sorts of things but generally do one action whereas the room temperature thing, he could do a lot of
> There are two actions but there was only one thing you can look at
> (*Curtis' final temperature control design had two actuators and one sensor, whereas his object-tracking design had one actuator and multiple sensors.*)

And, when I asked David if the cruise control system was similar to the previous two projects, David also answered according to which components his final designs had in common:

> David: It's like a mixture of them.
> More the frog because I used the difference comparator, but it's also like the heating one because I have to have a setpoint with the, you know, to get the closest fly. But this looks a lot like
> This [cruise control design] looks very much like the heating one.

Similarity judgments were, at least partially, based on the components that their final project designs shared. It is not too surprising then that students sometimes judged two feedback system designs as being dissimilar because their designs often differed in the number and type of parts that were used.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.4.3 Patterns in Design Work

The above similarity judgment, however, is just one measure of whether or not students saw similarities in their completed designs. The process of creating a successful design itself involves recognizing that certain relationships that applied in one design apply in another design, while other relationships do not. I therefore also looked at students' design work for patterns that students used and reused across their design projects.

6.4.3.1 The Skeletal Model

The analysis of student work shows that students applied the same general model to their design problems and that this model is similar to the one that they learned earlier during the paper-based instruction described in Section 2.1. Although students almost always began with an on-off design, a detailed look at their protocols reveals that in most cases, the components used in this on-off design served as placeholders for the type of functions that students expected to be included in their solutions. For instance, some students would refer to the threshold comparator in their initial design as simply the comparator and would specify the nature of the comparison only later in their redesign. In fact constructing the general model seems to precede any detailed understanding of how the design should work. For example, during the object-tracking project, Becky began by building an on-off design and only afterwards tried to determine if the right types of information were communicated and the right type of components were included in the design. In fact, Becky did not know what the feedback loop that she built did until *after* she had constructed it. And, all three students began the collision avoidance project by recreating a feedback loop that would control the braking system before they began to change their designs.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The canonical model was, therefore, used as a skeletal design that students could then tailor for the specific design project. Moreover, it structured the manner in which students changed their designs along functional lines. For example, in the second project, David created a proportional control system from the general model by specifying in greater detail the type of comparator and controller he needed and then by replacing the more general form of these components with their more specific subtypes. (This case is described in more detail in Section 6.2.2.3.) Students also created more elaborate subsystems by combining components and signals to substitute for a familiar component in the canonical model. For example, in the second design project, Curtis tried to build an object-tracking design that would track two objects by combining components to create a new type of setpoint value. (See Section 6.3.3.) These cases point to a possible advantage in teaching a general model: the general model provides the skeletal structure from which more detailed and elaborate designs can emerge. Furthermore, a model that partitions a system into its functional parts may help students to focus on one subsystem at a time and so divides the design problem to manageable pieces.

6.4.3.2 Other Patterns

There were also other patterns that were reused across projects. For example, some parts, such as the sensor and, for some students, the SPU were used in a consistent way across different projects. In some cases, a student would even refer back to a previous design to explain how a part should work. For instance, to explain how he would specify the position of his targeted fly in the second design project, Curtis recalled the way the SPU was used in the previous temperature control design:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Curtis: You know, like with the thermostat it tries to get to a certain point and it's trying to get to that certain point [points to 300 degrees] and it's right there right now [points to 250 degrees]. So I was thinking that it'll 'roop' go like that, you know [traces arc from 250 to 300].

Other parts such as the comparator and the controller, however, took on more specific definitions within each design. In fact, it is this differentiation that distinguishes the on-off from the proportional control systems, two feedback system types that have different detailed behavioral patterns. Were students able to transfer this level of detail across designs?

There are some examples from the protocol that indicate that students did. For example, when Becky was interested in shortening the rise time in her cruise control system, she recalled what she had done with the proportional controller to increase the frog's speed:

Interviewer: Is this a similar problem to the frog?
Becky: Well kind of because you can always make it fast, go faster. But, if it want to going faster than, I guess, I could put it [numbers in controller mapping] a little bit lower number.

As another example, when David was asked if the previous designs helped him to create his cruise control system, David referred back to his object-tracking design:

David: Like especially from doing the frog one I needed to
I knew from the threshold comparator that it was just turning on and off, and if you do that it would just be way too jerky and the oscillation would be way too high.
And, I realized the more you got into the range of around 50 [miles per hour] or so it should start to tell the controller and the controller should adjust accordingly.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Notice that David not only saw similarities in the behavior of these two systems (i.e., the jerky movements of the cruise control system corresponded to the large oscillations in an on-off system), but also attributed the behavior to a specific component, the threshold comparator. One of the reasons why David was so quick in designing a proportional cruise control system is because he noticed similarities in the behavior and structure of the cruise control design to previous project designs and used his experiences from his prior cases to inform his design.

This was not always the case. At one point during the cruise control project, Becky had created an on-off design that oscillated beyond acceptable bounds. Although she remembered seeing this behavior in the temperature control system, she could not recall why the temperature in the room oscillated. It appears that even though Becky was able to retrieve a similar case, the case did not help her understand her current design because she did not recall the details of her prior design:

> Interviewer: Okay. Why was it doing this [points to oscillations] for the heating system?
> Becky: I don't remember.
> Interviewer: Okay, so when the heating system, when it got above a certain point
> Becky: it would shut itself off
> Interviewer: Right. And when it got below a certain point
> Becky: and then it would turn on you want
> Interviewer: And so what you think that controller is telling the actuator to do?
> Becky: It's going speeds up and then slow down again and then speed up and then slow down again and speed up.
> Interviewer: What are the only two things that that controller is telling it to do?
> Becky: Oh, to just turn on and off.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Furthermore, the similarities students noted were not always helpful in solving their design challenges. For instance, during the second project Becky noticed that the frog's desired orientation is similar to the acceptable temperature range specified in the previous, temperature control project. They each are the setpoint in their respective systems. But, this prompted her to try to implement a similar mechanism, a bracketed on-off system, to keep the frog's orientation within a certain range of the fly's position instead of resorting to a proportional control solution. This is understandable in light of the fact that Becky at this point was just beginning to explore a proportional control system. However, even after she had built a proportional control system, during her third project, Becky twice referred to using additional components to essentially implement the same on-off bracketed control algorithm that she implemented in the first project. (She would eventually dismiss bracketed control for a proportional control system.) So, although students did see similarities between projects, it was not always straightforward which similarities should be transferred to address a new design challenge. The process of design was in part a process of determining which solutions should and should not be transferred.

6.5 Summary

This chapter has presented a set of examples from three students' work with FAVL with the intent of describing through cases the type of learning that students engaged in during their computer work. At the end of these case studies, what have we learned in answer to the questions that the previous analyses raised:

1. How did students gain a more sophisticated understanding of feedback systems?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2. Did students see and use patterns shared between feedback systems regardless of the particular system instantiation?

Examples from student work gave some indications of what and how students learned through their design work in FAVL. In order to build systems in FAVL, a student who previously held a predominantly system-as-whole view of feedback systems began to articulate the internal functional subsystems that make up the feedback system. Students also disambiguated previously confounded subsystems and learned to differentiate types of functional subsystems into more specialized subclasses. So, for some students the comparator was no longer just a comparator; instead, it made a difference if the comparator was a threshold comparator or a difference comparator. Also, it made a difference if the controller was an on-off controller or a proportional controller.

Refining the functional parts of a feedback system was not the only type of change that occurred while students worked with FAVL. Design work in FAVL forced a level of specificity that required that students pay attention to the signal values that traverse the system from part to part. This is not to say that each particular value was important; instead, values became associated with particular events or changes in behavior, and in order to create a design that met behavior specifications students began to pay attention to how those values were changing or needed to change.

One of the advantages of learning the signal perspective, I assumed, would be that it would provide students a way of causally stepping through their designs. That is, signal propagation

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

could be used to express causality in a system and to link the different parts of the system together into a coherent whole. The cases analyzed in this chapter, however, do not give a clear indication as to whether the signal perspective helped students tie system parts together into a self-consistent whole. Some portions of the protocols do show that students can trace the signal to explain system behavior. Alternatively, there are data that show that design decisions can be local. For example, students would change one parameter and would not bother to propagate values to understand its impact on other parameters, and when a student traced a signal, s/he would trace it to the next component and immediately try to change that component's parameters. One of the advantages of a computational tool is that it performs tedious calculations as well as offloads other cognitively demanding tasks. It could be the case, therefore, that students did not focus on carefully stepping through a design because it was much easier to change a portion of a design on the computer and see if that would solve the problem, than it would be to step through a design to explain faulty behavior.

This may also explain why there was no marked improvement in the multiple-choice test for the FAVL students. Although stepping through a system using signal propagation is a systematic means of reasoning through any feedback system, or in fact any system, work on the computer as it was defined within the current design did not necessitate the development or practice of this skill. What working on FAVL did seem to allow for is experimenting with and establishing relationships between key parameters and system behavior. For example, after tuning the gain for their proportional control designs in their second and third projects, all the students were able to articulate the relationships between the system's gain and the system's overshoot, rise time and settling time, system characteristics that experts often focus

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

on in their descriptions of feedback systems. This may also explain why many more FAVL students were able to explain in more detail a system's control algorithm during their clinical interviews compared to their Non-FAVL counterparts. They recognized the overall pattern of behavior and associated that to a particular type of feedback mechanism, for example the proportional controller. This knowledge is something that Non-FAVL students did not get a chance to construct without the computer work.

The cases described in this chapter also showed that students not only refined but also redefined the parts and the signals described in the canonical feedback model. Students used familiar components in novel ways and began to combine parts and signals to create signals that convey new types of information. A design context to some extent forces students to creatively adapt the parts they are given to create innovative solutions to a challenge. It is, therefore, promising to see that students were able to gain enough fluency with FAVL to create designs that went beyond the canonical model.

A look at whether or not students saw and used similarities between different design projects showed that students almost always began with the canonical model that they then refined or extended to create a model to meet the specific design challenge. To some extent, then all the designs that the students created came from and shared a common basis. Some students also realized that different designs led to different patterns of behavior that are characteristic of certain types of feedback systems. Some students had to learn these patterns by experimenting with different design possibilities during their project work. The act of design itself is in part a process of trying to determine which solutions should and shouldn't transfer.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

7 Summary and Conclusion

The purpose of this dissertation has been to investigate how students understand and reason about feedback systems and how that understanding can change in a learning environment that makes use of comparison and design activities. The first part of this dissertation (Chapter 1 and 2) presented the motivation for helping students develop a richer understanding of feedback systems, hypothesized a set of challenges students may face when learning about feedback systems, and described the instructional tools we designed to help students apply and reason with the expert model of feedback. The succeeding four chapters then described a set of analyses using various methodologies, from detailed case studies to multiple-choice pre-post test scores, that examined students' understanding at various points during instruction. These analyses aimed to characterize students' changing understanding of feedback systems, with Chapter 5 and 6 focusing in particular on how comparison and design work in an articulate virtual laboratory, respectively, can help students develop a richer understanding of feedback systems.

This final chapter summarizes the main findings from these analyses organized according to the initial set of challenges to learning the feedback model that were originally proposed in Chapter 2. This presentation pulls together the observations from the various analyses to summarize the initial difficulties students had, how students met or failed to meet these challenges, and the efficacies and shortcomings of the instructional material that we designed

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

in helping students with these challenges. Where appropriate, I also suggest possible changes to the instructional material that may, in future work, address the shortcomings identified here.

Finally, I discuss briefly the contributions that this study can have in the broader context of teaching students to reason not only about feedback systems but other types of systems and future work that needs to take place to integrate these or similar materials into a classroom environment.

7.1 Summary of Findings

Table 7-1 organizes the key findings of this dissertation according to the main pedagogical challenges we faced in teaching students about feedback systems. The following sections give a more detailed review of these key findings.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 7-1. Summary of Changes in Students' Understanding (continued on next page)

Pedagogical Challenge: To help students construct mental models that include the internal parts and their interactions that give rise to the self-correcting behavior of feedback systems		
Before Instruction: Student models lacked internal details	**After Model Instruction with Comparison Activities**: Students described self-correcting behavior in terms of the internal functions and interactions that make up a feedback system.	**After Design Work in FAVL**: Students described self-correcting behavior in terms of the internal functions and interactions that make up a feedback system. Furthermore, some students specified the algorithm for the control system and were able to explain the details of the system behavior including long-term oscillations.
Pedagogical Challenge: To help students parse feedback systems according to their functional subsystems		
Before Instruction: Students did not identify all the functional subsystems but focused on parts of the system that were familiar from daily interactions	**After Model Instruction with Comparison Activities**: Students were able to identify functional subsystems that make up the canonical model. However, some functions remained conflated for some students.	**After Design Work in FAVL**: Students were able to identify functional subsystems that make up the canonical model. (There are also some indications that functional subsystems became more closely associated with how they process the signal that traverses the feedback system.)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 7-1. Summary of Changes in Students' Understanding

Pedagogical Challenge: To help students reason about the interactions of the parts of the system according to signal propagation that gives them a systematic way of describing cause and effect		
Before Instruction: Students did not always propagate cause and effect from part to part to explain behavior. Students had difficulty or were reluctant to step through the feedback system more than once to determine long-term behavior.	**After Model Instruction with Comparison Activities**: Students were able to identify the information that is passed from one part to the next and to describe the relationship between one functional subsystem and its downstream neighbor	**After Design Work in FAVL**: Students were able to identify the information that is passed from one part to the next and to describe the relationship between one functional subsystem and its downstream neighbor. Also, there are some examples of students tracing signal values to inform their design work. However, this strategy was not always used.
Pedagogical Challenge: To help students see the underlying structure common to all feedback systems		
Before Instruction: Students did not describe feedback systems according to the shared set of canonical parts and interactions.	**After Model Instruction with Comparison Activities**: Students did not spontaneously or consistently apply the canonical model to their descriptions of feedback systems. However, students were able to re-represent the feedback examples they were given according to the canonical parts and part interactions when they were given a template with the general relational terms.	**After Design Work in FAVL**: Students used the template of the canonical model to create their designs in FAVL. However, in paper-based activities that followed, students still did not spontaneously apply the canonical model to their feedback system descriptions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

7.1.1 Opening the Black Box

In Section 2.2.2, I posited that part of helping students to develop a richer understanding of feedback systems involves revealing what in most cases has remained hidden from casual observation. Although students may have encountered feedback systems, they may not have considered or have had cause to consider the feedback mechanism behind the self-correcting systems that they've observed. Part of the point of instruction was to help students construct more inferentially powerful mental models that include the internal parts and their interactions that give rise to the self-correcting behavior of feedback systems.

An analysis of student models (Chapter 4) before instruction showed that a majority of the students were unable to explain the behavior of a proportional control system (though an on-off system was easier to explain). Their models lacked internal details and most students simply described the system as a reactive system with no further explanation regarding how the system determines when and how to react. After the instructional unit a majority of the students were able to explain the proportional control system by referring to the internal interactions that led to a response. This was true for the FAVL and Non-FAVL groups with the FAVL group giving more detailed final explanations than the Non-FAVL group. This was evidence that the instructional material allowed students to formulate more detailed models of what happens within a feedback system.

Using Comparison and Relational Vocabulary to Foster Learning

What was the nature of this transformation and how did the instructional material contribute to this change? Chapter 5 probed for the answers by looking specifically at how students were

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

aligning their model to the expert model. In summary, the results of these analyses showed that after working through the material designed to teach the general model through comparisons, students learned to identify the canonical functions and information flow for physically different feedback systems. Model instruction through comparison activities and alignment to a general model seem to play a part in helping students open up the 'black box' of feedback systems.

Although the explicit mappings from a specific example to the general model using a template were helpful in allowing students to re-represent their models according to the canonical functions, students still referred to the relationships of other less sophisticated model types and obscured more detailed relationships depending on context. For example, many students, even after model instruction, did not align feedback systems according to the canonical functions during a comparison task (Section 5.2.2); some students used looser criteria to decide if a system is a feedback system and, consequently, misidentified positive feedback systems and feed-forward systems as negative feedback systems (Section 5.3.3). This suggests that students' initial representation of these systems may reside on a less detailed level. Novices may differentiate systems not according to their internal, and hidden, interactions but instead simply on how systems react to their environments. Re-representation seems to depend on a need to look inside the system boundaries. This would explain why students who did not align feedback systems according to their shared internal functional subsystems and interactions were, nonetheless, able to describe these systems according to the canonical model when given a template that focused on the internal parts (Section 5.3.4), and were able

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

to describe the internal subsystems and interactions when asked to explain self-correcting behavior in the post-instructional interview (Section 4.2.3).

Design Work in an Articulate Virtual Laboratory

Working in FAVL also gave students a context in which they began to explore the parts and interactions that make up a feedback system. By asking students to select, alter, and connect parts to create systems to meet dynamic requirements, the design projects helped students make explicit the connection between internal parts, their interactions and system behavior. The case study of Becky's first design project (Section 6.2.2.1) gave one example of how a student who began with a system-as-whole model learned to design with the functional parts FAVL provided and to link these parts together according to information passed from one component to the next, a process that involved refining and coordinating her initial understandings of these elements.

7.1.2 Describing Feedback Systems According to their Functions

Learning the expert's feedback model, however, involved opening up the black box to see not just physical mechanism but functional subsystems. Initially, students did not parse feedback systems consistently according to canonical functions. Instead, the data collected indicate that the functions students identified within a feedback system depended on the system considered (Section 4.2.3). For example, the furnace and thermostat and their associated functions in a home heating system are more familiar than the functions of the ciliary muscle and the retina in the eye pupillary control system. Furthermore, certain functions were more readily identified than others. For example, students pointed out the setpoint object in most of the system examples used in the study but had more difficulty identifying the controller, the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

comparator or even a regulator function (Section 5.2.2 and 5.3.2). This may be because most students have had some direct experiences with setting a desired value of a system. The comparator and the controller, on the other hand, are usually encapsulated within a black box in implementation and the most removed from user experience since they lie furthest from the system boundaries. These observations concur with findings from Penner's study on how novice-expert parse systems: Novices focus on those parts and functions of the system that are "directly experienced and personally meaningful"(Penner, 1998, p. 828).

Using Comparison and Relational Vocabulary to Foster Learning

The analysis in Chapter 5 showed that comparison activities alone were not sufficient to draw out all the functional parts that make up the canonical model. I suspect part of the reason is because alignment depends on making one-to-one mappings between entities in the two systems being compared. If students' mental representations are based on discrete objects and the relationship between these physically distinct objects, a comparison will not draw out the functions that are either encapsulated within one or spread over several objects. This is a concern for teaching students to extract the functional components from not only a feedback system but from any system.

Even after students were taught the general model and the relational terms that highlight the functional similarities, students continued to have problems distinguishing certain functions, especially the comparator and the controller. This may be because the comparator and controller are the least familiar and are not often differentiated within implementation. When students first described these functions, they were often embedded in narrative and not

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

associated with an identifiable part, or if the student did identify a physical part then it was often the same part that encompassed both functions.

In addition, part of separating these two functions seems to depend on distinguishing the two according to the type of information each processed and sent. When students were asked to identify the functional parts and the information each part sent to the next, some students had difficulty identifying the type of information that was transferred from the comparator to the controller (Section 5.3.4). Differentiating functional parts requires that students develop a signal perspective as well as a functional perspective for the system. The comparison activities themselves may not have placed enough emphasis on how the signal is changed with each subsystem.

Design Work in an Articulate Virtual Laboratory

Design work in FAVL allowed students an opportunity to further refine and differentiate between the functional subsystems along lines that may have seem arbitrary in the general model. The case studies of students' design work (Section 6.2) show how students learned to differentiate functional component types into subtypes and to use these more specific definitions to create designs that meet behavior specifications in their projects. In particular, Section 6.2.2.3 illustrates how one student was able to work from the more general canonical model and distinguish between the types of comparator and controller used in an on-off from those used in a proportional control system to generate a different set of behaviors.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Also, student learned to distinguish previously confounded parts in FAVL. For example, in the first design project, students were asked to build a system that would appropriately control both the heater and the air-conditioner in a temperature regulation system. To do so, students had to implement two controllers each of which processed the comparison result differently, which forced students to differentiate the controller from the comparator. In Becky's case (Section 6.2.2), this distinction was also tied to developing a more detailed specification of the signal and the information that is communicated from one component to the next within the system. Learning the functions that make up a feedback system, therefore, depends not only on seeing the relationship between a set of physical parts and their behavior to the overall system goal, but also on how different functional subsystems change the signal that links them. More broadly, then, learning to partition a system into its functional parts relies on concurrently learning to integrate a system according to the information flow.

7.1.3 Developing a Signal View

Part of developing an expert understanding of feedback system is learning to describe the interactions of the parts of the system according to the signal that flows through them. The signal flow is used to capture causality within a system with information passed from one part to the next representing cause and effect. There were, however, several difficulties students had in reasoning with and about the signal flow. The following point to some of the patterns I noticed throughout the study.

<u>Directed Stepwise Reasoning</u>. Directed, stepwise reasoning is a systematic means of tracing a signal from part to part to determine how a change in one part of the system can change its

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

downstream neighbors and the overall system. It can be used to generate explanations for short-term or long-term behavior and is useful for debugging designs by allowing the student to trace a problem back to its source, akin to the topological search strategy described by Rasmussen (Rasmussen, 1986).

However, there were several indications that students were unfamiliar or reluctant to use stepwise reasoning and did not focus on step-by-step accountability within their explanations or their design decisions. Protocol analyses of students' multiple choice answers showed that directed stepwise reasoning was not always used and if used was used for only one iteration of the loop from the changed part to the part in question (Section 4.3.4.2). Likewise, the case study of Curtis' first design projects in FAVL shows that this student did not systematically propagate change through successive parts of the system and, consequently, ran into difficulties in troubleshooting his designs (Section 6.2.2.2).

The Weakest Link. The data also indicate that students often terminated their description of the signal flow at the controlled process. For example, in answering their multiple-choice questions, few students reasoned through several iterations of the loop. Instead, once they determined the first corrective action, students would extrapolate from this first iterations and draw upon other constraints, such as knowledge that the system should move towards equilibrium, to determine the long-term behavior of the system (Section 4.3.4.2 and 4.3.4.3). The few times when students tried to step through the loop multiple times, they would lose track of the changing values. This explains why some students, even students with an internally connected model, had difficulties explaining system transients such as damped

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

oscillations for a proportional control system in their clinical interviews and on their multiple-choice tests.

Students sometimes completely lost sight of the continuous readjustments that are characteristic of feedback systems. For example, during the post-instruction interview when they were asked to identify the feedback systems from three systems, many of the students identified the feed-forward system as a feedback system (Section 5.3.3.). The main distinction between a feed-forward system and a feedback system is that a feed-forward system makes a corrective calculation once and does not change that calculation based on changing environmental factors whereas a feedback system is constantly adjusting for changing conditions. Furthermore, several times within their design work, especially during the second, object-tracking project, students would initially try to design a system that would calculate exactly how much to move the frog forgetting that if the frog missed on its first attempt, the feedback system would compensate for the error.

<u>The Order of the Change.</u> The above set of difficulties seem to arise more often in students' description of proportional as opposed to on-off control systems. In general, students were much better at describing the adjustments made by on-off systems than proportional systems. This was the case in the pre-test where most students were able to explain the behavior of the home heating system with greater detail than the behavior of the pupillary system (Section 4.2.3). As I've already posited, part of the reason for this difference lies in the familiarity of the former. However, I suspect some of the difficulty may also lie in the fact that the home heating system is an on-off system and the pupillary control system is a proportional control

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system. To support this conjecture, I note that in the multiple-choice questions, some students had problems simply understanding the proportional algorithm that was described and within their protocols described a system that adjusts by a constant amount (Section 4.3.4). Also, as I already mentioned, students had a more difficult time describing and implementing a design for the proportional control system.

Part of the difficulty, I conjecture, is that a step-through of a proportional control system requires tracking incremental change which is much more demanding than tracking discrete changes in binary states. This concurs with White and Frederisken's hypothesis that students have an easier time learning zero-order models first and then learning incremental models (White & Frederisken, 1990). Furthermore, as I posited in Section 6.2.1, students try to tell short narratives of what happens to a system when they explain a system. These narratives contain the main episodes, which corresponds to object states, and the events, or transitions between these states. Telling a narrative where there are distinct states is much easier that telling a narrative of incremental change. It is possible that students need to also learn to construct narratives in which key episodes are characterized by increasing value or decreasing value with key events being transitions between such states. That is, students need to learn to describe behavior in terms of first-order and higher-order qualitative relationships and not just according to zero-order relationships. Work in qualitative reasoning has shown that these qualitative relationships can be used to generate causal explanations of change in physical devices (de Kleer & Brown, 1984). This may help students with connecting the signal description of proportional control systems to the more familiar narrative form.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Using Comparison and Relational Vocabulary to Foster Learning

The base example used in the comparison activities was designed to introduce students to the signal flow that characterizes a feedback system. A subsequent discussion about how a problem with each part of the system could affect its downstream components tried to encourage students to step through the system to propagate change. In addition, the general model which students used to help them align different feedback systems to the canonical parts also depicted the same signal flow. After model instruction, students were able to identify the information that was passed between the functional subsystems when they were asked to describe a given feedback system according to the canonical model (Section 5.3.4).[1]

Why were students reluctant to trace a change through the system in their subsequent work? In part, the comparison activities may not have placed enough emphasis on these links. Although introducing the base example included a discussion of how a problem with one part of the system affects its downstream components, a similar activity was not repeated during the subsequent comparisons between the two target examples to the base example, nor were these relationships discussed when the general model was introduced. More emphasis on tracing the flow of the signal may have helped. In particular, asking students to give causal explanations for the dynamic behavior of each system and then asking them to compare those explanations may have encouraged students to use and reuse the causal links between components in problem solving.

---

[1] As I mentioned earlier, some students did, however, continue to have problems distinguishing between the information generated by the comparator from the information generated by the controller.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Furthermore, the focus of these comparison activities was on the functional make up of the system and the signal that traveled from one function to the next. Many of the questions that were asked with the base example concerned how one part would affect the controlled variable, and only one of these questions required the students to reason about what would happen in the long term.[2] These factors may explain why students sometimes forgot that the signal flow represented a continuous exchange of information. In addition, the diagram of the general model may have obscured this characteristic. Because it depicted each part and each intervening signal once, students may have been misled to thinking that the signal traverses the system once. In the future, this diagram should be augmented to emphasize the continuous nature of these interactions.

Design Work in an Articulate Virtual Laboratory

Working on the design projects in FAVL offered students a context in which to refine their understanding of the signal flow. The case studies gave examples of how students began to construct a more detailed understanding of the nature of the signal flow within their designs. This included examples in which students assigned meaning to the signal values propagated through their systems and used these signals to select parts and to isolate fault (Section 6.2.2). The signal and its information content even became a reified entity that they manipulate within their designs (Section 6.3.2 and 6.3.3).

[2] In this question, the controller was reversed, turning the system into a positive feedback system. Students were expected to reason through the system several times to argue that the temperature of the water became increasingly hot (or increasingly cold) depending on the initial state.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

However, even as students worked in FAVL they did not always step through their designs to isolate fault and sometimes lost sight of key relationships. Why was this the case? One of the advantages of FAVL is that it allows students to modify parameters and otherwise revise their designs with a few mouse clicks. It is possible that it was more efficient to alter parameters and see what happens than doing a more laborious step through of the design. Often, students would alter a design all the while claiming that they don't know what it'll do or why it should work.

Also, the design that students create in FAVL is an artifact that embodies the integrated set of relationships for the designed feedback system. The design off-loads the cognitively demanding task of keeping track of all the relationships between parts, signals, and behavior. However, when students work on the design, they may be adding to this design in fragments. At times, design work focuses on the local while obscuring the global. To foster a more integrated view of feedback systems during the design process, future versions of the software and the curriculum should include prompts to encourage students to reflect on their overall design and the signal that continuously loops through its parts. This can include prompting students for explanations of how they think their designs work before they make a simulation run. Also, when more sophisticated systems are built, then instruction along with software features should encourage and allow students to partition the more complex system into meaningful subsystems to manage the cognitive complexity.

We should not lose sight of this study's results that indicate that students who worked with FAVL not only gave more sophisticated explanations for the feedback system behavior in the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

post interview, but more FAVL students were able to explain certain behavior such as damped oscillations that most Non-FAVL students could not (Section 4.3.2). So, in some sense, students in the FAVL group were learning to make a connection between the parts and the interactions in a design and the overall behavior of the system that they generated through simulation. But, it was not always clear if signal propagation is how students made or remembered this connection between the simulation results and the design's component parts and part interactions. Additional work on the nature of this connection(s) and how it is forged and used in contexts outside of computer work will be an important contribution to understanding what and how students learn when they build and simulate dynamic systems in a virtual environment.

7.1.4 Learning the Common Underlying Structure

Learning the expert model involves describing the internal subsystems and interactions that make up a feedback system according to a *uniform* set of functional parts and signal interactions that are applicable to describing all negative feedback systems regardless of their physical instantiation. The pre-instruction data indicate that students did not come to the instructional unit with an abstract schema of a feedback system that they then applied to the explanation of different feedback examples. In fact, although many more students were able to give a much more detailed description of the home heating feedback system, these same students failed to transfer the explanation to the pupillary system within the pre-instructional interview.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Using Comparison and Relational Vocabulary to Foster Learning

Comparisons activities guided by relational vocabulary were the primary means used to help students construct a relational abstraction that captures the functional compositions and the signal interactions that characterize a feedback system. The conjecture was that through progressive alignment of different feedback systems guided by linguistic and iconic labels, students would extract and abstract the shared relationships within and across systems.

After the instructional comparison activities, many students still did not align feedback systems in the subsequent comparison tasks according to the canonical model (Section 5.3.2), and their criteria for identifying feedback systems did not always hinge on the relationships embodied in the model taught (Section 5.3.3). Students, therefore, did not spontaneously or consistently apply the relationships they learned. However, when given the general model, students were able to re-represent the feedback examples they were given according to the canonical parts and part interactions (Section 5.3.4). To some extent, this result is not too surprising. If relational abstractions were easily formed through a few comparisons and liberally applied, we run the risk of constructing abstractions that lack inferential power. In fact, there was one clear example of this over-extension in this study; a student interpreted the canonical relationships so loosely that he was able to fit a positive feedback system into the negative feedback model (Section 5.4.2). In the design of future instructional material, we need to ask students to perform more comparisons between analogous systems to highlight the functions and the interactions that make up the canonical feedback model as well as the overall behavior of these systems and to give enough specificity to these relationships to avoid over-extension.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Design Work in an Articulate Virtual Laboratory

The FAVL interface was also designed so that it would provide students with a uniform set of parts that represent the functions typically found in feedback systems. This served to reinforce the commonality between the feedback systems that students would design for different projects. The case studies of students work in FAVL indicate that, of the students considered, students did learn the template for the general feedback systems, which they would then specify and otherwise transform in order to meet the particular requirements for the project. However, students did not always transfer more appropriate design solutions. For example, some of these students would start with the on-off model and then change the model to create a proportional control system instead of simply starting with a proportional control solution. This may simply reflect a lack of experience with specific types of feedback systems, and it would be interesting to see if students would become better at identifying which solutions to transfer as they gain more experience and complete more design projects in FAVL.

7.2 The Broader Context and Future Work

7.2.1 Teaching about Systems

There is increased emphasis within the educational community to introduce system concepts to pre-college students, and the development of tools such as STELLA, Model-It and StarLogo has enabled and encouraged this effort. Although these different tools have different underlying metaphors for describing systems, any understanding of systems still needs to grapple with a similar set of key issues. Even though this study has focused on how student

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

learn feedback systems, many of the findings from this study can extend understanding of how student learn systems in general.

A system is defined as a set of parts whose interactions give rise to a set of behaviors attributed to the system as a whole. But, what makes for a good definition of a 'part'?[3] Within this particular study, I have focused on students learning to partition a system according to its functions. Functional partitioning not only creates parts that are useful to defining systems according to how it accomplishes its goals and, therefore, is instrumental in describing its behavior, but also represents a common way that experts see systems within design work and repair work. However, functional partitioning needs to be promoted explicitly within instruction, and the instructional design described in this thesis points to one way (i.e., through comparison guided with relational terms) in which that functional re-representation can be fostered. The functional subsystems of a feedback system are well defined. For other systems, it will be necessary to determine what are the key functional substructures that can broadly and accurately describe each class of systems.

Developing a system perspective also depends on integrating system parts. Integration does not necessarily need to rely on a signal perspective. In fact, previous work on how students connect structure, function and behavior do not make any mention of the idea of information flow or signal transport (Hmelo, Holton, Allen, & Kolodner, 1996; Hmelo, Holton, Allen, &

---

[3] Preliminary studies on students' use of Model-It suggests that novices within a domain have difficulties defining what a part should be (Shrader, Lindgren, & Sherin, 2000). A research study with business school students indicate that novices have trouble reasoning about stocks, a key 'object' used in the STELLA interface (Sweeney & Sterman, 2000).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Kolodner 2000; Chi et al., 1991; Penner, 1998). The advantage of describing systems according to their signals is that it provides a context-independent tool by which a modeler can come to integrate any system. And, system modeling tools like STELLA, Model-It and StarLogo all require students to define explicit connections that denote causal links between variables. Understanding how students propagate change and make connections between variables in a system is an important part of understanding how students reason about systems. This study has described some of the ways in which students come to an understanding of the signal as a means of integrating systems.

Finally, this thesis has focused on a specific external representation of feedback systems that borrows from the block diagrams typically used in systems work to represent functions and signals in a system. We assumed that making these entities, which experts use, available to students would provide a cognitive advantage. Specifically, these entities should help students see the underlying commonalities between systems and, thus, facilitate the transfer of explanation and prediction between different examples. However, students struggled with this representation and the ideas that it encompassed. It is not clear if another representation would have been more accessible to students and if a more accessible representation would have been more effective in helping students learn a model that they can apply to similar systems regardless of their physical instantiation. Also, although I have focused on the cognitive aspects of working with these representations, learning this particular representational form is an important part of developing expertise according to the socio-cultural framework. That is, block diagrams are tools that experts use to capture and exchange their ideas within a larger community, and learning to work with block diagrams is part of becoming enculturated within

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

a community of practice. The social and cognitive roles that different forms of representing systems can have on how and what students learn when they model and analyze systems merit further study.

7.2.2 Classroom Integration

The larger research agenda for this work was envisioned to consist of two phases. The first phase focused on designing a set of tools and accompanying curriculum to help students develop a richer understanding of feedback systems and on testing and refining those material in a laboratory setting. The work reported in this thesis contributes to that effort. The second phase of the research involves adapting these tools and curriculum to a classroom setting and eventually incorporating them into the educational institution in a sustainable and scalable way.

A substantial effort must be undertaken to integrate the material described in this thesis into the culture of the classroom. Like other new technological and curricular innovations, this instruction challenges what is taught and how it is taught. Instruction no longer comes from a teacher who lectures to a class but instead involves students who actively investigate systems that they themselves create. It changes both student activities as well as teacher roles. The interactions between the material, the students, and the teacher need to be further studied to determine how to adapt this material for classroom use.

In addition, introducing feedback systems as a topic unto itself challenges the traditional academic divisions by which courses, especially high-school courses, are organized.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Feedback is a concept that transcends disciplines. Teaching about feedback, therefore, does not neatly fall into any particular subject area. Feedback systems would need to be taught in various academic subjects in order to help students use these concepts broadly. It will be a challenge to fit this concept into already tight teaching schedules and to coordinate its introduction so that students are exposed to the general principles without learning to associate them to only one particular discipline.

As new and promising models for integrating technologically rich curriculum and innovative content emerge, it is hoped that some of the ideas presented in this thesis can find their way into classroom implementation.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

8 References

American Association for the Advancement of Science. (1991). *Science for all Americans - Project 2061*: Oxford University Press.

Brandes, A., & Wilensky, U. *Treasureworld.* [On-line]. Available: www.tufts.edu/~uwilensk/papers/treasureworld/treasure.html

Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: abstract transfer versus explanatory model construction. *Instructional Science*, *18*, 237-261.

Cassirer, E. (1923). *Substance and function*. Chicago: Open Court Publishing Co.

Chi, M.T.H., Chiu, M.H. & deLeeuw, N. (1991). *Learning in a non-physical science domain: The human circulatory system*. Pittsburgh, PA: Learning Research and Development Center.

Chi, M.T.H., Feltovich, P. & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121 - 152.

Clement, C. A., & Gentner, D. (1991). Systematicity as a selection constraint in analogical mapping. *Cognitive Science, 15*, 89-132.

Clement, C. A., Mawby, R., & Giles, D.E. (1994). The effects of manifest relational similarity on analog retrieval. *Journal of Memory and Language*, *33*, 396-420.

Clement, J. (1994). Use of physical intuition and imagistic simulation in expert problem solving. In D. Tirosh (Ed.), *Implicit and explicit knowledge* (pp. 204-244). Hillsdale, NJ: Ablex.

Collins, A. & Gentner, D. (1987). How people construct mental models. In D. Holland, &. N. Quinn (Eds.), *Cultural models in language and thought* (pp. 221-242). New York: Cambridge University Press.

de Kleer, J. (1984). How circuits work. *Artificial Intelligence, 24*, 205-280.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2&3), 105-225.

Driver, R., Guesne, E., & Tiberghien, A. (1985). Some features of children's ideas and their implications for teaching. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 193-201). Milton Keynes, UK: Open University Press.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education, 75*(6), 649-672.

Duit, R., Komerek, M. , Wilbers, J., & Roth, W.M. (1997, April). *Conceptual change during a unit on chaos theory induced by means of analogies.* Paper presented at the Annual Meeting of the National Association for Research in Science Teaching (NARST), Chicago, IL.

Forbus, K. D. (1984). *An interactive laboratory for teaching control system concepts* (Report 5511). Cambridge, Massachusetts: Bolt Beranek and Newman Inc.

Forbus, K. D, & Gentner, D. (1986). Learning physical domains: toward a theoretical framework. In R.S. Michalski, J.G. Carbonell and T.M. Mitchell (Eds.), *Machine learning: An artificial intelligence approach* (Vol. 2). Palo Alto: Tioga Press.

Forbus, K. D., Whalley, P.B., Everett, J.O., Ureel, L., Brokowski, M., Baher, J. Kuehne, S.E. (1999). CyclePad: An articulate virtual laboratory for engineering thermodynamics. *Artificial Intelligence, 114*(1-2), 297-347.

Gentner, D. (1983). Structure-mapping: a theoretical framework for analogy. *Cognitive Science, 7*, 155-170.

Gentner, D., Brem, S., Ferguson, R.W., Markman, A.B., Levidow, B.B., Wolff, P., & Forbus, K. D. (1997). Analogical reasoning and conceptual change: A case study of Johannes Kepler. *Journal of the Learning Sciences, 6*(1), 3-40.

Gentner, D., & Landers, R. (1985). Analogical reminding: A good match is hard to find. *Proceedings of the International Conference on Cybernetics and Society,* 607-613.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist, 52*, 45-56.

Gentner, D., & Namy, L. (1999). Comparison in the development of categories. *Cognitive Development, 14*, 487-513.

Gentner, D., & Rattermann, M.J. (1991). Language and the career of similarity. In S.A. Gelman & J.P. Byrnes (Eds.), *Perspectives on thought and language: Interrelations in development* (pp. 225-277). London: Cambridge University Press.

Gentner, D., Rattermann, M.J., & Forbus, K.D. (1993). The roles of similarity in transfer: Separating retrievability and inferential soundness. *Cognitive Psychology, 25*, 524-575.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Gentner, D., Rattermann, M. J., Markman, A., & Kotovsky, L. (1995). Two forces in the development of relational similarity. In T.J. Simon, & G.S. Halford (Eds.), *Developing cognitive competence: New approaches to process modeling* . Hillsdale, NJ: Lawrence Erlbaum.

Gick, M. L., & Holyoak, K.J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15*, 1-38.

Glaser, R., & Chi, M. T. H. (1988). Overview. In R. Glaser, M. T. H. Chi, & M. J. Farr (Eds.), *The nature of expertise* . Hillsdale, NJ: Lawrence Erlbaum.

Goel, V., & Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science, 16,* 395-429.

Greeno, J. G. (1983). Conceptual entities. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 227-252). Hillsdale, NJ: Lawrence Erlbaum.

Hmelo, C. E., Holton, D.L., Allen, J.K., & Kolodner, J.L. (1996). Designing for understanding: children's lung models. *Proceedings of the 18th Annual Conference of the Cognitive Science Society*, 298-303.

Hmelo, C. E., Holton, D.L., Allen, J.K., & Kolodner, J.L. (2000). Designing to learn about complex systems. *Journal of the Learning Sciences, 9*(3), 247-298.

Hollan, J. D., Hutchins, E.L., & Weitzman, L. (1984). STEAMER: an interactive inspectable simulation-based training system. *AI Magazine*, *5*(2), 15-27.

Jackson, S. L., Stratford, S.J., Krajcik, J., & Soloway, E. (1994). Making dynamic modeling accessible to precollege science students. *Interactive Learning Environments*, *4*, 233-257.

Kempton, W. (1987). Two theories of home heat control. In D. Holland & N. Quinn (Eds.), *Cultural models in language and thought* (pp. 221-242). New York: Cambridge University Press.

Kotovsky, L., & Gentner, D. (1996). Comparison and categorization in the development of relational similarity. *Child Development, 67*, 2797-2822.

Kuehne, S., Forbus, K., Gentner, D. & Quinn, B. (2000). SEQL: Category learning as progressive abstraction using structure mapping. *Proceedings of the 22nd Annual Conference of the Cognitive Science Society,* 286-291.

Kurtz, K. J., Miao, C.H., Gentner, D. (in press). Learning by analogical bootstrapping. *Journal of the Learning Sciences.*

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Larkin, J. H. (1983). The role of problem representation in physics. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 75-98). Hillsdale, NJ: Lawrence Erlbaum.

Lesgold, A., & Lajoie, S. (1991). Complex problem solving in electronics. In R.J. Sternberg, & P.A. Frensch (Eds.), *Complex problem solving: Principles and mechanisms*. Hillsdale, NJ: Erlbaum.

Loewenstein, J., & Gentner, D. (2001). Spatial mapping in preschoolers: Close comparisons facilitate far mappings. *Journal of Cognition and Development, 2*(2), 189-219.

Loewenstein, J., Thompson, L., & Gentner, D. (1999). Analogical encoding facilitates knowledge transfer in negotiation. *Psychonomic Bulletin & Review, 6*(4), 586-597.

Ma, J. (1999, November). *A case study of student reasoning about feedback control in a computer-based learning environment.* Paper presented at the Frontiers in Education Conference, San Juan, Puerto Rico.

Mandinach, E. B., & Cline, H.F. (1994). *Classroom dynamics: Implementing a technology-based learning environment.* Hillsdale, NJ: Erlbaum.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 299-324). Hillsdale, NJ: Lawrence Erlbaum.

Milsum, J. H. (1968). Mathematical introduction to general system dynamics. In J. H. Milsum (Ed.), *Positive feedback - A general systems approach to positive/negative feedback and mutual causality* (pp. 23-65). New York: Pergamon Press.

Mioduser, D., Venezky, R.L. , & Gong, B. (1996). Students' perceptions and designs of simple control systems. *Computers in Human Behavior, 12*(3), 363-388.

Miyake, N. (1986). Constructive interaction and the iterative process of understanding. *Cognitive Science, 10*, 151-177.

National Research Council. (1996). *National science education standards.* Washington, DC: National Research Council.

Novick, L. R. (1988). Analogical transfer, problem similarity, and expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14*, 510-520.

Penner, D. E. (1998). Understanding phenomena: investigating structure-function relationships. *Proceedings of the 20th Annual Conference of the Cognitive Science Society*. 824-829.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Ploetzner, R., & Spada, H. (1993). Multiple mental representations of information in physics problem solving. In G. Strube & K. F. Wender(Eds.), *The cognitive psychology of knowledge* (pp. 285-312). Amsterdam: Elsevier Science Publishers.

Rasmussen, J. (1986). *Information processing and human-machine interaction*. (Vol. 12). New York: North-Holland.

Resnick, M. (1996). Beyond the centralized mindset. *Journal of the Learning Sciences, 5*(1), 1-22.

Richardson, G. P. (1991). *Feedback thought in social science and systems theory*. Philadelphia: University of Pennsylvania Press.

Rubin, M. D. (1968). History of technological feedback. In J. H. Milsum (Ed.), *Positive feedback - A general systems approach to positive/negative feedback and mutual causality* (pp. 9-22). London: Pergamon Press.

Samarapungavan, A. W., & Reinout W. (1997). Children's thoughts on the origin of species: A study of explanatory coherence. *Cognitive Science, 21*(2), 147-177.

Sherin, B. (in press). How students understand physics equations. *Cognition and Instruction*.

Shrader, G., Lindgren, R. & Sherin, B. (2000, April). *A pedagogically-oriented analysis of the modeling process*. Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans, LA.

Sime, J. A. (1996). *An investigation into teaching and assessment of qualitative knowledge in engineering*. Paper presented at the EUROAI-Ed: European Conference on Artificial Intelligence in Education, Lisbon.

Skorstad, J., Gentner, D., & Medin, D. (1988). Abstraction processes during concept learning: a structural view. *Proceedings of the 10th Annual Conference of the Cognitive Science Society*. 419-425.

Snir, J., Smith, C. & Grosslight, L. (1995). Conceptually enhanced simulations: A computer tool for science teaching. In D.N. Perkins, J.L. Schwartz, M.M. West, & M.S. Wiske (Eds.), *Software goes to school - Teaching for understanding with new technologies* (pp. 106-129). New York: Oxford University Press.

Stark, L., & Theodoridis, G.C. (1973). *Information theory in physiology*. (Vol. 1). New York: Academic Press.

Steed, M. (1992). STELLA, a simulation construction kit: cognitive process and educational implications. *Journal of Computers in Mathematics and Science Teaching, 11*, 39-52.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Stratford, S. J. (1997). A review of computer-based model research in precollege science classrooms. *Journal of Computers in Mathematics and Science Teaching, 16*(1), 3-23.

Sweeney, L. B., & Sterman, J.D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review, 16*(4), 249-286.

von Bertalanffy, L. (1968). *General system theory.* Middlesex: The Penguin Press.

Vosniadou, S., & Brewer, W.F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535-585.

White, B. Y. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction, 10*(1), 1-100.

White, B. Y., & Frederiksen, J.R. (1990). Causal model progressions as a foundation for intelligent learning environments. *Artificial Intelligence, 42*, 99-157.

Wiener, N. (1961). *Cybernetics or control and communication in the animal and the machine.* (2nd ed.). Cambridge, Massachusetts: The M.I.T. Press.

Williams, M. D., Hollan, J.D., and Stevens, A.L. (1983). Human reasoning about a simple physical system. In D. Gentner and A. L. Stevens (Eds.), *Mental models* (pp. 131-154). Hillsdale, NJ: Lawrence Erlbaum.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix A. Summary of Student Misunderstandings

This appendix summarizes the difficulties students had with different aspects of the expert model, organized according to common student misunderstandings of the canonical parts and their interactions.

A.1 Student Misunderstandings of the Canonical Functional Parts

Sensor. Some students, especially those who held a system-as-whole model, believe that the sensor is a display unit that indicates the current condition of the controlled process. The sensor is not connected to the mechanism that allows the system to reach and maintain a desired condition. Instead, the sensor is used to provide information to people who may need information about the process being controlled, and can be removed without affecting the rest of the system. This problem is manifest in certain students' multiple-choice protocols. (See Section 4.3.4.1)

SPU. Students often correctly equate the SPU value with the steady-state, equilibrium value of the feedback system. They also correctly describe the SPU as the component that specifies the desired state of the system and passes that value to the comparator. However, students sometimes fail to see that the latter descriptions of the SPU (i.e., its interactions with the rest of the feedback system) gives rise to the first, more global property of the SPU. This difficulty was evident in students' design work in FAVL (See Section 6.3.1)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Comparator. Some students conflate the comparator and the controller. The conflation was apparent from the intermediate and the post-instructional interview when students were asked to identify the comparator and the controller and the information that is passed between these two parts (Section 5.3.4.2). Also, students' work in FAVL indicates that the comparator is sometimes given both the comparison and the controller functions (Section 6.2.2.1).

Controller. The controller function is conflated with the comparator function. The comparator subsumes both the controller and the comparator functions. In this case, the controller does not seem to have any role in the system and it is unclear why students include this part in their system descriptions and designs besides the fact that they learned that the controller is a part of a feedback system and must be included in their descriptions. Evidence for this conflation is described in Section 5.3.4.2 and Section 6.2.2.1.

Controlled Process. Students do not always readily identify the controlled process, especially if the variable to be controlled (e.g., light influx into the eye) is hidden from common experience. (See Section 4.2.4.)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

A.2 Student Misunderstandings of the Interactions in a Feedback System

Comparator-Controller Connection. Students sometimes have trouble identifying the signal that is passed between the comparator and the controller. (See Section 5.3.4.2.) This is a result of conflating the comparator and the controller functions.

Higher-order relationships. Some students seem to have more difficulties describing proportional control systems in contrast to on-off control systems. (See Section 4.3.4.2 and Section 6.2.2.3.) I speculate that students are not as adept at using higher-order qualitative relationships that would be required to describe the change characteristic of proportional systems, in which the error signal and the action amount decrease proportionally with each iteration through the loop.

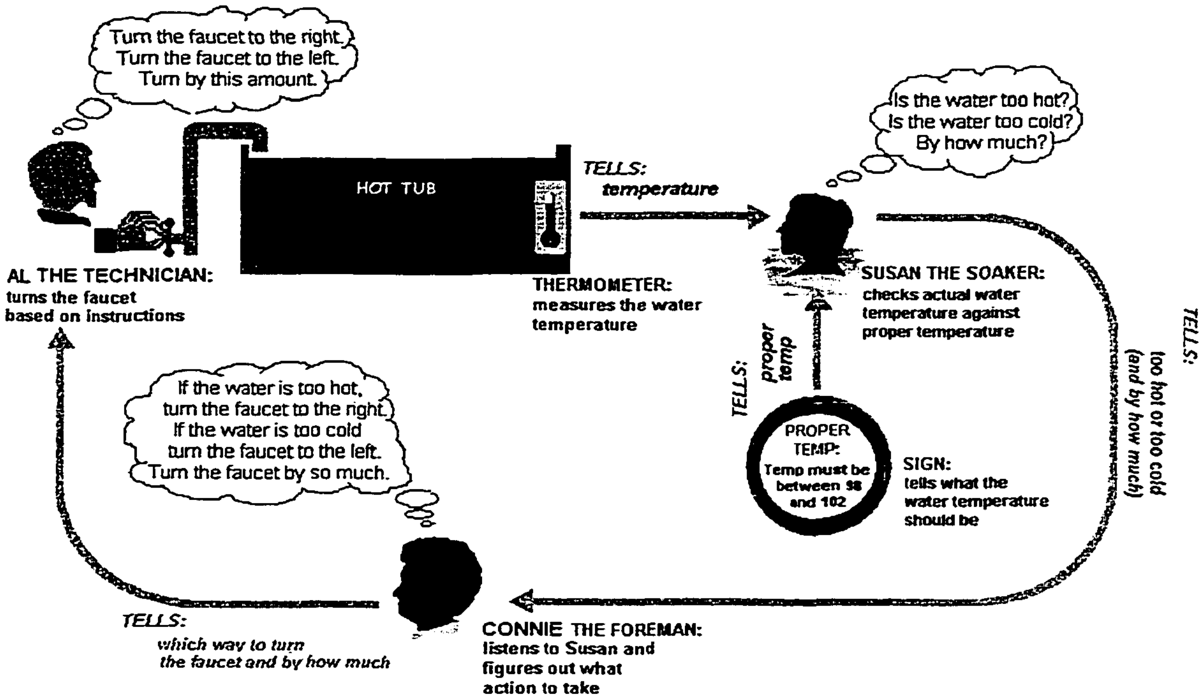
One Iteration. Students tend to propagate change through the feedback loop only once and stop at the controlled process. This was evident both in students' multiple-choice protocols (Section 4.3.4.2) and in their descriptions of their FAVL designs (Section 6.2.2.2). This tendency is not necessarily a misunderstanding of the expert model, but indicates that instruction needs to encourage students to step through the feedback loop several times to determine long-term behavior.

Feedback as an open-loop system. A few students believe that feedback systems make a one-time, precise adjustment to the setpoint value (See Section 4.3.4.2 and Section 5.3.3.). This may be tied to the tendency for students to reason through the feedback loop only once.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B. Material Used in Model Instruction

B.1 The Base Example



<u>Ye Olde Spa</u>

Susan recently injured her back in a soccer game. Her doctor advises her to try soaking in a hot tub since the heated water may help soothe and relax her back muscles. After looking around for a while, Susan finally found an affordable place, Ye Olde Spa, which will allow her to soak in their therapeutic, hot tubs at a reasonable price. The spa was one of the first of its kind, and its systems are somewhat old-fashioned.

Nonetheless, Ye Olde Spa operates on a strict set of safety rules. For one, the water temperature in the hot tub must always be between 98°F and 102°F. A temperature lower than 98° doesn't seem very hot, and some of the therapeutic value may be lost if the water is not hotter than 98°. A temperature higher than 102°F can be dangerous because it can elevate

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

body temperature beyond a safe limit, and people soaking in such hot water can become nauseous, dizzy and faint.

When Susan goes to Ye Olde Spa, she notices that a whole team of people and equipment is used to try to keep the temperature in the hot tub within the right range. This is how it works at Ye Olde Spa.

There is always a thermometer in the hot tub that measures the water temperature. Susan checks this reading on this thermometer while she's in the hot tub. (This is because it is safer to use the thermometer than to try to guess the temperature in the tub.) She then checks this temperature against the proper temperature range posted on the sign next to the tub. If the water is too hot, she tells Connie, the foreman, that it's too hot. If the water is too cold, she tells Connie that the water is too cold. Susan also tells Connie how much hotter or colder the water is relative to the proper temperature.

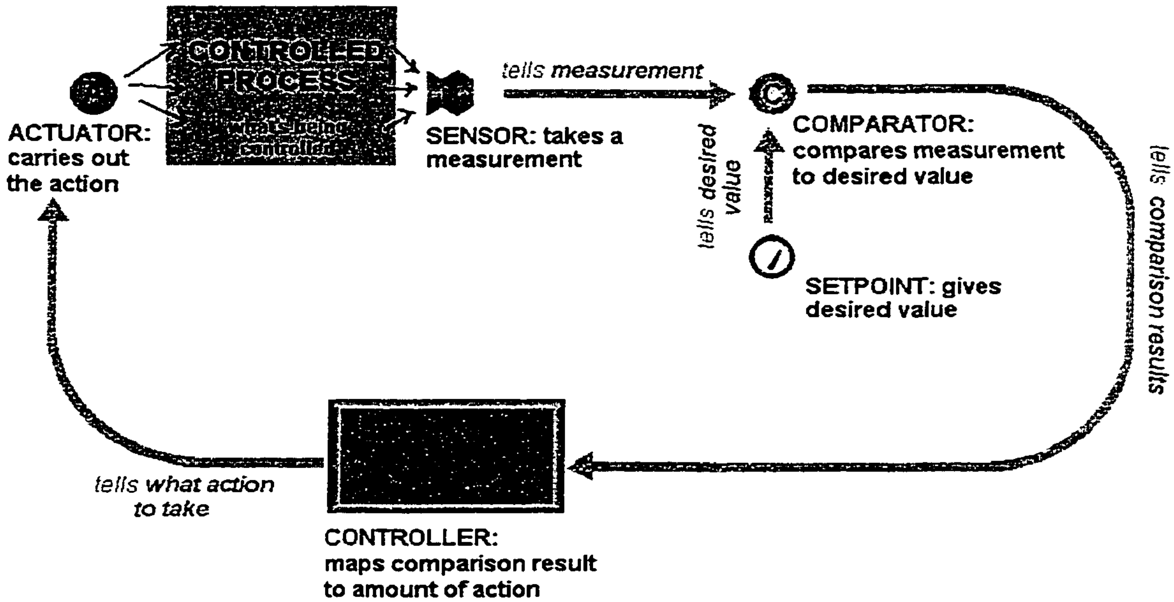
Connie makes sure she is always within earshot of Susan. When Susan yells 'too hot' or 'too cold', Connie knows which way to turn the faucet to change the temperature. But, Connie does not turn the faucet herself because she is usually wet. (It is a safety policy at Ye Olde Spa that anyone wet cannot touch any devices such as heaters, faucets, and pumps.) So, Connie uses her walkie-talkie to tell Al, the technician who runs the hot tub equipment, to turn the faucet and by how much.

Al follows Connie's instructions and turns the faucet in the right direction and by the right amount. This changes the temperature in the hot tub.

The whole process is repeated to make sure that the temperature in the hot tub stays within the safe range.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

B.2 The General Model with Relational Terms



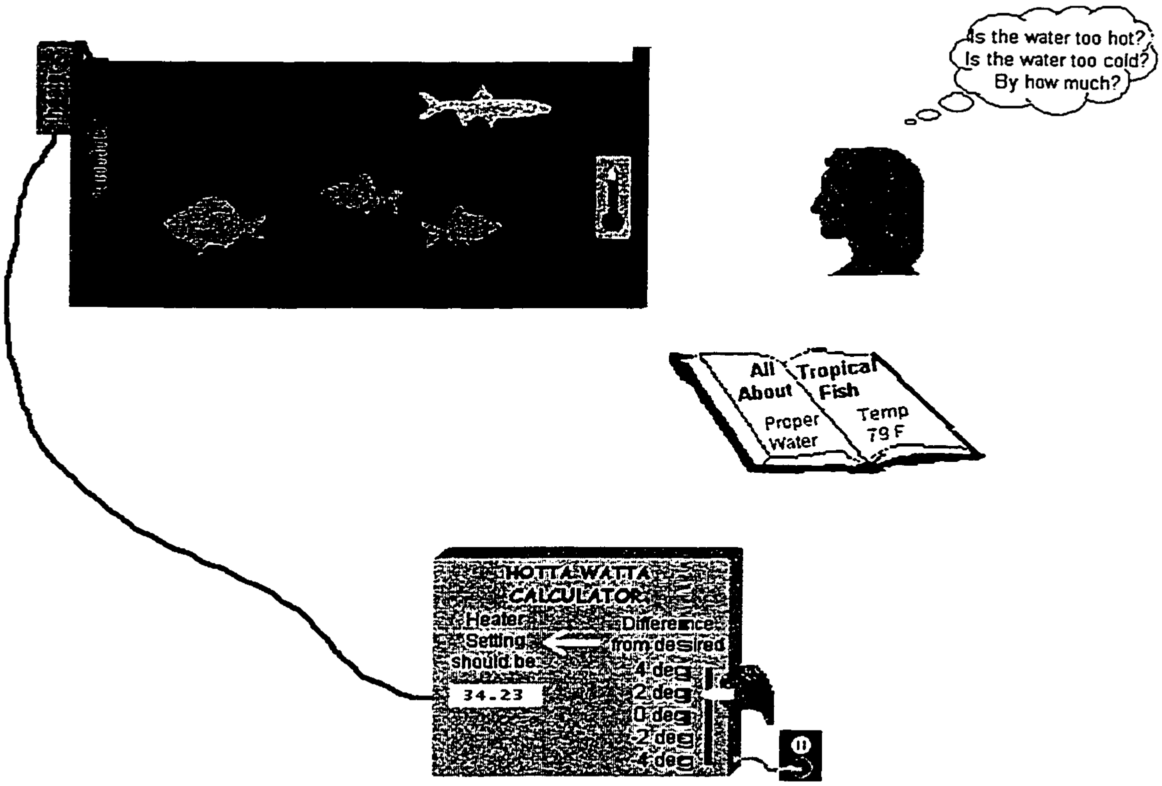
<u>Feedback Systems</u>

In general, a feedback system is a group of things that behave in a certain way in order to control something about itself. The 'something' is typically called the controlled process. And, the purpose of a feedback system is to keep the controlled process at a desired level called the setpoint. For a feedback system to do this, it needs to have a way of sensing the current condition of what it's trying to control. This is called a sensor. The purpose of the sensor is to take measurements of the controlled process. A comparator then compares the measurement from the sensor to the setpoint value to determine if it is too high or too low. Depending on the comparator, it may also determine how much higher or lower the measurement value is from the setpoint. The results of this comparison are passed on to what is called a controller. The purpose of a controller is to map the results of the comparison to the amount of action that should be taken to correct for any error between the measured level and the desired level. The controller then tells the actuator to take a certain amount of action. The actions in turn will affect the controlled process.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The sensor, comparator, controller, and actuator all work together continuously to keep the controlled process at or at least near the setpoint.

B.3 Target Example 1 – Aquarium Heating System



A Home-Made Aquarium Heat Regulator

Marnie keeps very rare and expensive tropical fish. These tropical fish are incredibly sensitive to the temperature of the water in their aquarium. If the water temperature is either too high or too low, the fish will go 'belly up'. Marnie, therefore, needs to keep the temperature of the water within an acceptable range. Marnie has invented her own solution to this problem.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Marnie installed a very accurate thermometer in her aquarium to measure the water temperature. Marnie checks the reading on the thermometer every hour. (It is a large tank, so the temperature changes very slowly.) She uses a book, *All About Tropical Fish,* that tells her what temperature her particular type of fish require. By looking at the thermometer and the information in her book, Marnie figures out if the temperature is too high or too low and by how much. She then tells a special computer, the Hotta Watta Calculator, the difference between the actual temperature of the water and the temperature the water should be.

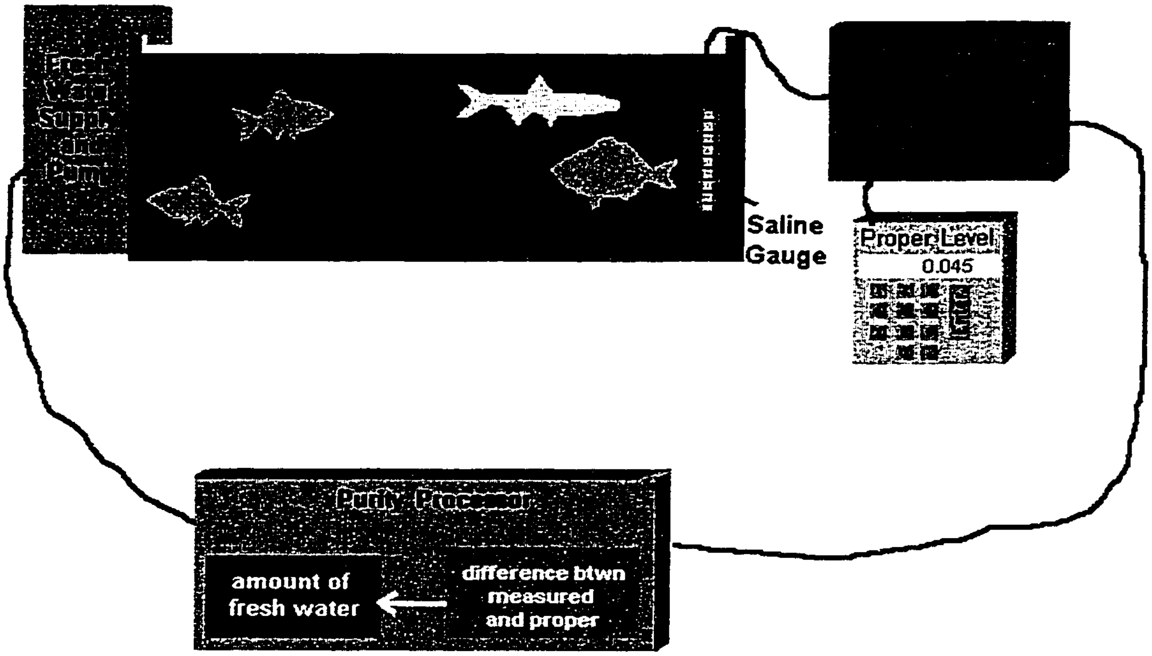
Depending on what Marnie tells it, the Hotta Watta Calculator figures out how much heat the heater needs to supply and sends a message to the aquarium heater to tell it to make the necessary adjustments.

The aquarium heater heats the water in the aquarium tank according to the instructions the Hotta Watta Calculator sends it.

This entire process is repeated to keep the water in the aquarium within the acceptable temperature range.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

B.4 Target Example 2 – Salinity Regulation System



<u>A High-Tech Salinity Regulator</u>

It is also very important to keep the saline level (the percentage of salt in water) in Marnie's aquarium at the proper level because too high or too low salinity will cause the fish to become very sick and die. (If left alone, the saline level in a salt-water aquarium can change due to evaporation and other chemical processes occurring in the tank.) To keep the saline level of the water at the right level, Marnie has put together some parts that she's bought from the pet store and from Radio Shack. She hopes that after she's installed her system, her system will keep the water saline level within the proper range automatically (without her doing any more work whatsoever).

In her system, Marnie installed a saline gauge that can measure the salinity of the water. The saline gauge sends information to the Difference Calculator telling the calculator the saline

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

level of the water. Marnie has also hooked up a punch pad that allows her to enter in the proper saline level for the fish species in her tank. Once a number has been entered in this punch pad, that value is sent to the Difference Calculator. The Difference Calculator figures out the difference between the actual saline level and the proper saline level that was entered into the punch pad.

The Difference Calculator then sends this information to the Purity Processor. Using the information it receives, the Purity Processor figures out how much fresh water to add to the aquarium to adjust the salinity of the water. It sends this information to the Fresh Water Supply and Pump.

The Fresh Water Supply and Pump then pumps the required amount of fresh water into the aquarium.

This entire process is repeated to keep the salinity level in the aquarium at the proper level.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C. Design Plans

C.1 Design Plan for Home Heating and Cooling System

<u>Figure out how room temperature changes without automatic feedback control</u>

- Predict what happens to the room temperature on a cold day in Feb
  - Sketch a graph of the room temperature over time
    - Assume that the room starts out at 68°F
    - Assume that it is 20°F outside
- Simulate what happens to the room temperature on a cold day in Feb in FAVL
  - Model a cold day in Feb
    - Go to the design called 'Feb-Just the Room'
    - Go to the Virtual Laboratory
      - Under Run a Simulation, under Name, choose 'Feb - Just the Room'
    - Model the initial conditions inside the room
      - Right click on the picture of the room
      - Pick 'Properties'
      - Select 'Room-Temp' under Property in the pop-up window
      - Enter in the initial temperature for the room
      - Click 'Set'
      - Click 'Okay'
    - Model the outside temperature
      - Right click on the picture of the room
      - Pick 'Properties'
      - Select 'Outside-Temp' under Property in the pop-up window
      - Enter a 'cold' value for the initial outside temperature under 'Initial Value'
      - Click 'Set'
      - Click 'Okay'
  - Run a simulation to see how the room temperature changes
    - Open a graph to look at how the room temperature changes
      - Right click on the picture of the room
      - Pick 'Properties'
      - Select 'Room-Temp' under Property in the pop-up window
      - Click 'graph'
    - Click on the play button under Run a Simulation
  - What happened?
    - Look at the graph for the room temperature
    - Look at the graph for the outside temperature
      - Right click on the picture of the room
      - Pick 'Properties'

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- Select 'Outside-Temp' under Property in the pop-up window
- Click 'Graph'
▪ Go "Ask a Question" to see
    - Click on 'Ask a Question'
    - Click on 'What happened?'
▪ Print out a graph of the room-temp
    - Right click on the graph of room-temp
    - Click on 'Print Graph'
    - Click 'Okay' in the printer dialogue
▪ How does your graph compare to your predictions?

- Predict what happens to the room temperature on a hot day in July
    - Sketch a graph of the room temperature over time
        - Assume that the room starts out at 68°F
        - Assume that it is 95°F outside
- Simulate what happens to the room temperature on a hot July day
    - Model a hot day in July
        - Go to the design called 'Feb-Just the Room'
        - Set the outside temperature to model a July day
            - Right click on the picture of the room
            - Pick 'Properties'
            - Select 'Outside-Temp' under Property in the pop-up window
            - Enter a 'hot' value for the initial outside temperature under 'Initial Value'
            - Click 'Set'
            - Click 'Okay'
    - Run a simulation to see how the room temperature changes
    - What happened?
        - Look at the graph for the room temperature
        - Look at the graph for the outside temperature
        - Print out a graph of the room-temp
            - Right click on the graph of room-temp
            - Click on 'Print Graph'
            - Click 'Okay' in the printer dialogue
        - How does your graph compare to your predictions?

<u>Figure out how the current control system design works</u>

- Identify the functions needed to control room temperature
    - What does the sensor do?
    - What does the threshold comparator do?
    - What does the setpoint do?
    - What does the controller do?
    - What does the actuator do?
    - How are the functional devices related to each other?
- Evaluate the current design against the design requirements

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- Retrieve the original design
    - Go to the Virtual Lab
    - Under Run a Simulation, select 'Original Design' for Name
- Test out the current design for a cold Feb day by running a simulation
    - Model the outside temperature for a cold day in February
    - Run a simulation (for a 5 hour period) to see how the room temperature changes
    - Interpret your results
        - Look at your simulation results
        - Is this what you expected?
        - Did you meet your requirements?
    - You can go "Ask a Question" to see
        Click on 'Ask a Question'
        Click on 'How can I improve my controller?'
        - Print out a graph of the room-temp
        - How do your results compare to when you had no feedback control?
- Test out the current design for a hot July day by running a simulation
    - Model the outside temperature for a hot day in July
    - Run a simulation (for a 5 hour period) to see how the room temperature changes
    - Interpret your results
        - Look at your simulation results
        - Is this what you expected?
        - Did you meet your requirements?
    - You can go "Ask a Question" to see
        Click on 'Ask a Question'
        Click on 'How can I improve my controller?'
        - Print out a graph of the room-temp
        - How do your results compare to when you had no feedback control?

<u>Add functions to your current design to meet all the requirements</u>

- Identify how keeping the room cool in July is similar to keeping a room warm in February
- Identify how keeping the room cool in July is different from keeping a room warm in February
- Identify the functional devices you will need in your redesign
- Add functional devices you will need to your design in the Virtual Lab
    - Under Add a Device, select a device you want to add to the current design
    - Put your mouse somewhere on the "blueprint" area where you want that device to be placed and click on the mouse to drop it into the blueprint
    - To connect the device to something else, click on one of its ports (arrows), move the mouse to the port you want to connect to
    - Set the property values for your devices

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Test and debug your design

- Run a simulation for a February day to see if it meets our requirements
- Run a simulation for a July day to see if it meets our requirements
- Rebuild if necessary
  - Remember: The SAME design must work for both Feb as well as July
  - Go to 'Ask a Question' for help
  - Also check you efficient your design is
    - Look to see if the heater turns on at all in July
    - Look to see if the cooler turns on at all in Feb
- As the final 'fun' test, see if your design works when the temperature outside varies
  - Model varying outside temperature
    - Right click on the picture of the room
    - Pick 'Properties'
    - Select 'Varying-Outside-Temp?' under Property in the pop-up window
    - Enter a '1' for the initial value (this indicates that it should vary)
    - Click 'Set'
    - Click 'Okay'
    - Make a simulation run with your new design
  - Print out a graph of how the room-temp changes
  - Print out a graph of how the outside-temp changes
  - Does your design work?

C.2 Design Plan for Fly Catching Model

Manually control the direction of the frog

- Go to the design called 'manual control'
  - Go to the Virtual Lab
  - Under Run a Simulation, under Name, choose 'manual control'
- Try to move the frog so it faces one of the flies
  - Manually control the amount of kicking the frog does
    - Right click on the signal generator that represents 'something' that tells the frog how much to kick (Frog Commander)
    - Select 'Set Signal'
    - In the window, under Signal Type, choose 'manual'
    - Run a simulation
    - Put the mouse cursor over the red line in the blue bar (the cursor should now look like a finger)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

    - Move the finger up or down along the blue bar to change how hard 'something' tells the frog to kick

Add functional devices to your design that essentially do what you did when you controlled the frog kicks manually

- Figure out what you had to do to be successful at a hunt with manual control
  - When did you tell the frog to kick hard?
  - When did you tell the frog to kick more softly?
  - What kinds of information did you need to figure out how much the frog should kick?
  - What type of comparison did you do?
    - Was it simply 'too far left' or 'too far right'?
    - Was it more 'how many degrees away'?
  - What type of controller do you need?

Test and debug your design

- Run simulations to see if your frog can catch non-moving flies
- Run simulations to see if your frog can catch moving flies
  - Model moving flies
    - Right click on the picture of the frog
    - Pick 'Properties'
    - Select 'Moving-Prey?' under Property in the pop-up window
    - Enter a '1' for the initial value (this indicates that the insects should move)
    - Click 'Set'

Can you improve your design?

- If your frog is too slow to respond, think about how to get it to take more action
- If your frog 'over-reacts', think about how to get it to take less action
- Try to get your frog to catch the closest fly

C.3 Design Plan for Cruise Control Design

Manually control the velocity of the car

- Go to the design called 'manual control'
  - Go to the Virtual Lab
  - Under Run a Simulation, under Name, choose 'manual control

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- Try to keep the car speed between 47 and 52 mph on level ground
  - Open a graph of the car's velocity
    - Click on the picture of the car
    - Pick 'Properties'
    - Select 'velocity' under Property in the pop-up window
    - Click 'graph'
  - Manually control the amount of fuel to the engine with the fuel pedal
    - Click on the signal generator that represents the fuel pedal
    - Select 'Set Signal'
    - In the fuel pedal window, under Signal Type, choose 'manual'
    - Run a simulation
    - Put the mouse cursor over the red line in the blue bar (the cursor should now look like a finger)
    - Move the finger up or down along the blue bar to change the value of the fuel to the engine

Figure out how the old on-off control design worked

- Go to the design called 'on-off control'
  - Go to the Virtual Lab
  - Under Run a Simulation, under Name, choose 'on-off control'
- Try the design for cruising at 50mph
  - Set the cruise control's desired speed by setting the set point unit
    - Click on the device representing the set point for the desired speed
    - Select 'Properties'
    - Choose 'setting'
    - Under Initial Value, enter the value 50 miles/hour
  - Run a simulation
  - What requirements does this design not meet?
  - Why can't this design meet this requirement?

Figure out how to complete the proportional control design

- Go to the design called 'proportional control'
- Identify and add functions you'll need for this design to meet all the requirements
  - What functions are already modeled in the proportional design
  - Figure out how you tried to manually control the velocity of the car
    - What functions did you perform?
      - How did your manual control differ from the on-off control system?
      - How did you make your comparison when you manually controlled the car velocity?
    - Is this different from how the on-off control system does its comparison?
  - Model those functions with the devices in the Virtual Lab

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- Set values for your devices
  - Adjust the gain (the multiplying factor in a proportional controller)
    - Try different values for the gain
    - What happens when there's a higher gain value?
      - What happens to the overshoot?
      - What happens to the oscillations?
    - What happens when there's a lower gain value?
      - What happens to the overshoot?
      - What happens to the oscillations?
  - Set the property values for other devices in your design

Test and Debug your design

- Run a simulation for level road to see if the design meets our requirements
- Rebuild if necessary

Build the design using more basic devices for the controller

- Right click on the controller
- Select 'Properties'
- Under 'Mode', pick Devices (This will show you how more basic devices can be used to implement this controller.)
- Now replace the controller with this set of more basic devices (Doing this will allow you to work with more sophisticated designs in the future.)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix D. Semi-Structured Interview Protocol for a Home Heating System

Pretend it's late autumn.

It's about 40 degrees outside. Let's say that you and your family go away for vacation for about a week and before going away you turned the heat off. A week afterwards you come back and you turn the heating system back on. What happens?

Does it keep getting warmer and warmer?

– So it starts to warm up the house and then ... what happens

– How warm does it get?

– Does it stay that warm from then on?

- What might cause it to change?

– Does it get hotter than that temperature?

- How come it <never> gets hotter than that temperature?

– Does it get colder than that temperature?

- How come it <never> gets much colder than that temperature?

– Why does it stop rising at a certain point?

– How do you think it's able to do that?

- Do *NOT* Ask unless details are first given

  How can the room tell how warm it is?

  How can the room tell that it's colder than that temperature?

  What does it do when it's colder than that temperature?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

What happens if the temperature outside is unusually warm for fall? What happens inside the house?

What if the heater is just partially working?

It's on the fritz, so it used to work fine but now it's working at just 75 % capacity so for the same amount of fuel it's going to only generate 75% of the heat that it used to. What do you think will happen in that case?

Can you draw a graph of how the temperature inside the house changes over time?

– Explain the graph?

Can you think of anything else that works like this?

– How is that similar to this?

– How is it different?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix E. Multiple-Choice Tests

E.1 Marketing System Multiple-Choice Test Set

Try to answer these questions the best you can. Feel free to write or draw in the margins to help you think through these questions.

Questions 1-5 refer to the following description of a clothing store:

Karl Engels is the owner of a small, local clothing store. He sells a particular brand of jeans that is very popular with the customers in his neighborhood. Karl gets one and only one shipment of these jeans at the beginning of the season. So, the shipment needs to last the whole season.

It's important to Karl that he always has pairs to sell because an unhappy customer may go to another store and never come back to Karl's store for jeans or, in fact, anything else. It is also important that Karl 'moves' (sells) most of his inventory at a profit.
Karl needs to make sure that he's selling a certain number of jeans every week. To do this, he's asked Adam Smith, his assistant, to count the number of pairs the store sells every week. Based on what Adam tells him, Karl will then set the price of his jeans. If the jeans are not selling fast enough, Karl marks down the price. If the jeans are selling too fast, Karl raises the price. From years of experience, Karl knows that the number of pairs of jeans he sells is determined largely by the selling price. The lower the price, the more he sells. The higher the price, the less he sells.

Karl has decided that the right number to sell is **45 pairs per week.** (Karl doesn't know it, but if the price is set to $29, then the store will sell exactly 45 pairs per week.)

1) If Adam tells Karl that they sold 38 pairs of jeans last week, then Karl should

(Check one)

☐ mark up the price
☐ mark down the price
☐ keep the price the same

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2) Every week, Karl adjusts the price of the jeans according to a plan:

> <u>Karl's Plan</u>
>
> - If the jeans aren't selling fast enough, he subtracts $10 from the price.
> - If the jeans are selling too fast, he adds $10 to the price.

The very first week of the season, Karl sets his price to $35 per pair. With Karl's plan, the number of jeans sold each week will eventually

(Check one)

☐ be 45 pairs per week

☐ be less than 45 pairs per week

☐ be more than 45 pairs per week

☐ swing between more than 45 and less than 45 pairs per week

3) Karl's friend, Lenny, wants Karl to change his plan. Instead of adding and subtracting $10, Lenny wants Karl to use the following plan:

> <u>Lenny's Plan</u>
>
> - For every pair the store sells over the 45 pairs per week, Karl adds $1 to the selling price of his jeans.
> - For every pair the store fails to sell out of the 45, Karl subtracts $1 from the selling price.

Under Lenny's plan, the number of jeans sold each week will eventually

(Check one)

☐ vary less

☐ vary more

☐ be the same

compared to Karl's old plan.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4) Another friend, Neville, wants Karl to change his plan to what he claims is a new and improved pricing strategy.

Nevilles's Plan:
- For every pair Karl's store sells over the 45 pairs per week, Karl adds \$2 (instead of \$1) to the selling price of his jeans.
- For every pair Karl's store fails to sell out of the 45, Karl subtracts \$2 (instead of \$1) from the selling price.

Assume that Karl will start selling at \$35 per pair under either Lenny's or Neville's plan.

a) Compare Lenny's and Neville's plans. Which plan is better if Karl never wants to sell much more than 45 pairs during any one week?

(Check one)

☐ Lenny's Plan

☐ Neville's Plan

☐ There's no difference between these two plans.

b) Which plan will allow Karl to sell a larger number of jeans the first few weeks of the season?

(Check one)

☐ Lenny's Plan

☐ Neville's Plan

☐ There's no difference between these two plans.

5) It is time consuming for Adam to keep a very accurate count of the number of jeans sold each week. So, in most cases, Adam just estimates the number. Adam, however, has a tendency to underestimate the number sold. After a while, then the rate at which jeans are being sold by the store will be

(Check one)

☐ higher than if Adam kept an accurate count.

☐ lower than if Adam kept an accurate count.

☐ the same as if Adam kept an accurate count.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

E.2 Home Heating System Multiple-Choice Test Set (Version I)

Questions 1-7 refer to the following home heating system:

The Lorry family has a home heating system that can automatically regulate the temperature in their house. In this system, the thermostat senses the temperature in the house. There is a dial on the thermostat that allows the family to set the temperature they want the house to be at.

When the temperature in the house falls below the temperature that the family set on the dial, the furnace will turn on to heat the house. When the temperature in the house rises above the temperature set on the dial, the furnace will turn off. The furnace can only turn on or off.

Right now, it is winter and cold outside (20°F).

1) If the thermostat is set to 62°F, then the temperature of the house will eventually

(Check one)

- ☐ rise to a temperature much higher than 62°F
- ☐ stay around 62°F
- ☐ drop to 20°F

2) Something has gone wrong with the furnace. It will only work at 50% capacity. (This means that for the same amount of fuel, it now puts out half as much heat.) When this happens, then the temperature of the house will eventually be

(Check one)

- ☐ twice as high as 62°F
- ☐ around 62°F
- ☐ somewhere between 20°F and 62°F
- ☐ 20°F

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3) After a week, the furnace will not turn on at all. When this happens, then the temperature of the house will eventually

(Check one)

- ☐ rise to a temperature much higher than 62°F
- ☐ stay around 62°F
- ☐ drop to 20°F

4) The family replaced the broken furnace. But, after some time, the Lorry family notices that something is wrong with the thermostat. Now, when the room is 60°F, the thermostat senses that it's 70°F. When the room is 70°, the thermostat senses that it's 80°. So the thermostat always senses the room is warmer than it actually is.

a) Now, when the Lorrys set the thermostat to 62°F,

(Check one)

- ☐ it will be warmer in the room than before the thermostat problem.
- ☐ it will be cooler in the room than before the thermostat problem.
- ☐ the temperature will be the same as before the thermostat problem.

b) The Lorrys cannot replace the thermostat just yet. But, they still want to keep the house at around 62°F. To do this, they need to

(Check one)

- ☐ set the dial to a value higher than 62°F.
- ☐ set the dial to 62° F.
- ☐ set the dial to a value lower than 62° F.

5) The Lorry family eventually replaced the defective thermostat, and everything is working the way it was before the thermostat problem.

Now Mr. Lorry decides that he wants his house to be at 70°F. He wants the house to get to 70°F as quickly as possible. So, Mr. Lorry decides to set the dial to 100° in hopes of getting the house to warm up fast. After the temperature inside the house gets to 70°, he plans to come back and reset the dial to 70°.

Following this plan, how will the temperature of the house change over time?

(Check one)

- ☐ The temperature of the house will rise a lot faster than if he just sets the dial to 70° instead of 100°.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- ☐ The temperature of the house will rise a lot slower than if he just sets the dial to 70° instead of 100°.
- ☐ The temperature of the house will rise at the same speed as if he just sets the dial to 70° instead of 100°.

6) Now winter is over. In preparation for the hot days of summer, Cal, the inventor in the Lorry family, decides to change the current heating system into a cooling system. To do this, he disconnects the thermostat from the furnace and connects it to a powerful air-conditioner. He does this on the first warm day of the year, when it is 80°F inside and outside the house.

Assume that the dial is still at 62°F. When Cal connects in the air-conditioner, the temperature of the house

(Check one)

- ☐ rises to a temperature a lot higher than 80°F.
- ☐ stays at 80°F.
- ☐ drops to and then stays around 62°F.
- ☐ drops to a temperature a lot lower than 62°F.

Why?____

7) The following winter, another family tried to put in a home heating system for their house, but they had some trouble with the installation. After putting in their system, they noticed that when the temperature in the house falls below the temperature set on the dial, the furnace would turn off. When the temperature in the house rises above the temperature set on the dial, the furnace will turn on.

What will happen to the temperature in this family's house if the dial is set to 60°F and if the house temperature starts out at 65°F? Assume that it is still 20°F outside.

(Check one)

- ☐ The house temperature will rise to a temperature much higher than 60°F.
- ☐ The house temperature will rise to around 60°F.
- ☐ The house temperature will stay at 40°F.
- ☐ The house temperature will drop to 20°F.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

E.3 Home Heating System Multiple-Choice Test Set (Version II)

Try to answer these questions to the best of your ability. Feel free to write or draw in the margins to help you think through these questions.

For questions 1- 3, think about the following home heating system:

This home heating system can automatically regulate the temperature in a house. The thermostat senses the temperature in the house. There is also a dial on the thermostat that allows you to set the temperature you want the house to be at.

When the temperature in the house falls below the temperature set on the dial, the furnace will turn on to heat the house. When the temperature in the house rises above the temperature set on the dial, the furnace will turn off. The furnace can only turn on or off. Right now, it is winter and cold outside (20°F).

1) If the dial is set to 60°F, then temperature of the house will eventually

(Check one)

☐ rise to a temperature much higher than 60°F.

☐ stay around 60°F.

☐ drop to 20°F.

2) Suppose that the thermostat is in the bathroom. Someone is now blowing drying his hair in the bathroom, and the hot air from the hair dryer is directed right at the thermostat.

What do you think will happen when this hair dryer is on? The average temperature in the house will now be

(Check one)

☐ the same as

☐ higher than

☐ lower than

before the hair dryer was turned on.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3) Now assume that the hair dryer is off. Some time much later, another person who's feeling cold decides that she wants the house to be at 70°, and she wants the house to get to 70° as fast as possible. So, she decides to set the thermostat setting to 90° in hopes of getting the house to warm up faster. After it gets to 70°, she plans to come back and reset the setting to 70°.

Following this plan, how will the temperature of the house change over time?

(Check one)

- ☐ The temperature of the house will rise a lot faster than
- ☐ The temperature of the house will rise a lot slower than
- ☐ The temperature of the house will rise at the same speed as

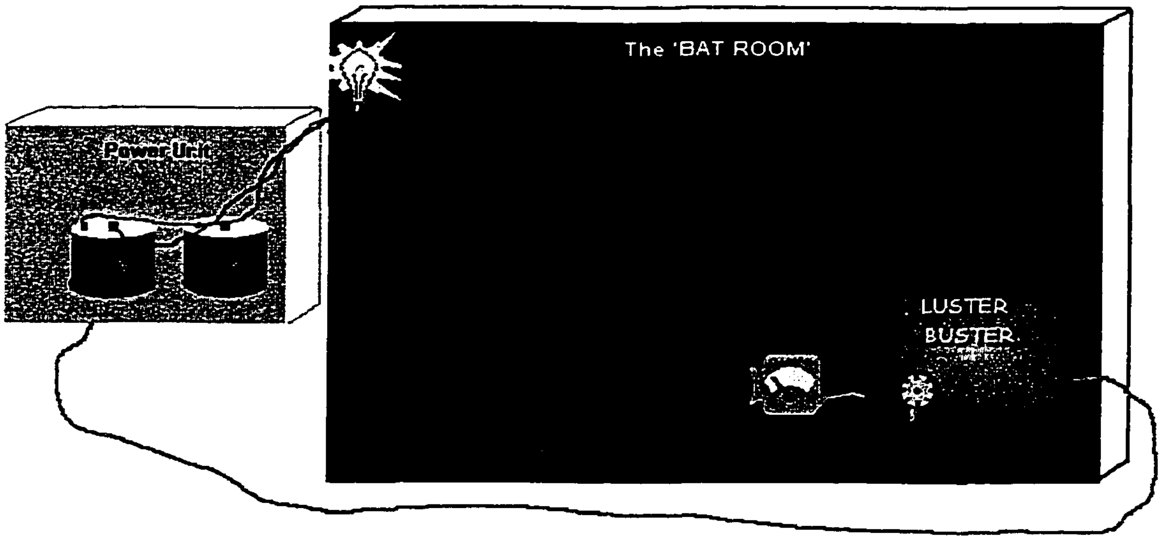
if she just sets the thermostat to 70° instead of 90°.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

E.4 Light System Multiple-Choice Test Set

Questions 1- 4 refer to a light regulation system

It is important to keep the light level inside the bat exhibit (called the 'Bat Room') at the local zoo within a certain range. Lucy, our local engineer, has decided to build the following system to regulate the light in the 'Bat Room'.



Lucy put in a light meter inside the Bat Room that measures the current level of light inside the room. Lucy also put in a homemade gadget called the Luster-Buster. The Luster-Buster is attached to the light meter and receives the light reading from the light meter. There is also a dial on the Luster-Buster. The zoo worker can use this dial to enter in the light level he wants the room to be at. (0 is dark and 10 is very bright.) The Luster-Buster then determines if the current light reading is higher than or is lower than the level that the zoo worker entered in.

If the Luster-Buster determines the light is too low, it sends a message to the power unit to deliver 5 more watts. Alternatively, if the Luster-Buster determines the light is too high, it tells the power unit to deliver 5 less watts. The lightbulb will shine more or less brightly depending on how many watts are delivered to it.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1) Assume that the dial is set to 7. If the light meter detects that the light level in the Bat Room is 5, then the power unit in this system should deliver

(Check one)

- ☐ more watts
- ☐ less watts
- ☐ the same amount of watts

to the lightbulb.

2) After some time, the light meter begins to degrade. It's not as sensitive to light at before and detects less light than there actually is.

a) When this happens, the Bat Room

(Check one)

- ☐ will be brighter than before
- ☐ will be dimmer than before
- ☐ the light level will be the same as before

the meter problem.

b) Given that the light meter has degraded, if the zoo worker wants the light level in the Bat Room to be at 7, he should

(Check one)

- ☐ set the dial to a value higher than 7.
- ☐ set the dial to a value lower than 7.
- ☐ set the dial to 7.

3) Lucy replaced the light meter. A few weeks afterwards, she decides to redesign the Luster-Buster. Instead of adding or subtracting 5 watts at a time, the new Luster-Buster 2000 now tells the power unit to deliver more or less power based on the difference between the light reading and the light setting. The power adjustment is a percentage of the difference the Luster-Buster calculates.

a) Lucy builds the Luster-Buster 2000 so that the power adjustment it asks for is a large percentage of the difference between the light reading and the light setting. What will happen when the zoo worker changes the dial setting from 0 to 7?

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The light level in the room will reach 7

(Check one)

☐ a lot faster than

☐ a lot slower than

☐ at the same speed as

if the power adjustment is a smaller percentage of the difference.

b) When the zoo worker changes the setting from 0 to 7 the light level in the room will go above the light level of 7 and then eventually come back down and stay at 7. But, it's very important to the zoo worker that the light level never exceeds 7 when he sets the dial to 7 (it scares the bats). How should Lucy fix the Luster-Buster 2000?

She should use

(Check one)

☐ a smaller percentage of the difference to figure out the power needed from the power unit.

☐ a larger percentage of the difference to figure out the power needed from the power unit.

☐ the same percentage of the difference. (Changing the percentage will not solve the problem.)

4) Another zoo tried to install the same system in its bat exhibit, but something seems very wrong with the way that zoo's system is working. Instead of keeping the brightness of the bat exhibit at the level the zoo worker wants, it does the following:

- If the light in the room starts out brighter than the desired brightness level, then the light grows brighter and then even brighter.
- If the light in the room starts out dimmer than the desired brightness level, then the light grows dimmer and dimmer until it's pitch dark in the room.

a) What part of the system do you think is malfunctioning?

(Check one)

☐ the light meter

☐ the Luster-Buster

☐ the dial on the Luster-Buster

☐ the light bulb

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

b) Make a guess as to what might be wrong. Be as specific as possible

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix F. Semi-Structured Interview Protocol Questions for Eye Pupillary Control System

From the Encyclopaedia Britannica:

When a person is in a dark room his pupil is large, perhaps eight millimetres (0.3 inch) in diameter, or more. When the room is lighted there is an immediate constriction of the pupil, the light reflex; this is bilateral, so that even if only one eye is exposed to the light both pupils contract to nearly the same extent. After a time the pupils expand even though the bright light is maintained, but the expansion is not large. The final state is determined by the actual degree of illumination; if this is high, then the final state may be a diameter of only about three to four millimetres (about 0.15 inch); if it is not so high, then the initial constriction may be nearly the same, but the final state may be with a pupil of four to five millimetres (about 0.18 inch). During this steady condition, the pupils do not remain at exactly constant size; there is a characteristic oscillation in size that, if exaggerated, is called hippus.

Describe a model of the light reflex mechanism that can explain the above behavior.

Your model should, in particular, explain

1. why the eye can adjust to different brightness levels.
2. the dynamic behavior of the contraction and expansion of the pupils.
3. what may cause hippus.

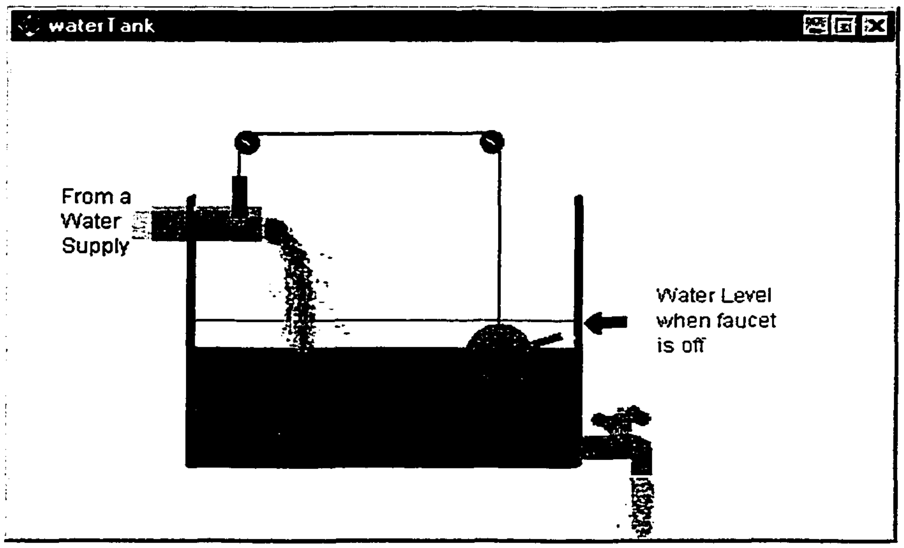
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix G. Materials Used in Comparison and Partitioning Activities

G.1 Pre-Instruction Interview

G.1.1 Water Regulation System

Verbal Instructions: Here is an animation of a system. You can turn the faucet on or off. Will you now turn the faucet on and tell me what you think is happening in the animation?



Screen shot of the water regulation system after the faucet has been turned on.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

G.1.2 Creating a Common Representation for Home Heating and Water Regulation System

Verbal Instructions: Here are text descriptions of the two systems we have discussed. You can look these over, if you like, to make sure you understand both systems.

A Home Heating System

The home heating system can regulate the temperature in a house. The thermostat measures the temperature in the house. There is also a dial on the thermostat that allows you to set the temperature you want the house to be at.

When the temperature in the house falls below the temperature set on the dial, the furnace will turn on to heat the house. When the temperature in the house rises above the temperature set on the dial, the furnace will turn off. The furnace can only turn on or off.

A Water Level Regulation System

This water tank system tries to keep the water level in the tank at a constant value even when someone turns on the faucet. In this water tank system, the ball float moves up and down with the water level. The float is connected to a stopper valve by a string and a set of pulleys. When the ball float moves down, it raises the stopper valve. When the ball float moves up, it lowers the stopper valve. When the stopper valve is down, it does not let any water into the tank. When the stopper valve is up, it lets in some water into the tank from a larger water supply. The rate at which water is let in depends on how high the stopper valve is raised.

A person can change the water level that the tank system tries to maintain by lengthening or shortening the string connecting the ball float to the stopper valve.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Verbal and Written Instructions: Compare the home heating system to the water level regulation system. How are the two systems the same? Think about what is similar and try to come up with one representation that can be used to show how both systems work. (To do this you need some way of representing what is similar with these two systems.)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

G.2 Intermediate Interview

Example 1 – Depth Control System

Scuba divers routinely perform what they call a 'safety stop' when they come back to the surface of the water. A safety stop is when a diver 'hangs out' at a certain depth for a certain amount of time before she continue her ascent. (The amount of time for a safety stop depends on how long she's been at a depth and what depth she's been at.) These safety stops allow a diver's body to adjust to the changing water pressures during a dive and is crucial in preventing the 'bends', a painful and sometimes fatal physical condition caused when a diver ascends too quickly to the water surface.

To perform a safety stop, a diver can use several indications to help her determine what depth she's at. Sometimes divers can figure out how far down they are by looking for certain types of fish which tend to swim only at a certain depth. There is also equipment that a diver can wear (a depth gauge) that tells her how far below the surface she is. The diver then needs to figure out if she is at the right depth. She typically carries a dive table that tells her what is the proper depth to stop at. If she isn't at the right depth she needs to determine what adjustments she should make. For example, she may need to inflate or compress a certain amount of air in her inflatable vests to make her more or less buoyant. Even the manner in which she breathes can cause her to move up a bit (when she takes a big breath) or move down a bit (when she exhales).

However, if the diver performs all these tasks properly, she can keep herself at a certain depth for a while so that her body can adjust and she can perform a safe ascent.

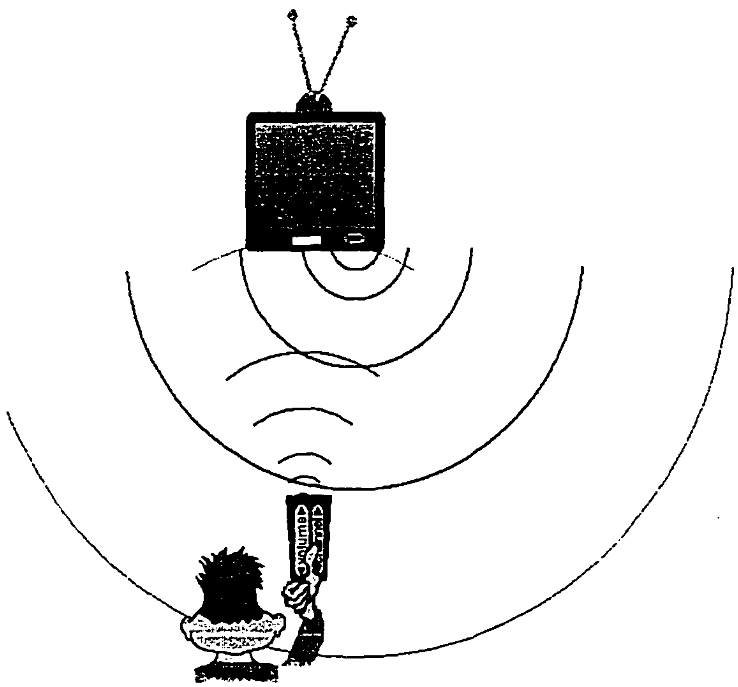
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Example 2 – TV Volume System

Alex is watching his favorite show, the X-files, on an older television set. While watching this show, he notices that the sound for the commercials is much louder than the sound for the show itself.

Alex has very sensitive ears and does not like the sound level to change. So, whenever a commercial comes on, Alex uses the remote control to lower the volume. When Alex presses the button to lower the volume, the remote control unit sends a signal to the TV set. The TV set then lowers the amount of power it sends to the speaker and amplifier system and the sound becomes softer.

When the commercials end and the X-files returns, Alex uses the remote control to raise the volume. When Alex presses the button to raise the volume, the remote control unit sends another signal to the TV set. And, the TV set increases the amount of power it sends to the speaker and amplifier system. The sound then becomes louder.



In this way Alex tries to keep the sound level the same while he's watching TV.

(In newer TV sets, there are devices in the television set that automatically adjusts the volume so that both the commericials and the show have the same volume level.)

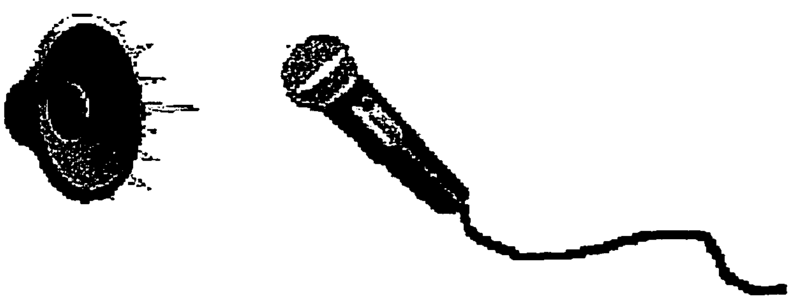
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

<u>Example 3 – Microphone-Speaker System (Distracter)</u>

Alex works on the audio visual squad at his school. As a rule, when he sets up the equipment, he never puts the microphone too close to the speakers. This is because when the microphone is too close to the speakers, the system produces a high pitch squeal. Why does this happen?

The microphone is a device that senses sound waves and changes sound waves to electric waveforms with the same pattern as the incoming sound wave. It then amplifies this electric waveform and sends it to a speaker which in turn, converts the electrical signal back to sound waves.

When the microphone is too close to the speaker, any weak sounds picked up by the microphone is amplified and passed to the speakers. This sound from the speaker is then picked up again by the microphone and amplified again. This happens many times until the amplifier 'saturates'. This means that the amplifier can no longer make the sound any louder. The result is the high pitched noise that you hear sometimes when a person turns on a microphone near a loud speaker.



Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

G.3 Post-Instruction Interview

Example 1 – Human Thermoregulation

Thermoregulation is the process by which we humans (as well as other animals) can control our own body's internal temperature. Typically, your internal body temperature is 98.6° Fahrenheit. If you're standing in a room that is 72° Fahrenheit and you are wearing a T-shirt and shorts, then your body temperature remains the same (at 98.6° F). This is because even though the temperature of the room is cooler than your body temperature, the cells of your body are producing heat at a rate equal to the rate your body loses heat to the room.

If we now raise the temperature of the room to 95° Fahrenheit, then the amount of heat the body loses to the room is less than the amount of heat produced by your body. As a result, your body temperature begins to rise.

Very quickly, however, your body will respond to try to keep the internal temperature at its desired temperature (98.6° F). There is a small group of temperature-sensitive cells in various parts of your body, called thermoreceptors, that sense your body temperature. These cells send temperature information through the nervous system to the hypothalamus, a section of your brain. The hypothalamus determines if the body temperature is at the "right" level. If it determines that the body temperature is not "right", then it sends information to your sweat glands to release sweat. Sweating allows your body to lose heat more quickly.

The result of all these actions is that the heat lost from your body and the heat produced by your body are both once again equal. Your body temperature then stops rising.

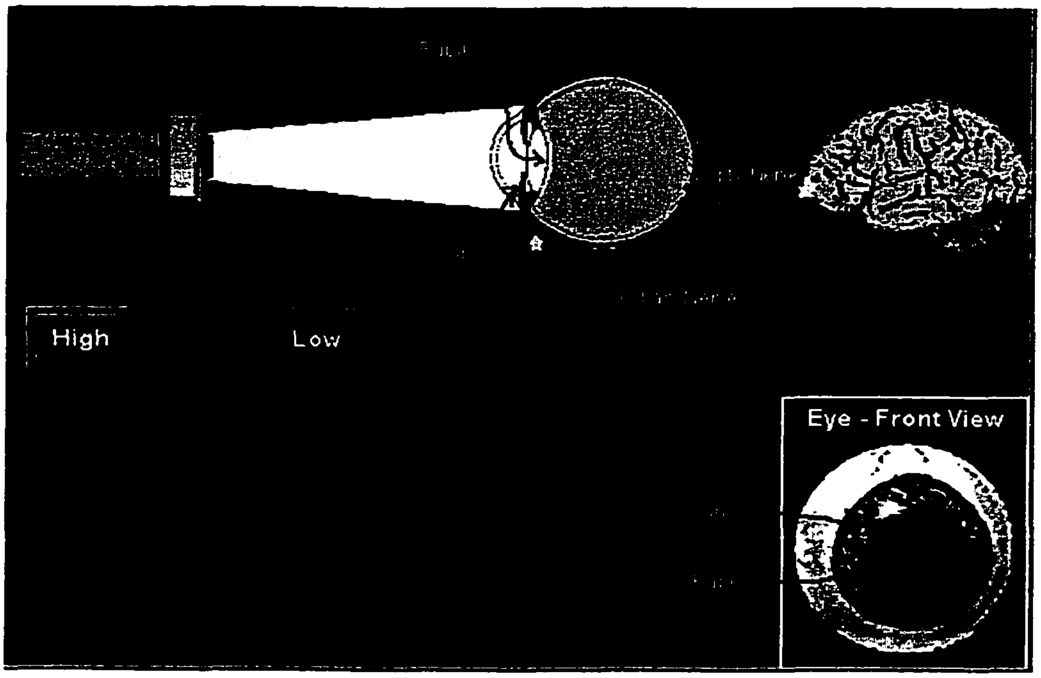
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Example 2 – Eye Pupillary Control System

In order to allow us to see clearly, the human eye must be able to regulate the amount of light that enters through its pupil (the opening in the eye). If you've every looked in a mirror at your pupils when the light level in the room changes, you'll notice that your pupils get larger and smaller depending on how the ambient (environmental) light level has changed. How does that work?

When the room gets brighter, the amount of light that enters your eyes increases. The retina, the light sensitive cells at the back of your eyes, detects the amount of light entering the eye. Biologists hypothesize that the retina determines if the amount of light is larger or smaller than an ideal light influx, and then sends a message through the optic nerve to the brain. The brain (as well as other parts of the central nervous system) determines how to compensate for the larger light influx. It then sends a message to the ciliary muscle in the iris. This muscle can move the iris to decrease the size of the pupil, letting in less light.

Alternatively, if the room becomes darker, your eyes will readjust the pupil size to allow in more light. The result of all these actions is that the amount of light entering the eye remains about the same.

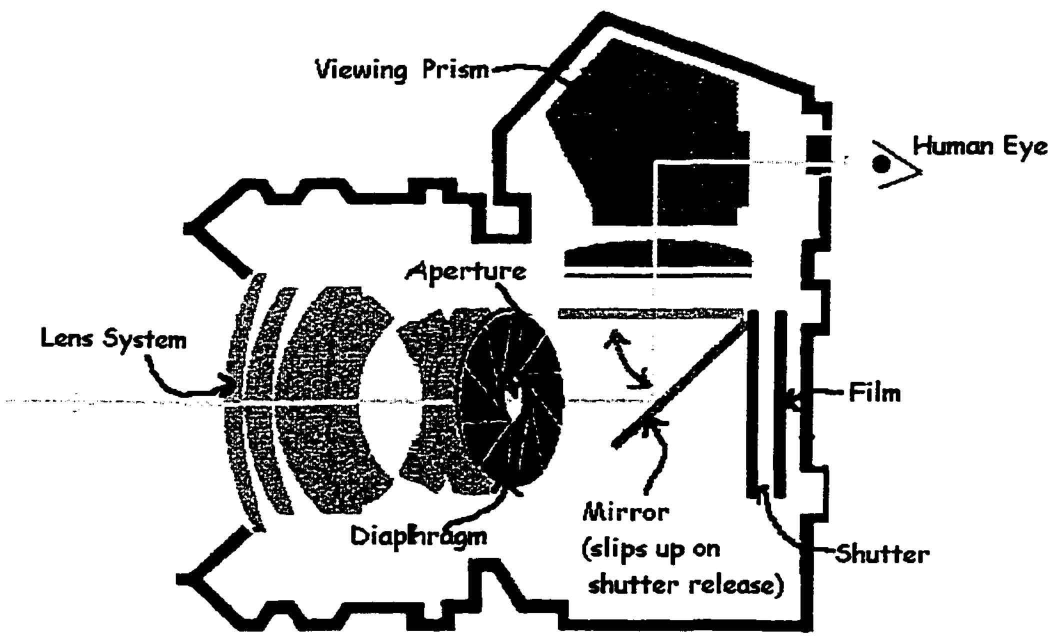


Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Example 3 – Camera Aperture System (Distracter)

Most automatic cameras today comes with a feature that allows the camera to adjust its own aperture (an opening in the camera) so that a certain amount of light will fall on the film for proper exposure. This is how it works:

There is a photosensitive light meter placed in the camera body, behind the camera lens, but before the shutter (a curtain that raises and quickly lowers when you snap a picture) and before the film. This light meter reads the amount of ambient light in the scene. This reading is then passed to a microchip that calculates the right aperture size to use to properly expose the film. (The calculations are based on the film speed, the shutter speed, and the amount of ambient light.) Once it has calculated the proper aperture setting, it changes the size of the diaphragm opening. When you next snap a picture, the camera should let in just enough light to properly expose the film.



Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix H. Data Tables for Statistical Tests

This appendix provides the contingency tables for the statistical tests that were performed and reported in Chapter 6. These data are organized according to the three sets of analyses presented in that chapter. All probabilities reported are for two-tailed tests.

H.1 Data for Analysis I: McNemar Tests Comparing Functions Identified Before Comparison and During Comparison in Pre-Instruction

For All Students (N=30)

Sensor (During)	**Sensor (Before)**	
	Not Identified	Identified
Not Identified	7	8
Identified	2	13

Binomial distribution
p=0.109

SPU (During)	**SPU (Before)**	
	Not Identified	Identified
Not Identified	0	5
Identified	1	24

Binomial distribution
p=0.219

Comparator (During)	**Comparator (Before)**	
	Not Identified	Identified
Not Identified	5	9
Identified	5	11

Binomial distribution
p=0.424

Controller (During)	**Controller (Before)**	
	Not Identified	Identified
Not Identified	5	10
Identified	5	10

Binomial distribution
p=0.302

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Actuator (During)	Actuator (Before)	
	Not Identified	Identified
Not Identified	0	1
Identified	1	28

Binomial distribution
p=1.0

For Students who initially held the system-as-whole or boundary model (N=9)

Comparator (During)	Comparator (Before)	
	Not Identified	Identified
Not Identified	4	0
Identified	4	1

Binomial distribution
p=0.125

Controller (During)	Controller (Before)	
	Not Identified	Identified
Not Identified	4	1
Identified	4	0

Binomial distribution
p=0.375

Regulator (During)	Regulator (Before)	
	Not Identified	Identified
Not Identified	2	0
Identified	7	0

Binomial distribution
p=0.016

For Students who initially held the internally connected model (N=6)

Comparator (During)	Comparator (Before)	
	Not Identified	Identified
Not Identified	0	2
Identified	0	4

Binomial distribution
p=0.5

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Controller (During)	Controller (Before)	
	Not Identified	Identified
Not Identified	0	2
Identified	0	4

Binomial distribution
p=0.5

Algorithm (During)	Algorithm (Before)	
	Not Identified	Identified
Not Identified	6	0
Identified	0	0

H.2 Data for Analysis II: Parts Identified through Comparison

H.2.1 McNemar Tests Comparing Functions Identified before Instruction and After Instruction

H.2.1.1 Pre-Instruction vs. Intermediate Comparison

For All Students (N=30)

Sensor (Intermediate)	Sensor (Pre)	
	Not Identified	Identified
Not Identified	10	7
Identified	5	8

Binomial distribution
p=0.774

SPU (Intermediate)	SPU (Pre)	
	Not Identified	Identified
Not Identified	3	8
Identified	2	17

Binomial distribution
p=0.109

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Comparator (Intermediate)	Comparator (Pre)	
	Not Identified	Identified
Not Identified	7	13
Identified	7	3

Binomial distribution
p=0.263

Controller (Intermediate)	Controller (Pre)	
	Not Identified	Identified
Not Identified	9	12
Identified	6	3

Binomial distribution
p=0.238

Actuator (Intermediate)	Actuator (Pre)	
	Not Identified	Identified
Not Identified	0	14
Identified	1	15

Binomial distribution
p=0.001

For Students who initially held the system-as-whole or boundary model (N=9)

Comparator (Intermediate)	Comparator (Pre)	
	Not Identified	Identified
Not Identified	3	4
Identified	1	1

Binomial distribution
p=0.375

Controller (Intermediate)	Controller (Pre)	
	Not Identified	Identified
Not Identified	4	3
Identified	1	1

Binomial distribution
p=0.625

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

For Students who initially held the internally connected model (N=6)

Comparator (Intermediate)	Comparator (Pre)		
	Not Identified	Identified	
Not Identified	1	1	Binomial distribution
Identified	2	2	p=1.0

Controller (Intermediate)	Controller (Pre)		
	Not Identified	Identified	
Not Identified	2	2	Binomial distribution
Identified	0	2	p=0.5

H.2.1.2 Pre-Instruction vs. Post-Instruction Comparison

For All Students (N=30)

Sensor (Post)	Sensor (Pre)		
	Not Identified	Identified	
Not Identified	9	6	Binomial distribution
Identified	6	9	p=1.00

SPU (Post)	SPU (Pre)		
	Not Identified	Identified	
Not Identified	3	8	Binomial distribution
Identified	2	17	p=0.109

Comparator (Post)	Comparator (Pre)		
	Not Identified	Identified	
Not Identified	6	9	Binomial distribution
Identified	8	7	p=1.00

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Controller (Post)	Controller (Pre)	
	Not Identified	Identified
Not Identified	7	10
Identified	8	5

Binomial distribution
p=0.815

Actuator (Post)	Actuator (Pre)	
	Not Identified	Identified
Not Identified	1	12
Identified	0	17

Binomial distribution
p=0.000

<u>For Students who initially held the system-as-whole or boundary model (N=9)</u>

Comparator (Post)	Comparator (Pre)	
	Not Identified	Identified
Not Identified	2	5
Identified	2	0

Binomial distribution
p=0.453

Controller (Post)	Controller (Pre)	
	Not Identified	Identified
Not Identified	3	4
Identified	2	0

Binomial distribution
p=0.688

<u>For Students who initially held the internally connected model (N=6)</u>

Comparator (Post)	Comparator (Pre)	
	Not Identified	Identified
Not Identified	1	2
Identified	1	2

Binomial distribution
p=1.0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Controller (Post)	Controller (Pre)	
	Not Identified	Identified
Not Identified	2	2
Identified	0	2

Binomial distribution
p=0.5

H.2.2 Fisher's Exact Test Comparing FAVL and Non-FAVL Groups

Pre-Instruction Comparison

Sensor	Group	
	Non-FAVL	FAVL
Not Identified	9	6
Identified	6	9

p=0.466

SPU	Group	
	Non-FAVL	FAVL
Not Identified	4	1
Identified	11	14

p=0.330

Comparator	Group	
	Non-FAVL	FAVL
Not Identified	8	6
Identified	7	9

p=0.715

Controller	Group	
	Non-FAVL	FAVL
Not Identified	9	6
Identified	6	9

p=0.466

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Actuator	Group	
	Non-FAVL	FAVL
Not Identified	1	0
Identified	14	15

p=1.000

Intermediate Comparison

Sensor	Group	
	Non-FAVL	FAVL
Not Identified	7	10
Identified	8	5

p=0.462

SPU	Group	
	Non-FAVL	FAVL
Not Identified	8	3
Identified	7	12

p=0.128

Comparator	Group	
	Non-FAVL	FAVL
Not Identified	9	11
Identified	6	4

p=0.700

Controller	Group	
	Non-FAVL	FAVL
Not Identified	10	11
Identified	5	4

p=1.000

Actuator	Group	
	Non-FAVL	FAVL
Not Identified	6	8
Identified	9	7

p=0.715

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Post-Instruction Comparison

Sensor	**Group**		
	Non-FAVL	FAVL	
Not Identified	7	8	
Identified	8	7	p=1.000

SPU	**Group**		
	Non-FAVL	FAVL	
Not Identified	3	8	
Identified	12	7	p=0.128

Comparator	**Group**		
	Non-FAVL	FAVL	
Not Identified	9	6	
Identified	6	9	p=0.466

Controller	**Group**		
	Non-FAVL	FAVL	
Not Identified	10	7	
Identified	5	8	p=0.462

Actuator	**Group**		
	Non-FAVL	FAVL	
Not Identified	7	6	
Identified	8	9	p=1.000

Control Type	**Group**		
	Non-FAVL	FAVL	
Not Identified	15	10	
Identified	0	5	p=0.042

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

H.3 Data for Analysis III: Were Relational Labels Used in Comparison?

H.3.1 Fisher's Exact Test Comparing FAVL and Non-FAVL Groups

Intermediate Comparison

Sensor	**Group**	
	Non-FAVL	FAVL
Not Used	14	15
Used	1	0

p=1.000

SPU	**Group**	
	Non-FAVL	FAVL
Not Used	14	14
Used	1	1

p=1.000

Comparator	**Group**	
	Non-FAVL	FAVL
Not Used	14	14
Used	1	1

p=1.000

Controller	**Group**	
	Non-FAVL	FAVL
Not Used	13	14
Used	2	1

p=1.000

Actuator	**Group**	
	Non-FAVL	FAVL
Not Used	14	14
Used	1	1

p=1.000

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Post-Instruction Comparison

Sensor	**Group**		
	Non-FAVL	FAVL	
Not Used	13	10	
Used	2	5	p=0.390

SPU	**Group**		
	Non-FAVL	FAVL	
Not Used	11	12	
Used	4	3	p=1.000

Comparator	**Group**		
	Non-FAVL	FAVL	
Not Used	14	11	
Used	1	4	p=0.330

Controller	**Group**		
	Non-FAVL	FAVL	
Not Used	15	9	
Used	0	6	p=0.017

Actuator	**Group**		
	Non-FAVL	FAVL	
Not Used	15	10	
Used	0	5	p=0.042

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.