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Effects of computer simulation construction on shifts in cognitive representation : a case study using STELLA.

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EFFECTS OF
COMPUTER SIMULATION CONSTRUCTION
ON SHIFTS IN COGNITIVE REPRESENTATION:
A CASE STUDY USING STELLA

A Dissertation Presented

by

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ABSTRACT

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A CASE STUDY USING STELLA

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This research explores changes in students' cognition while using multiple portrayals available in STELLA, a computer-based simulation construction kit. A case study was conducted with four high school students. The researcher videotaped the students constructing and testing their own simulation models and conducted clinical interviews probing student thinking in order to identify learning environment attributes from which cognitive shifts could be inferred.

Videotaped sessions were transcribed and analyzed. Students evidenced progression through increasingly sophisticated assumptions and encountered learning barriers that made this environment challenging. STELLA portrayals were useful for inferring student mental representations of dynamic systems and STELLA appeared to enable students to move their frame of reference gradually to a dynamic perspective. STELLA's multiple portrayals highlighted diverse dimensions of the information and facilitated shifts in

thinking by juxtaposing an individual's cognitive representations. Educational implications for other computer portrayal tools are discussed.

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INTRODUCTION

1.1 Purpose and Rationale

This research investigates the influence of a computer tool on changes in student thinking. The computer is not seen merely as ancillary; rather it can act as a medium to enhance communication both for learner and instructor. The computer is also a platform for research into learning since its computational power furnishes transformational possibilities to the user that can encourage cognitive restructuring. Such interactions will be the basis for documenting how cognitive change occurs. The overall aim of this research is to understand students' thinking with computer-based "portrayal tools".

A computer portrayal tool creates a frame of reference by the perspective it activates in a user's knowledge structure and usually has multiple forms of depiction. Each form of portrayal highlights unique information yet has linkages with other forms of depiction. Multiple portrayals have potential for activating divergent sets of knowledge structures. When these disparate knowledge structures are integrated with content, reconceptualization of knowledge may occur.

The basic thesis of this study is that a computer portrayal tool stimulates shifts in thinking. There are two levels at which shifts will be investigated. One will be at the conceptual level. "Conceptual change" can be defined as change of ideas and their relationships (White and Gunstone, 1989). Another is at a meta-level that involves a change in perspective or the way problems are viewed.

Since educators are faced with a variety of potential pedagogical possibilities, observable examples of shifts in thinking may provide a better understanding of dynamic thinking and how to promote it. Investigating STELLA's influence on cognitive change may inform educational intervention and facilitate the creation of innovative learning environments.

1.2 Overview of the Research Study

This study used a computer portrayal tool called STELLA. STELLA (Richmond, and Peterson; 1990) is a commercial software program that facilitates simulation construction of dynamic systems, particularly in science. The reason STELLA was selected was because it excels in translating from algebraic expressions and diagrams to graphs, tables, and animated icons.

This research study was conducted with four high school students. Each student was given background instruction and experience with STELLA. Students were then asked to create their own STELLA models. Students' interaction with STELLA were analyzed by identifying progression in their assumptions about dynamic systems. Sessions were videotaped and the resulting protocols were analyzed to seek an understanding of student thinking. Student protocols were composed of verbalizations, manipulations of the simulation model, and gestures. Analysis included monitoring student development of dynamic thinking, identifying attributes of the environment with inferential effects on student thinking, and listing barriers to student progress.

1.3 Portrayal Tools

One class of simulation tools, termed "spatial portrayal tools" aid in communicating mental representations. "Portrayal" suggests getting information outside mental boundaries into an external medium. The medium is a channel of communication that allows symbolic expression of ideas (for example, on paper or a computer screen). The term "portrayal" seems less ambiguous than using the common term "representation", which has multiple meanings. In this document "representation" or "mental model" will refer to the structure of knowledge in the mind. The term "tool" connotes an actual instrument for performing a function and also suggests a sense of empowerment. The term "spatial" indicates semantic understanding derived from the arrangement in space. The three terms together comprise "spatial portrayal tools" -- instruments that provide cognitive leverage for expressing ideas spatially in an external medium. STELLA falls into this broad class of tools. Alternative terms have been ascribed to such tools: "graphic organizers" (Lambiotte, 1989), "graphic forms" (Winn, 1987), and "visual argument" (Winn, 1987). Specific examples of these tools include flowcharts, outline processors, tables, tree diagrams, conceptual maps, Venn diagrams, graphs, idea mapping (Ambruster and Anderson, 1989), concept mapping (Novak, 1984), k-map (Rewey, 1991), semantic mapping (Heimlich, Pehrsson, 1989), semantic networks (Holley and Dransereau, 1984), schematizing (Brueker, 1989), mind maps, clustering, causal diagrams (Roberts, 1983), STELLA models (Richmond, 1987), Boxer (diSessa, 1986) and other types of schematized illustrations that use visual/spatial orientation to activate semantic representations. Insight into STELLA's cognitive benefits will provide a framework for understanding the broader value of spatial portrayal tools.

1.4 Cognitive Studies

This research is concerned with cognitive change. The literature in this domain is so extensive that a comprehensive review will not be included here. Instead, selected theoretical perspectives that hold implications for the intended research will be presented. Additionally, an orientation to the researcher's view of cognition will establish a context for the study.

This dissertation lies in the broad area of cognitive studies. Cognitive studies are investigations into means of knowing. Of specific interest here are the cognitive processes involved in learning. Knowledge is acquired in a variety of ways. One may be innate knowledge gained through genetic expression. Another is through interactions with social and physical environments. A third way is through reflection on internal knowledge structures. This document is particularly interested in the latter two ways of acquiring knowledge. Building a simulation involves both interactions in an environment and reflection on internal representations. The cognitive view of knowledge generally describes learning as coming from within. This perspective infers mental processes and structures that account for behavior. A recent awareness in education is that learners are builders of their own thoughts and that they bring to any educational situation a set of previously constructed conceptions (Glaser, 1991). This perspective is in the spirit of the "constructivism", as espoused by Piaget (Ginsburg and Opper, 1988), Papert (1980), and other contemporary thinkers in education (Kozma, 1991). There is empirical support for the constructivist perspective. Numerous researchers have noted evidence of students constructing meaning (Pinker, 1985).

Much of our educational system assumes the value of symbol systems in the learning process. Symbols are portrayals that stand for thoughts. Since symbols themselves don't carry meaning, meaning is constructed in the mind of the learner. When people listen to verbal information or read written passages, they don't always comprehend it in the same way or come to a common understanding (Kardash, Royer, and Greene, 1988). It is assumed that communication is in the minds of the communicators and that understanding is built by activating memory structures. However, this only accounts for part of the process. The learner may also be compelled to create new combinations of knowledge to generate new understandings (Pope, 1989).

Communication of ideas through symbols comes by negotiating meaning with others. Individual learning occurs in much the same way, by negotiating meaning with ourselves. For instance, a writer encodes ideas into written language and decodes those ideas as a reader of his own written work. Communication of ideas is both an individual as well as a social task. Cognition comes from experience with self and others and is the source for communications. Effective communicators are individuals who are good composers.

The implications of communication are that certain kinds of portrayals facilitate combinatory kinds of cognitive processes that are significant in constructing new understanding. Fundamental to the constructivist paradigm is the notion that knowledge construction is influenced by frameworks already in place. Kuhn (1984) summarizes this point:

> A great many other studies have suggested that, when processing a piece of information to be remembered, an individual does not store it in its intact form as an isolated unit. Instead, the individual assimilates the new information to a framework provided by the individual's existing knowledge, often altering or elaborating this new information in a way that is consistent with this existing knowledge base. (p.149)

The implications are that if cognitive frameworks are altered, learning will also be influenced. This is evidenced in experiments that involve the recall of objects. Learners who had cognitive organizational strategies performed better than those who didn't (Kuhn, 1984).

The nature of mental representations is a controversial matter. Kosslyn and Shepard (Winn, 1987) theorize that image-like structures are activated for representations. Conversely, Pylyshyn suggests that all representation, even imagery, is propositional (Larkin and Simon, 1987; Pinker, 1985). Pavio (1986) describes a dual coding approach, that involves activation of both a propositional representation and spatial imagistic representation. Hinton (Pinker, 1985) extends this thinking by suggesting that images can be hierarchically decomposed and that propositions are attached to images. Anderson (1983) contends that there is no way of empirically distinguishing between propositions and images. For the purposes of this discussion the nature of the representation for imagery makes little difference. The interest is not in how the graphical image gets generated, but is done with the graphic portrayal in terms of how it influences learning. Of interest in this dissertation is the visual image and its impact on cognitive restructuring.

Whether the visual image is stored as a proposition or reconstituted is of little consequence to the main thesis here.

Learning can be defined as the construction and/or transformation of internal representations. The representational structures determine the possibilities of transformations and connections. Initial representation is important because of the implications for later transformations. Initial representation is important in problem solving because in general, there is a tendency for that representation to suppress other alternatives (Glass and Holyoak, 1986; Greeno, 1986). It may cloud the existence of potential solution paths from the mind. Initial representations are important to this study because decisions about portrayals will set up initial representations and thus play a role in learning.

Kozma (1991) identifies two kinds of cognition: one view suggests that cognition is distributed among individuals and their tools (computers), whereas the second view focuses more on individual cognition. The former view sees tools as methods of analysis that are somehow combined with cognition. Tools are seen as extensions of intelligence. Referring to computer tools, Dickson (1985) and Olson (1985) suggest that intelligence be viewed as a "skill in a medium". Intelligence is not shared with the computer per se. The computer mediates interactions between knowledge structures and attributes of the tool. The tool provides a template for organizing and processing information, thus extending intelligence.

Portrayal tools represent illustrative devices of cognitive construction. Niedderer, Schecker and Bethge (1991) note that the implications of the constructivist perspective suggest a period where students develop their own views. Tools enable the expression of these ideas and helps account for student conceptions. This agues for external portrayal as a means of studying cognition.

External portrayal entails use of some medium to express thoughts outside of the mind. The technological medium places constraints on both the symbol systems and processes that can be used. Symbol systems are conventions with a set of elements that communicate meaning. Kozma (1991) notes that the use of different symbol systems activates different mental representations and may require different cognitive processes which can lead to the integration of information in novel ways. External forms of portrayal may also permit viewing problems from different perspectives. Thus, the computer as a portrayal tool can be used to equip learners with useful external symbolization facilities.

1.5 Symbol Development

Students engaging in the construction of simulations are involved in manipulating symbols. Piaget theorized that children at a young age begin to develop semiotic functioning by performing internal imitations of original objects (Ginsburg, 1988). He suggested it is not until the formal operational stage that learners are able to integrate abstract symbolic manipulations, where learners can make and see all the hypothetical possibilities in a situation. Problems are encoded through a repertoire of symbolic systems: language, mathematics, or other notational forms. These symbolic systems are abstractions. Abstraction involves taking specifics and allowing something more general to represent those specifics, creating something that is apart from reality. Kahney (1986) and Gilhooly (1988) both indicate the importance of abstraction in the problem-solving process. Gaining expertise in a field of endeavor seems to be associated with the development of abstraction (Hayes, 1989). Abstraction facilitates a deep understanding or insight of underlying principles without getting bogged down in details. Deep meaning allows individuals to make better connections with analogous problems. Abstraction thus affects how individuals can transfer problem solving strategies to new situations (Glass and Holyoak, 1986). When confronting novel problems there is a tendency to revert to concrete operational mode: seeking to make the problem as tangible as possible. Then, later, formal logic might be applied to the problem. For instance, physics students learn many abstract concepts by seeing them in action through physical demonstrations. Then, afterwards, they are able to deal with abstract equations, graphs, and conceptual issues because they now have some experiential framework on which to base knowledge construction (Brasell, 1987). Piaget's notion of reversibility seems to be important in order to relate mental representations to the externalized portrayal and then back to the content. Juxtapositioning differing symbolic systems with portrayal tools may facilitate this process. Thus symbolic processing is an important aspect of being able to learn through spatial portrayals such as STELLA.

1.7 Shifts in Thinking and Conceptual Change

The distinction between shifts in thinking and conceptual change is one of degree rather than a difference in kind. Conceptual change transpires on individual ideas. Shifts in thinking or a change in framework is a global view stimulated by numerous activated concepts. This document contends that shifts in thinking are impetuses for conceptual change and vice versa. These shifts are a consequence of reflecting on externalized conceptions with a tool like STELLA. Implications for portrayal tools will be the topic of a later discussion (chapter 3).

Driver (1989) and Pea (1985) suggest that in order to have informed ideas about education the dynamics of cognitive change need to be understood. So the reconfiguration of students' representations is of foremost interest. The following list is a partial account of differing views of cognitive change.

1.7.1 Gestalt Perspective

The Gestalt psychologists (Glass and Holyoak, 1986; Rock and Palmer, 1990) studied problem solving in terms of holistic aspects such as restructuring the problem or putting components together in new ways. They looked at the way individuals perceive. Problem solving was considered the reconstruction of perception. This is where the terms "functional fixedness", "blindness", and "mind sets" come from. This perspective is included because the gestalt way of seeing is thought to promote a different perspective. The gestalt is the perception of the whole. For instance, the gestalt perspective generates semantic understanding from the spatial arrangement of symbols. Seeing things with different perspective may well be an impetus for conceptual change. This type of learning is in contrast to the incremental learning involved in conceptual change that happens during Piaget's incremental processes of assimilation and accommodation (incremental in the sense of being relatively small changes) (Ginsburg, 1988). The implication is that a gestalt or a new outlook incorporated into portrayal tools may quickly skew thinking.

1.7.2 Analogy to Paradigm Shifts

There are parallels between how different levels of cognitive shifts occur. Rubinstein, Laughlin, and McManus (1984) as well as Driver (1986) suggest that we have individual cognitive paradigms analogous to the scientific paradigms described by Kuhn (1970). The argument is that cognitive paradigms undergo the same kind of transformations as scientific paradigms. That is, these paradigms undergo construction, stable equilibrium, and disintegration prior to the emergence of alternative structures. The newly accepted alternate framework better explains phenomena and provides an alternative perspective for seeing the world. The new paradigm holds promise for answering different questions.

There is an analogous process going on at the conceptual level as ideas are altered by seeing things in a new light. A change in conceptions results by activating alternative knowledge structures. Conceptual change and shifts in thinking are interactive. These two forms of learning feed back into one another. Conceptual change may be symptomatic of shifts in thinking. Conceptual insight is often the result of viewing a situation from a particular vantage point. A paradigm shift, however, might result when sufficient conceptual change challenges the current paradigm with counter evidence.

A "paradigm shift" (Kuhn, 1970) changes the perspective, it is a change in the way individuals view systems. A shift in thinking changes the bias through which problems are approached. An unknown author once said "in order to see, you have to believe". To accomplish cognitive change some theorists agree that belief, motivation, and commitment are necessary corequisites (Gustafson, 1991; Wertime, 1978). Perhaps goals and beliefs linked to portrayal tools are important agents in cognitive restructuring.

1.7.3 "Theory" Theory

There is some debate over the existence of true theories. There are some who suggest that learners construct transitory prototypes rather than intuitive theories (Yates, 1990). Others argue that learners require the generality that comes through true theories and that some of the observations of students can be rationalized by students holding multiple theories (Springer, 1990). For the purpose of this discussion, a theory will describe a set of coherent ideas whether it is transitory or even if there exists multiple and/or competing conceptions.

To assess the influence of portrayal tools on thinking, the nature of the learner's knowledge must be considered. Karmiloff-Smith and Inhelder (1975) suggest that children develop theories and are able to make hypotheses to judge consequences of behavior. Changes to a person's theory would involve one of two processes. One would be elaborating situational constraints; this process hones the selection of appropriate mental models. Another change may come from seeing a disadvantage in one's own theory as well as the advantage of alternative theories.

Nussbaum (1989) sees conceptual change as evolutionary more than revolutionary; change is slow. In numerous studies, conceptual change lagged behind instructional intervention (Nussbaum, 1989). Driver (1989) calls this "weak restructuring" as opposed to "radical restructuring". Developmental learning occurs through a series of elaborations and differentiations to the current knowledge structures. This view of the learner's knowledge is important, because it will influence instructional techniques. In pedagogical terms this translates into planning opportunities for students to express and elaborate knowledge structures. In the case of naive theories, the problem is moving students to culturally accepted theories. One approach is to confront shortcomings in naive theories with conflict, resulting in disequilibria. From this cognitive dissonance comes the impetus for cognitive change.

1.7.4 Conflict

Piaget's theory of structural development (Ginsburg, 1988) involves a conflict that arouses a state of disequilibrium. Individuals have a tendency toward equilibrium by altering their conceptions. Clement (1989) noted that students confronted with a conflict seemed internally motivated and this resulted in a more intense level of activity. Information processing theories suggest that learning involves restructuring which occurs when individuals develop new concepts. This happens when fine tuning of knowledge structures fail to account for new information. Restructuring takes place to allow for interpretations of the new information (Anderson, 1983; Goodyear, Njoo, Hijne, and van Berkum, 1991). However, there are those who argue that individuals don't usually perform a wholesale change to their conceptions just because some piece of evidence doesn't fit (Kuhn, 1970). Most of the time individuals come up with small modifications to their theories to account for conflict. The problem with the discrepant event approach is that often its relevance is ignored (Driver, 1989). A student's conceptions may be so strongly embedded that counter evidence is seen as unrelated or unbelievable and, therefore discarded (Gustafson, 1991). Students also modify their ideas to account for the exceptions to their rules (Gustafson, 1991). Driver (1986) points out that students often hold differing views from currently accepted ones. These alternative frameworks are notoriously resilient to change even after instructional intervention (White and Gunstone, 1989, Karmiloff-Smith, 1988, & Driver, 1986). Despite this there are those who believe that instructional intervention can be useful for encouraging conceptual change. For some educators the key is building on the students' present conceptions. Clement, Brown, and Zietsman (1989) report conceptual changes that have been accomplished through analogical bridging strategies that build on a student's preconceptions. These analogical bridges act to shift perspective of the problem, resulting in a change of conceptions. Portrayal tools may foster visualization of the underlying similarities between conceptions and target analogies.

Cognitive change of any sort requires hurdling two major barriers. One is overcoming the sense of being satisfied with the status quo. This may be compounded by a sense of ownership that is derived from self-constructed knowledge. This sense of ownership may be enough to support both student conceptions and scientifically accepted views concurrently. Some researchers (Solomon and Gunstone reported by Gustafson, 1991) concur that learners may not replace conceptions; rather, new conceptions are stored next to each other. The competing ideas are then activated based on the situation in which the learners find themselves. This would account for students reverting to naive conceptions when encountering real world problems. Learners may also replace conceptions on occasion and at other times tolerate the coexistence of competing conceptions. The second barrier is the risk that is involved in change. Failure to achieve a more desirable outcome is always a possibility.

Perhaps the key to making effective use of the discrepant event approach is to build the discrepant event on inferred student knowledge structures. This might make recognition of a conflict more probable. Gustafson, (1991) suggests that conceptual change involves recognizing discrepant information, accommodating mental constructs, and eliminating inconsistencies. Portrayal tools might make conflicts more salient by allowing students to recognize the conflicts based on their own knowledge structures. The portrayal devices might make it easier to make comparisons and rationalize changes to thinking.

1.7.5 Building New Theories

diSessa (1988) speaks of children not having theories per se, but "knowledge in pieces" that are not coherent but fragmented ideas. diSessa's argument calls for a totally new theoretical construction to integrate the isolated pieces of knowledge. He argues that it is important for learners to have experiences that relate easily to the real world and to provide opportunities for integrating knowledge. The spatial arrangement of portrayal tools may bring together disparate ideas into an integrated whole by emphasizing the interconnectedness of concepts.

1.7.6 Reflection

Reflection is a metacognitive process that monitors actions, consciously orchestrates processes, and challenges one's own thoughts. Self-regulation is a metacognitive awareness that includes judging success (or lack there of) and linking actions with goals. Glaser (1991) purports that metacognitive processes are signs of more advanced thinking. These skills probably play a significant role in transferring knowledge to new problems. Reflection seems to be a key factor in evoking shifts in thinking. Reflection is involved in portrayal tool use. Levie (1987) suggests that portrayals can reflect back on representations and cause cognitive changes.

One notion of development suggests that behavioral mastery is required before the internal representation is available to reflection (Karmiloff-Smith, 1990). In information processing terms, compiling procedures makes representations available for redescription by setting them up for activation by other processes. Karmiloff-Smith (1990) notes that this kind of redescription may account for cognitive flexibility and creativity. Portrayal tools might act as a stimulant for activating alternative processes on internal representations and for creating interrepresentational linkages.

1.7.7 Dynamic Self-Regulation

Iran-Nejad (1990) sets forth a theory that takes into account two forms of internal self-regulation. One being the traditional executive self-regulation that is governed by conscious control and involves sequential processing. Another is dynamic self-regulation that is parallel and involves automatic processing. The suggestion is that much of discovery learning comes through dynamic self-regulatory behavior. According to many cognitive theories, executive control is like a "flashlight of attention"; in other words only that which is attended to can be brought to bear on a particular problem (Anderson, 1983). Conversely, Iran-Nejad's theory of change suggests "localized capacity resources" for different modes of thinking. These internal sources may be such things as prior learning and learning strategies. From the perspective of conceptual change, this theory is appealing because it suggests that independent sites can function simultaneously to combine and form new structures:

> ...learning is no longer viewed as incremental internalization. Rather it is defined as reconceptualization of internal (previously learned) knowledge. ...For instance, the eyes are blind to sound waves, and the ears are deaf to light waves, but the internal knowledge construction system can make coherent sense out of the combination. (Iran-Nejad, 1990, p.584)

The real world is an abundant source of multisensory experiences that require simultaneous multimodal processing skills. The author goes on to suggest the reason children are able to learn verbal language so efficiently before formal schooling is that young children's dynamic self-regulations are not overridden by an immature executive control mechanism. Thus, learning comes from multiple sources, combining to form more complex representations. The change described here is a reconceptualization that suggests a change from one form of knowledge to another. The spatial properties of portrayal tools may encourage multimodal processing by activating visual skills that rely on automatic perceptual processes.

1.7.8 Discovery Learning

Bruner (1966) popularized the term "discovery learning". The basic idea behind this perspective is that learners ferret out new knowledge through exploration and experimentation. One aspect of discovery learning that seems most important is the emphasis on active learning -- "active" meaning that the learner takes on ownership of the learning process by being involved in decisions and exploration of information. One of the problems with the term "discovery learning" is that it can entail divergent cognitive processes. For instance, discovery can entail the assimilation of new entities and/or the reorganization of existing knowledge. As an example, Klahr and Dunbar (1988) found that some individuals approach discovery by inductive processes (experimenters) while others attack problems deductively (theorists). Many researchers feel that discovery often involves both processes (Goodyear, et al. 1991). The emphasis on discovery learning is not misplaced. The constructivist perspective continues to focus on the importance of student discovery. Portrayal tools might provide means to actively investigate conceptions and discover relationships through making relationships explicit and defining rules for those relationships.

1.7.9 Social Interaction as Stimulus

Rogoff (1990), Vygotsky (1962) and Case (1978) suggest that the above ideas are the internal means of conceptual change but that change is the product of joint thinking from social interaction. These individuals suggest that development involves the acquisition of tools that come from previous generations and from the surrounding culture. Vygotsky theorizes that learners internalize interaction with culturally accepted tools. The socio-cultural form of internalization differs from the behavioral form of internalization because the former is viewed as being mediated by the internal construction process and the latter form is merely the transfer of knowledge. Schooling has its influence by using specific kinds of tools. Tools carry values, goals, and problem-solving skills that will be acquired as learners interact with them and see them in use. In this view, guidance plays an important role in interactions with more experienced partners. Thus, conceptual change is seen as something that must be within a learner's grasp, referred to as the "zone of proximal development" and facilitated by the modeling of mentors. According to Kuhn's (1974) theory of scientific change,

change comes from the scientific community. If the analogy holds true for cognitive change then social interaction can be a catalyst for shifts in perspective and cognitive alteration. Thorley and Tregust (1987) suggest that peer sharing produces conflict and in turn is the impetus for change.

In the socio-cultural theory, guidance plays an important role. Models of more advanced concepts or strategies often exist in an individual's environment. The apprenticeship model is an added dimension to the real world that can actually take advantage of dynamic self-regulation. For instance, providing sensory input from observing a mentor's practice might stimulate the combination of otherwise distal knowledge structures. However, caution comes from studies done by Kotovsky and Simon (1990). They found that students who were given cues to help solve a difficult problem were helped to solve the immediate problem but failed to achieve any degree of transfer. The authors suggest that prompts which help students determine legal moves may teach nothing useful that can be applied to a structural isomorph; prompts may act as a "crutch" that fails to provide any useful information about the problem. In other words, if the cues are used without mindfully considering the underlying principles, then the hints are for naught. During social guidance, if the student is not mindful of the underlying rationale for guidance, it might have immediate effects but lack generalizability. Hence socially mediated learning has potential benefits with the proviso that students are aware of the rationale underlying the modeling or cues.

The previous discussion of cognitive change is useful because it reflects the diverse ways educators and researchers approach this topic. This research will use those theories or parts of them that add insight into the findings of this study.

1.8 Dynamic Thinking

This introduction has alluded to the bias of the tool. STELLA's bias comes through its focus on "system dynamics" (Roberts, Anderson, Deal, Garet, & Shaffer, 1983). Dynamic thinking is the identification of positive and negative feedback loops that influence system dynamics. Feedback is a fundamental concept of system dynamics. This feature is the result of a causal factor that either directly or indirectly loops back to affect itself. Instead of thinking in terms of A affects C, in system dynamics, A has a causal relationship to C, and C then feeds back to influence A. Few dynamic situations cannot be thought of in this manner. System dynamics models all situations with feedback loops. This view assumes that causation is not one directional and that the structure of the system is the source of system behavior. For instance, nondynamic thinking would view job frustration caused by work inefficiencies (see Figure1.1).

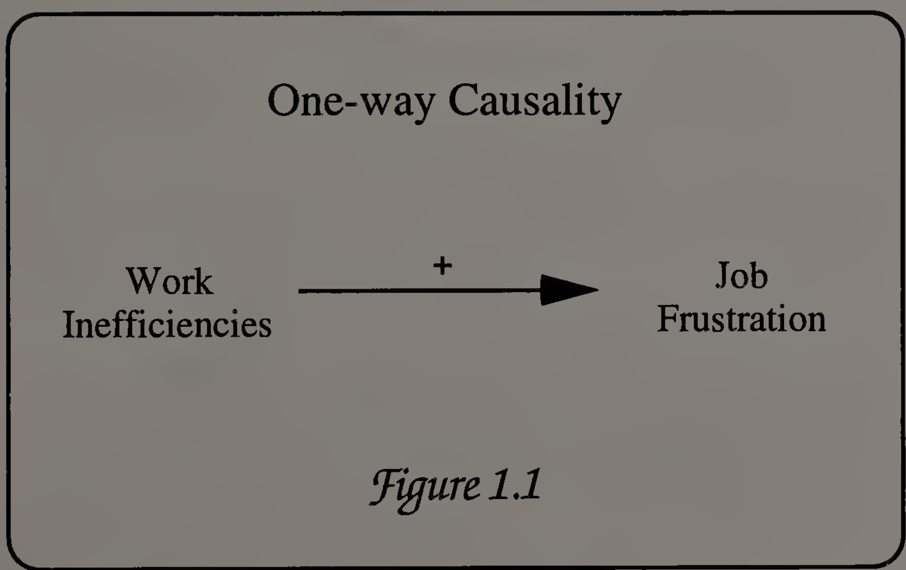


Figure 1.1 One-way Causality

The dynamic perspective would also view job frustration as a potential contributor to inefficiencies and this positive spiral would be seen as controlled by negative feedback loops. The negative feedback loop might be depicted by the degree of organization. As job frustration increases, the desire and energy devoted to organization increases and diminishes work inefficiencies (See Figure1.2). This perspective facilitates visualizing change over time and understanding the dynamics of a system.

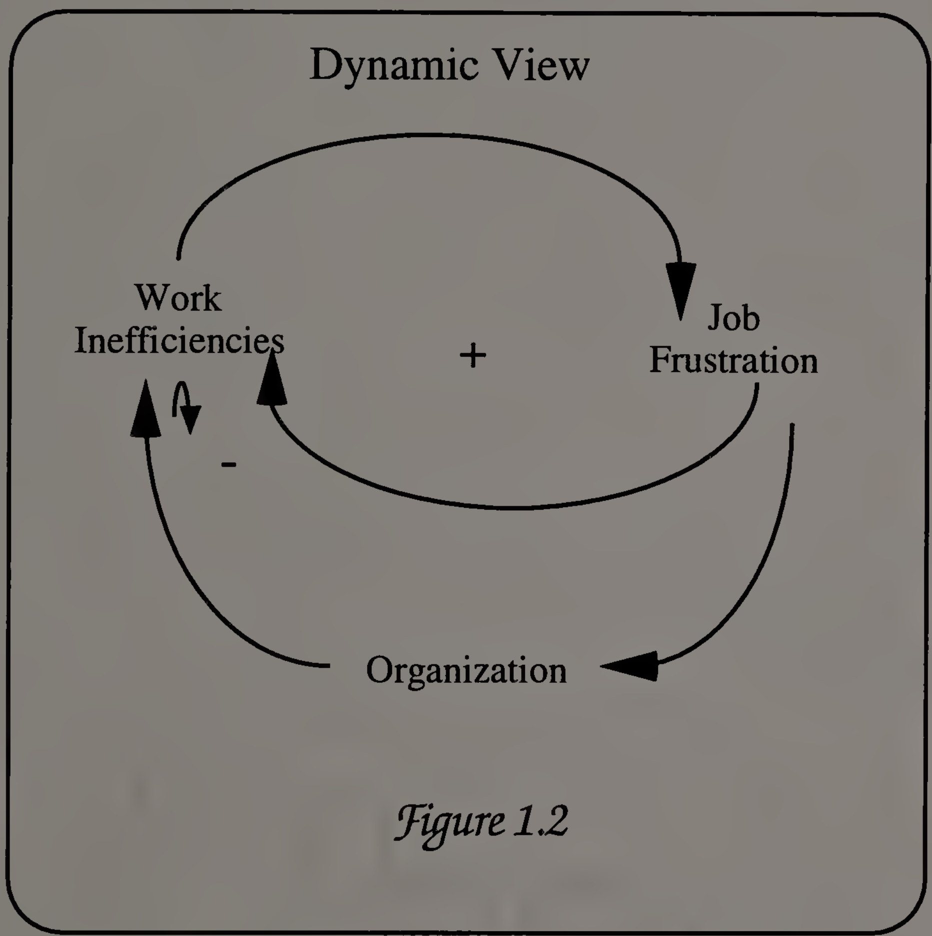


Figure 1.2 Dynamic View

One way to illustrate feedback loops is through the use of "causal loop diagramming" conventions for depicting the relationships between factors in dynamic systems (Roberts, et al., 1983). There are negative influences (factors that decrease another variable), and positive influences (factors that increase another variable). Dynamic changes come from the interplay between these two forces, as each vies for dominance in the system. For instance, in the figure below there are two loops, one negative (-) and another positive (+). The overall effect on the system is determined by the dominance of one of the factors. It is likely that at any given time both the positive loop increasing "success" and the negative loop increasing "failure" are at work. However, one of these loops will probably dominate and result in either less "confidence" and "failure" or increased "confidence" and "success". Causality is not linear, but circular and is the result of causal loops (See Figure 1.3).

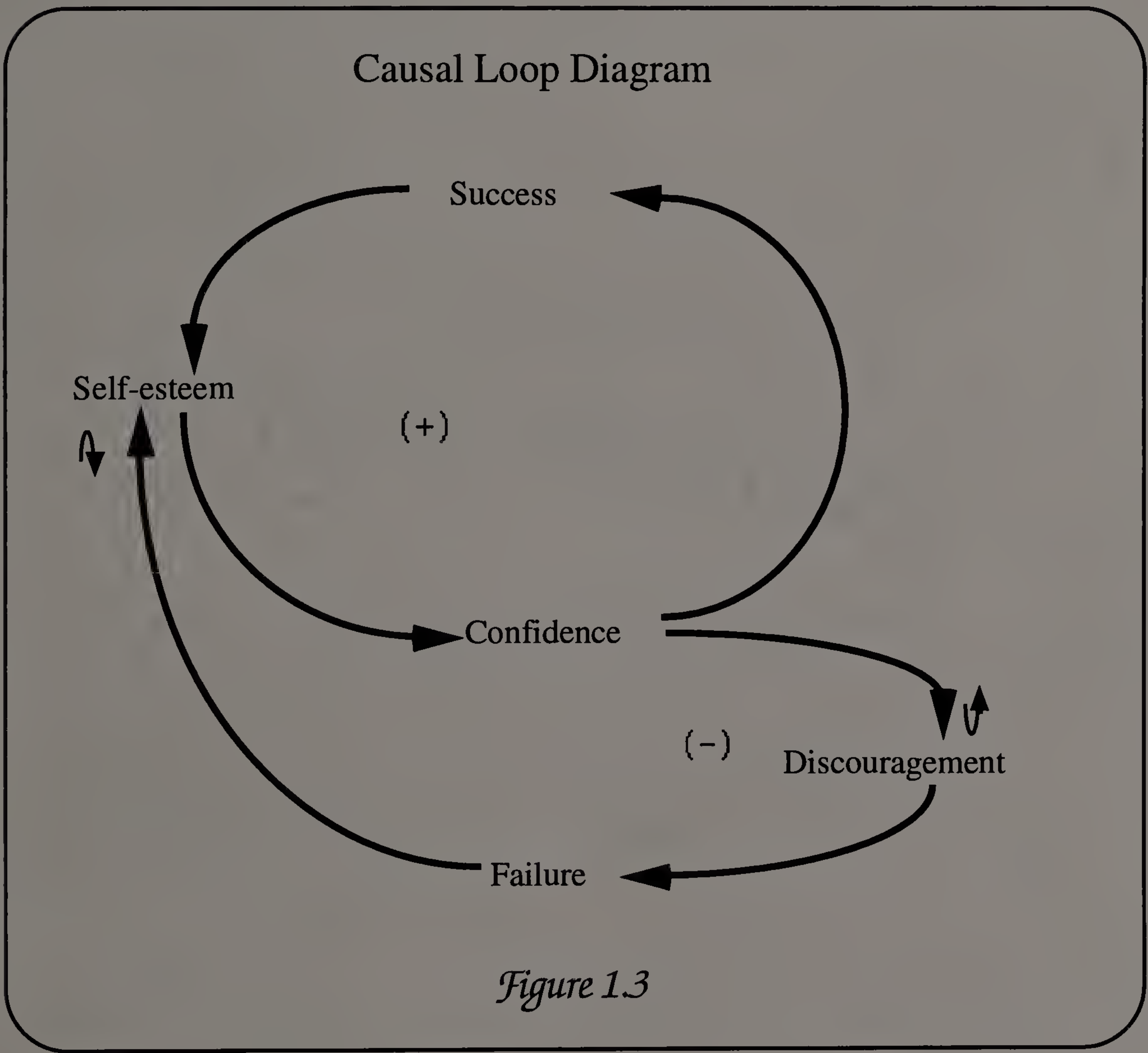


Figure 1.3 Causal Loop Diagram

Here is a brief summary of causal loop diagramming conventions:

1. the arrow is used to show causation
2. the factor at the tail of the arrow causes the change

3. the factor at the head of the arrow is affected
4. positive effect is indicated by no symbol
5. a negative effect is indicated by a small reverse arrow beside the head of the causal arrow (↑) (e.g. "Failure" has an inverse relation with "Self-esteem")

For a more elaborated description of the conventions for causal loops diagrams and dynamic thinking refer to Roberts, et al., (1983).

Fundamental to this research project is the notion that dynamic thinking is something worth encouraging. Most current curricula do not focus on change over time nor on the principle of feedback. The emphasis is, instead, on static facts. The static view of systems has become the installed base, and since the dynamic perspective is not always easy to envision, it is relegated to a less important place in learning. For instance, students learn the components of the nitrogen cycle, or how to balance a chemical equation, or what caused a social upheaval, but the dynamics of those events go unexplored. How do the components of these systems change over time and what feedback loops control their behavior? Such questions are, for the most part, ignored by current curriculum efforts. STELLA provides a tool for exploring the dynamic dimensions of such systems.

1.9 Summary

This chapter reveals that cognitive change is a complex process. Researchers are still hoping to find a theory that will account for the full range of student cognition; learning and its underlying mechanisms are not well understood. The mechanisms for how shifts in thinking take place is a topic of controversy (Clement, 1989). It is not clear whether cognitive shifts come as a result of inductive, deductive, intuitive, or analogical processes. Despite that, research exploring how learning takes place may offer an explanatory model that could provide insights and in turn have implications for education. This study will examine various kinds of learning, including the representation and organization of knowledge, self-regulation and other metacognitive processes, and the utilization of these processes in educational settings. Specifically, this study will investigate the relationship between the multiple forms of portrayal in the STELLA (computer software) environment and students' cognitive change in dynamic thinking.

CHAPTER 2

INTRODUCTION TO SIMULATIONS

This research utilizes computerized simulation software so an introduction to simulations will be useful. A brief description of STELLA will provide a concise overview of the specific tool selected for this research. These topics are discussed below.

2.1 Simulations

Simulations have been utilized by both educators and scientists to advance thinking. Wilson (1992) suggests reasons that simulations can play an important role for scientists:

> ...computer simulations can act as a bridge between the theoretical world of simplified equations on the one hand and, on the other, actual experiments, which are characterized by the complexity of the real world. Simulations are a theoretical experiment... (p. A21)

Scientists are learners, so if simulations are useful in advancing scientific thought then simulations may be a means of advancing student learning. The appeal of simulations is in controlling system parameters and the portrayal of output from that control. Pasquino and Peelle (1975) identify some of the benefits of simulations:

> Generally, simulations are economical, observable, changeable, and reproducible - hence, providing a benign environment in which the student may explore the bounds of an ecological model with no detriment to real populations (p. 487-488).

This dissertation deals with building models from internal representations, so the interest is not in canned simulations, but simulation construction kits. Canned simulations are models that are defined by preset rules. Traditional simulation programs such as SimCity (Broderbund), Oregon Trail (MECC), Oh Deer (MECC), Lemonade Stand (Apple Computer) work like "black boxes". The objective is to infer the inner working of the system by experimenting with external parameters. These underlying rules may represent a mismatch with students' frameworks. The underlying model in a canned simulation might be quite distal from a student's representation, making it difficult to bridge the gap. This is not to say there is no value in canned simulations. Canned simulations involve multiple cognitive processes: hypothesis generation and testing that involves experimental design, prediction, manipulation, and interpretation which includes observation, evaluation, and generalization (Goodyear , Njoo, Hijne, and van Berkum, 1991). Olson (1988) summarizes the role of the traditional computer simulation:

> The computer can make a complex simulation possible, but it does not make a unique contribution - the simulation is only made more effective, but not realized by the computer.... What is crucial about simulation is that teachers and students are able to actively probe complex systems, and so learn about the subject under study in a more sophisticated way. This places the computer in a modest but significant role - data processing and display. (p.63)

2.2 Introduction to STELLA

In contrast, STELLA acts more like a "glass box" (Peelle, 1984). The glass box metaphor suggests that the inner workings are viewable. Perhaps an "open box" might be a more appropriate metaphor since STELLA enables the modeler to reach inside the system and modify its internal workings. The rules of traditional simulation are fixed whereas simulation construction kits like STELLA provides a means for modifying the underlying structure to conform to students' way of thinking. STELLA represents a constructivist tool that permits students to build their own rules for how they believe the system works.

A model is a portrayal of a system. Using a simulation infers experimenting with the model. The distinction between modeling and simulation is that modeling implies construction while simulating connotes investigating the properties. However the distinction blurs because the process of modeling is iterative. A student begins by building a model, simulating the system, and then back to modifying the model based on the system's behavior (van Joolingen, 1991).

STELLA represents a compromise between qualitative simulations and quantitative simulations. It is quantitative because the simulation's rules are determined by algebraic expressions and graphic relations. It can be qualitative in the sense that the exact numeric relationships are often not known. The workings of the simulation are often qualitative judgments formed by matching qualitative knowledge about relationships with quantitative definitions. van Joolingen (1991) describes this mapping of qualitative attributes onto a numerical system as "instantiation". The computer models that were created by students in this study can best be described as qualitative. The STELLA program can model either discrete or continuous systems or a combination of the two. The current study limited itself to continuous simulations. Continuous simulations involve behavior that can be described by nondiscrete quantities over time (e.g. birthrate =

3.4/year), whereas discrete simulations study the progression of individual objects (e.g. the flow of objects through a factory).

STELLA is a computer software program (Richmond, B. and Peterson, S., 1990) that is in harmony with a constructivist perspective of learning. This view of learning suggests that students build mental models of the world. These personally constructed models influence students' behavior and perceptions. STELLA provides an environment wherein students translate their ideas by building structural models based on their perception of a process.

STELLA is an acronym for Structural Thinking Experiential Learning Laboratory with Animation. It is based on a system dynamic philosophy, sometimes called "systems thinking". Systems thinking is isomorphic with the term, dynamic thinking. STELLA also represents causal simulations that focus on the cause-effect relationships between two or more variables. Although STELLA is rather new, systems thinking has a rich history which can be summarized as being able to identify influences linked by causal loops and viewing the structure of a system as the source of behavior. System dynamics facilitates consideration of the multivariate perspective rather than in bivariate terms (Hanneman, 1988). STELLA basically uses the idea of causal loop diagrams (refer to section 1.7) but in a form that is more conducive to computationally defining the mechanisms of operation. The main difference is that the STELLA model is executable not just viewable.

Jay Forrester at MIT (1968) integrated system thinking into a computer program called DYNAMO, which was implemented on a mainframe computer largely inaccessible to educators. This program was primarily used by scientists to study complex dynamic situations and to suggest predictions. STELLA is a reimplementation of DYNAMO on a microcomputer making it more accessible to educators.

STELLA allows students to create simulations of dynamic systems. Examples of typical simulations include economic/financial models, population dynamics, psychology models, chemical reactions, nutrient cycles, and hormonal control. Almost any situation that has kinetic properties can be described in a STELLA model.

One aspect of STELLA that has educational appeal is that the learner can build the model. Self-construction is significant because the structural model will be more closely linked with the user's mental model than if some structure were imposed by an expert or teacher. The self-constructed model thus provides a window into student thinking. It is not possible to peer into learners' minds directly by viewing their constructed model, but it facilitates the generation of inferences regarding learners' mental models. However, STELLA models are not isomorphic with mental models. Despite that, using STELLA provides a platform for the expression of mental representations. Modelers create symbolic depictions of their mental representations and have an opportunity to test and verify them. While this guarantees nothing, having that capability available will lead students to either challenge their own thinking or bring the externalized model in synch with internal representations. In either case the interaction with the system communicates information that can be used to infer students' cognitive representations. Learners testing and modifying the external model may facilitate instructors building useful representations of student knowledge structures for pedagogical purposes.

2.3 STELLA Construction

The construction of a useful STELLA model requires numerous cognitive processes. The first task is identifying useful candidate scenarios to model. Students then map their mental models into STELLA using a plumbing metaphor. The mapping process involves equating aspects of the scenario to factors that accumulate, flow, or have external influences. After this initial mapping of the mental model, the modified mental model is translated into a STELLA diagram (See Figure 2.1). This structural diagram illustrates relationships in the system. The factors in the scenario are diagrammed by linking "stocks", "flows" , "converters", "connectors" and "clouds".

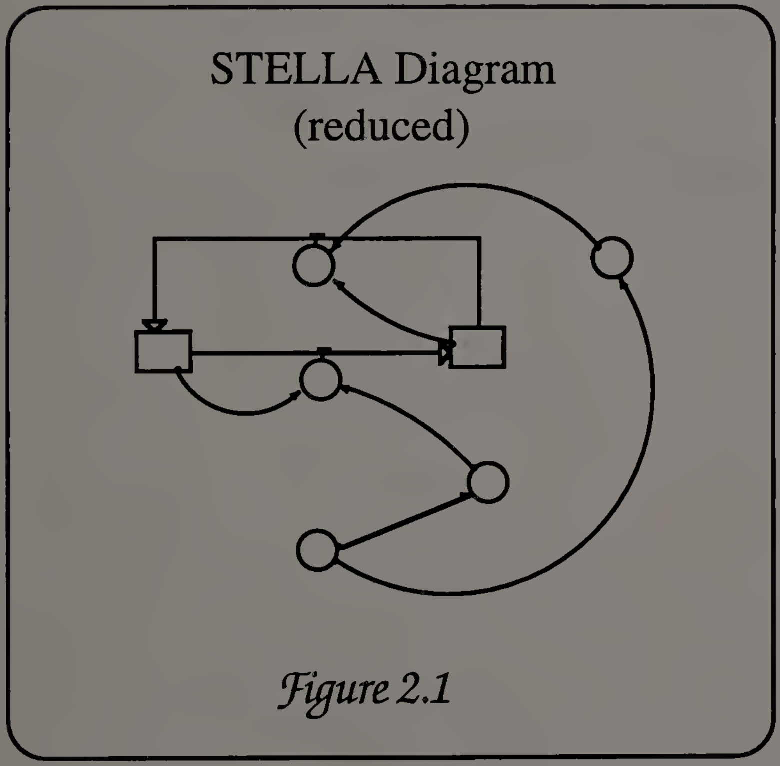


Figure 2.1 STELLA Diagram

The stock elements are likened to containers that fill up; the flows are like pipes with faucets that control the movement of materials to and from the containers (See Figure 2.2). Connectors are linkage arrows that establish causal relationships and show directionality. Converters are factors that influence the flows. Clouds delimit the model boundaries; they represent infinite depositories or infinite sources. For instance if the problem is filling up a tub with water the ultimate source of water or its destination once it is drained is not considered important to the problem.

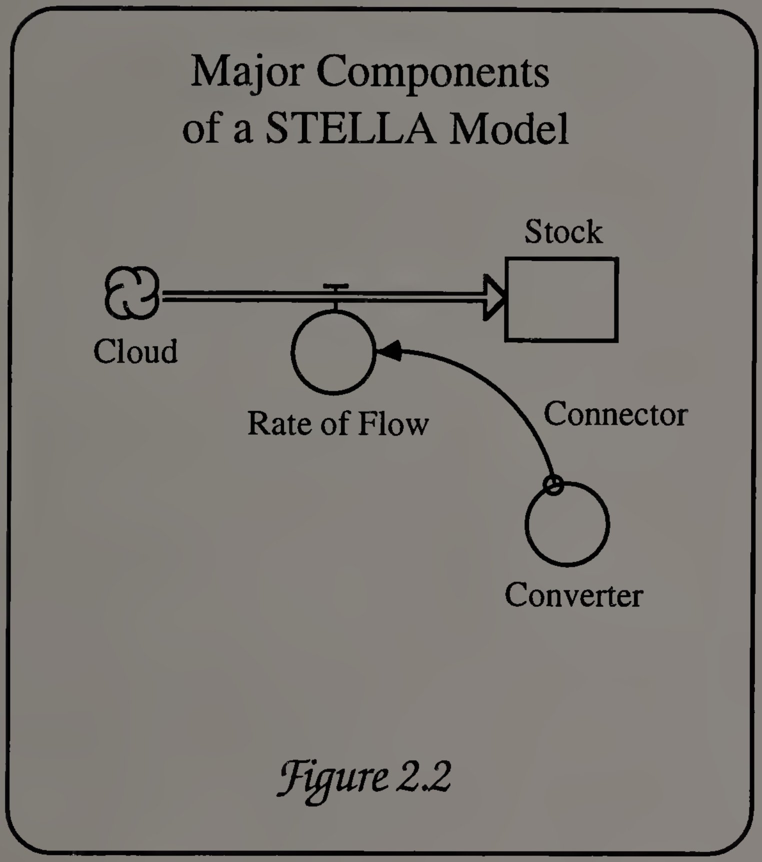


Figure 2.2 Major Components of a STELLA Model

Another level of translation occurs when the mental model becomes operationalized into algebraic expressions. The visual relationships become algebraic expressions. Some of these algebraic definitions are created automatically by STELLA through the structure of the diagram. Other equations and variables must be defined explicitly by the modeler. Jay Forrester (1968) proposes that such metaphorical mapping involved in translating mental models into a STELLA diagram and algebraic relations make assumptions explicit.

Hanneman (1988) sets forth a set of procedures for creating a model:

1. set the boundary
2. define the elements
3. describe the interrelationships
4. define the dynamic relationships; operationalize the rules

Although this represents a typical approach for most expert modelers, observations and personal experience suggest that apprentice modelers as well as those experienced don't strictly follow this ordering. For instance in the study investigated by this dissertation students often started by defining the elements and then began to think about the boundaries of the model. After executing the model it is common to revisit these procedures and modify the model.

After a simulation is created algebraic expressions can be inspected from two views. One display provides a complete listing of student generated algebraic expressions (See Figure 2.3).

Equations

N2O4(t) = N2O t0- dt) + (BECOMING - BREAKDOWN) * dt
INIT N2O4 = 2
INFLOWS:
BECOMING = NO2*BECOMING_FACT
OUTFLOWS:
BREAKDOWN = N2O4 RUAKDOWN_FACTOR

NO2(t) = NO2(t - dt) + (BREAKDOWN - BECOMI)0* dt
INIT NO2 = 2
INFLOWS:
BREAKDOWN = N2O4*BREAKDOWN_F T_R
OUTFLOWS:
BECOMING = NO2*BECOMING_FACTOR

BECOMING_FACTOR = GRAPH(TEMP)
(0.00, 0.495), (4.17, 0.4), (8.33, 0.365), (12.5, 0.34), (16.7, 0.31), (20.8, 0.265), (25.0, 0.25), (29.2, 0.185), (33.3, 0.145), (37.5, 0.125), (41.7, 0.09), (45.8, 0.03), (50.0, 0.00)

BREAKDOWN_FACTOR = GRAPH(TEMP)
(0.00, 0.0025), (4.17, 0.0175), (8.33, 0.0625), (12.5, 0.1), (16.7, 0.145), (20.8, 0.185), (25.0, 0.25), (29.2, 0.27), (33.3, 0.317), (37.5, 0.352), (41.7, 0.395), (45.8, 0.435), (50.0, 0.5)

TEMP = GRAPH(TIME)
(0.00, 0.25), (0.833, 4.50), (1.67, 7.25), (2.50, 12.0), (3.33, 16.5), (4.17, 21.5), (5.00, 26.5), (5.83, 30.0), (6.67, 33.5), (7.50, 36.8), (8.33, 39.0), (9.17, 43.0), (10.0, 49.5)

Figure 2.3

Figure 2.3 Equations

Another display exposes a dialog box that acts as a logic recepticle for a variable's algebraic expression or value (See Figure 2.4). This view allows a user to view, define, or modify the current condition of the open variable.

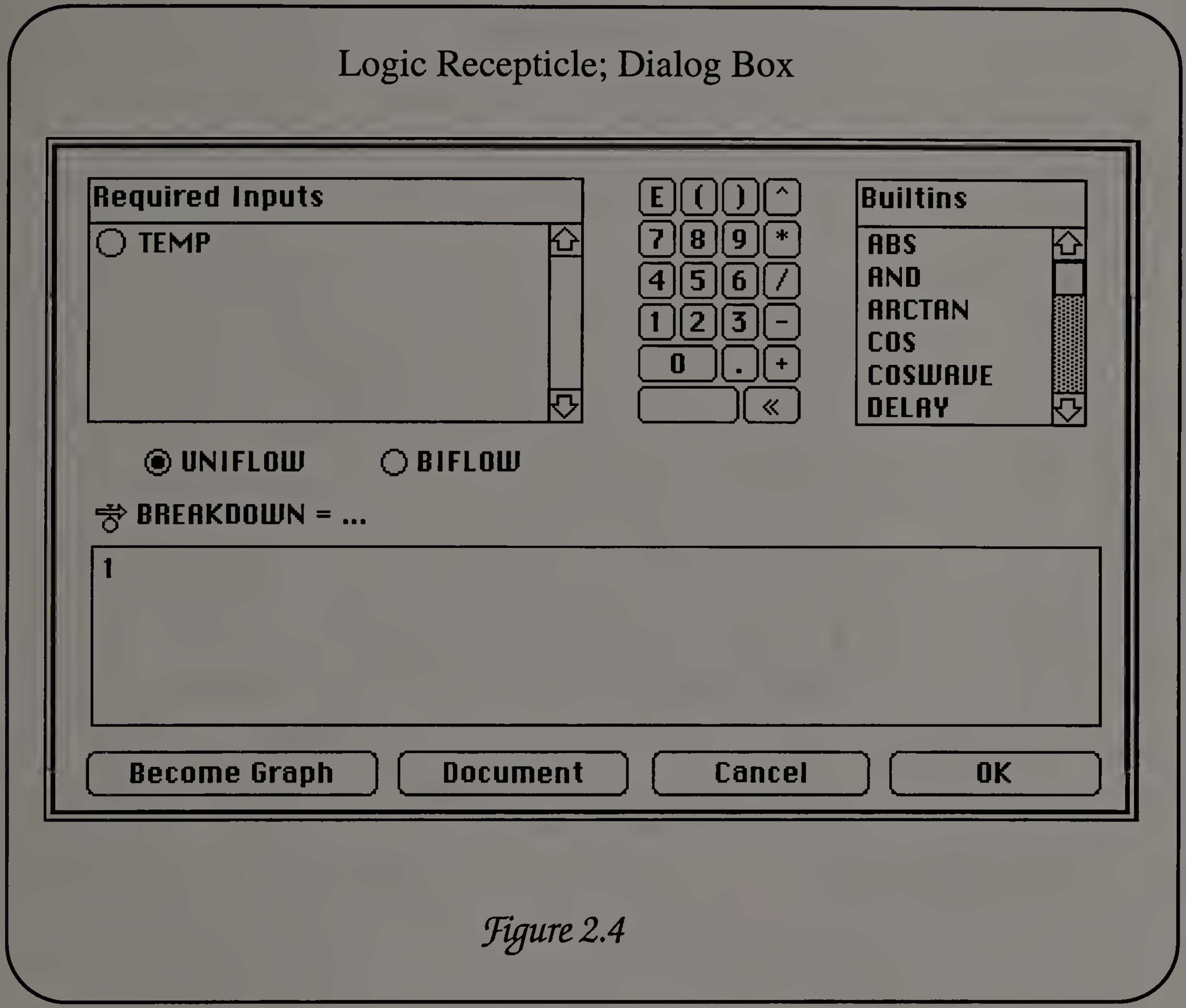


Figure 2.4 Logic Recepticle

STELLA utilizes finite differential equations that are transparent to the user. The user does not view these equations but does see the generated results. The differential equations operate on the algebraic expressions defined by the user to create continuous output that results in smooth time series graphs, animated diagrams, and tables of variable values.

Within the STELLA environment many systems share common generic structures. Generic structures include structural diagrams, equations, and sample graph output. These compose the building blocks for STELLA models and were provided to students in this study. Most, not all simulations share these common structures.

2.4 Simulating the STELLA Model

With the model operationalized, hypotheses and experiments can be generated to explore a system's behavior. The output can be represented in a number of different forms. The animated icon view is one depiction of an executable STELLA model. Animated icons display the stocks as levels that graphically change over time. The flows are depicted by a dial that rotates clockwise indicating an increase in the rate and counter clockwise for a decrease (See Figure 2.5, This diagram was one that was created by students in this study to simulate chemical equilibrium).

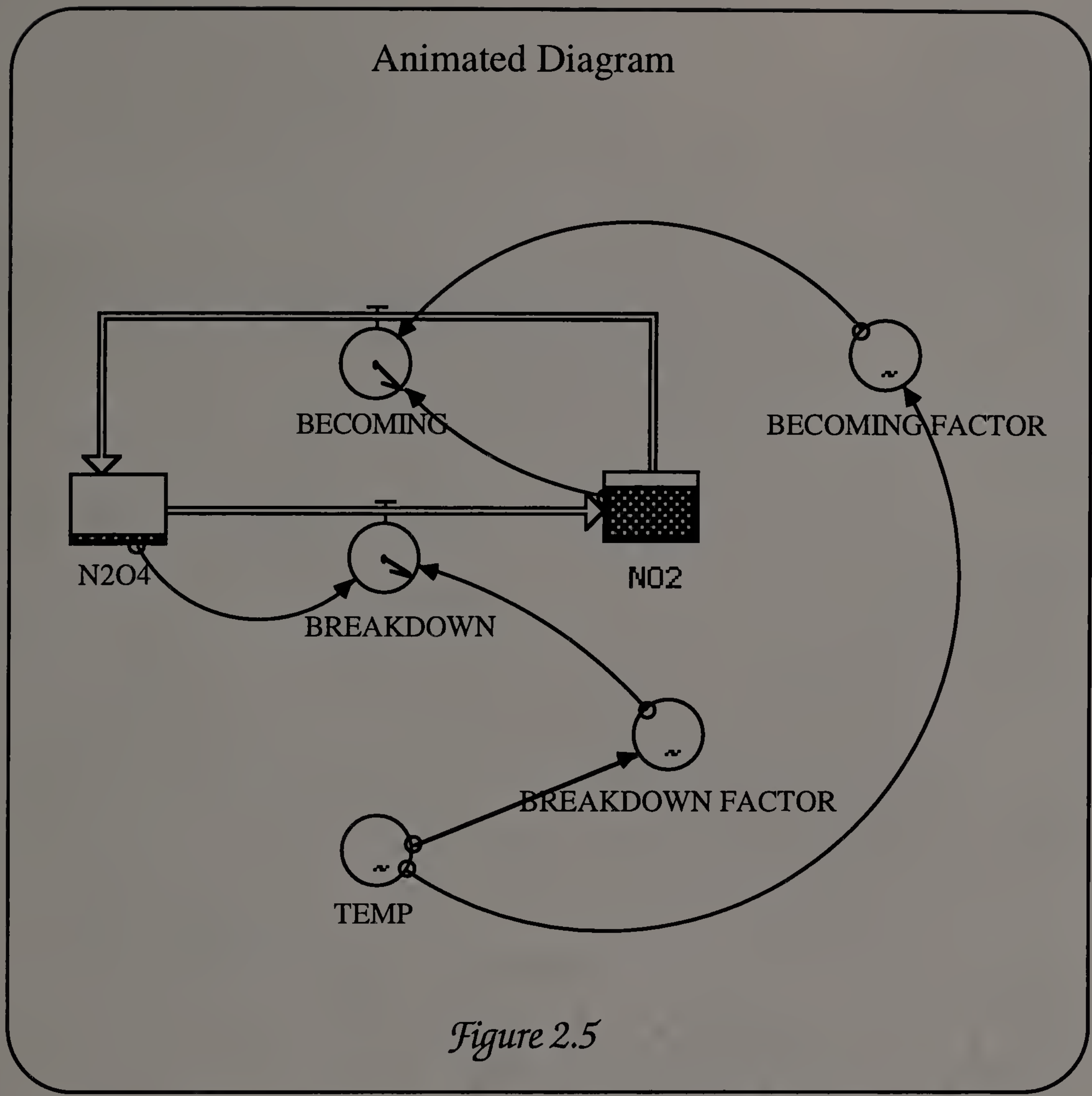


Figure 2.5 Animated Diagram

Time series graphs are alternate portrayals for displaying simulation output. Graphs are automatically scaled by STELLA and function to illustrate an historical record of dynamic behavior (See Figure 2.6).

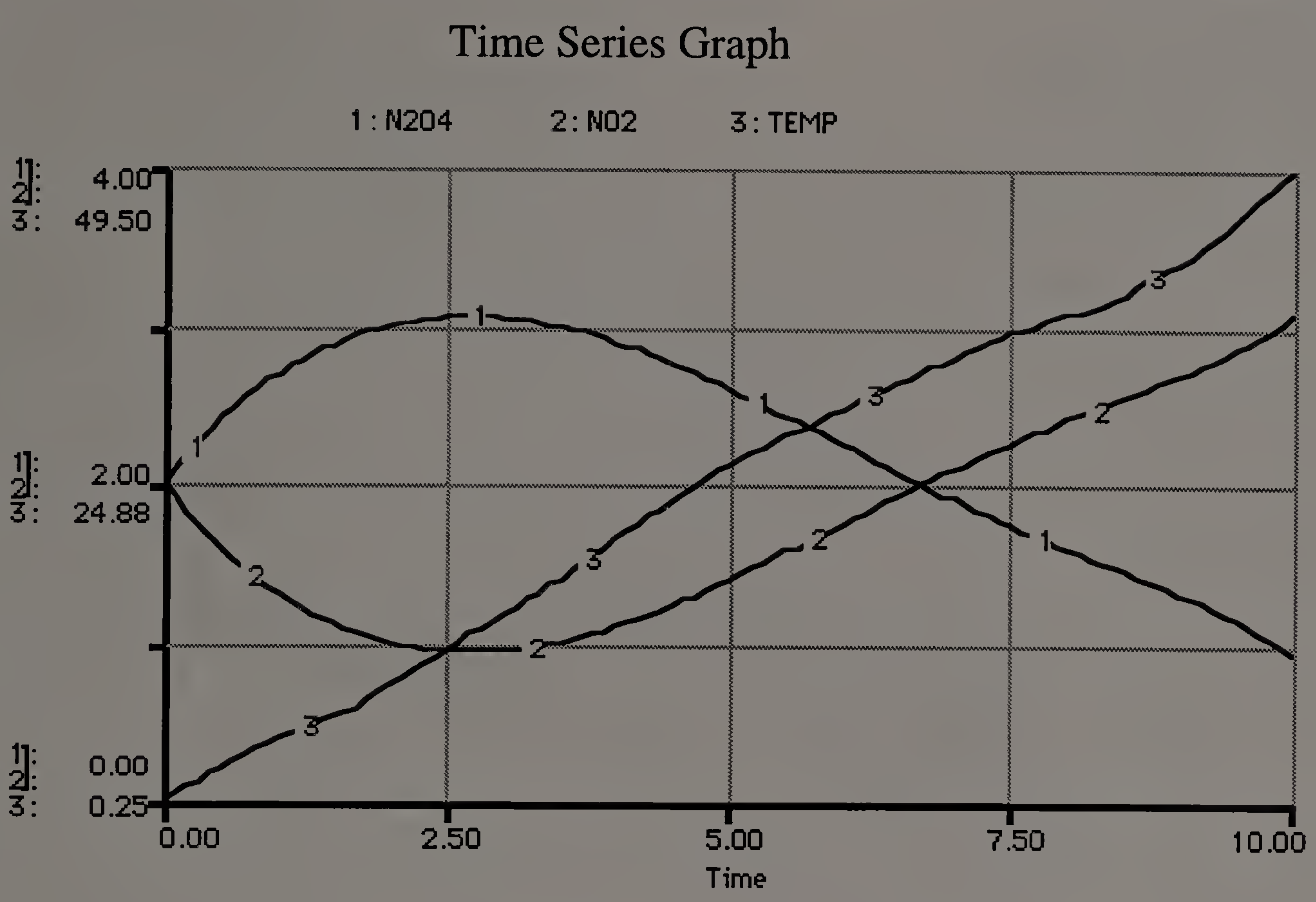


Figure 2.6

Figure 2.6 Time Series Graph

STELLA tables depict change in variables at discrete time intervals (See Figure 2.7).

Table of Values

Time	0	1	2	3	4	5
N204	2.0	1.2	0.8	0.6	0.5	0.4
NO2	2.0	2.8	3.2	3.4	3.5	3.6
BREAKDOWN	0.9	0.5	0.4	0.3	0.2	0.2
BECOMING	0.1	0.1	0.1	0.1	0.1	0.2

Figure 2.7

Figure 2.7 Table of Values

With a structural model in place, assumptions are available for inspection, testing, and editing. The first process is to select appropriate experimentation strategies. Students also need to interpret experimentation output that include graphs, tabular data, and animated diagrams.

2.5 Other Simulation Construction Kits

Several computer simulation construction kits exist. Extend (Imagine That Inc.) is commercial program that uses icons and lines to construct simulations in a similar to STELLA. There are also other tools that could be used in similar ways. For instance, Intelligent Maintenance Training System (IMTS) is a product that facilitates the authoring of interactive graphical models (electrical and mechanical models) that can be used as simulations for training purposes (Towne, Munro, Pizzini, Surmon, Coller, and Wogulis, 1990). This tool is not viewed as one for student constructed models, rather for authoring by subject matter experts. However it could be adapted and used as a student construction kit. Ogborn (1990) describes a project "Tools for Exploratory Learning" that uses a prototype program that provides students with simple schematic building blocks for mapping out a model. The model is only defined qualitatively yet able to provide graphic portrayals of system behavior without the necessity for defining the exact functional relations between the variables. The theory being that learners need a qualitative understanding first before moving to more quantitative terms. Smith (1991) describes a system called Alternate Reality Kit (ART) developed at Xerox Palo Alto Research Center. This system provides learners with a set of tools for creating interactive simulations. The rules for the simulations appear to the user as icons on the screen of the computer which facilitates the exploration of physical principles like gravity and velocity. Interactive Physics (Knowledge Revolution) is a commercial program that is also a simulation construction kit designed specifically for physics. More traditional programming languages can be adapted for the purposes of simulating dynamic systems. This is demonstrated by the creation of a population model by Pasquino and Peelle (1975) with APL (A Programming Language).

2.6 Conclusions

STELLA is a simulation construction kit that makes transformations between multiple portrayals. This program's feature set supports the dynamic perspective. Terminology and factual information about the content can be learned as a consequence of working with simulations like STELLA but these are incidental to learning the causal model underlying system behavior.

CHAPTER 3

BACKGROUND

This chapter outlines the benefits and shortcomings of spatial portrayal tools and relates them to computer modeling generally and to STELLA specifically. Insights from divergent domains, such as Cognitive Psychology, Developmental Psychology, Social Cognition, Computer Education, and Affective Psychology will be brought to bear. In addition, a general discussion of computer tools and related educational research will provide background for this study. This discussion builds towards a unified view of the impact STELLA has on thinking.

3.1 Theoretical Perspective

3.1.1 Computer Tools

STELLA can be categorized into a general class of software programs termed “computer tools”. This is in reference to computer programs that equip the user with transformational capabilities. Computer tools make transformations on symbol systems by massaging the format the symbols are displayed (e.g. a word processing program formats text based on user parameters) or by converting one symbol system into another (e.g. a music processor converts musical notation to sound). STELLA is an example of such a computer tool because it involves defining the goal of the simulation, initial state, operators (the functions or formulas in each node), and any restrictions (boundaries and level of analysis) that apply. The resulting symbolic definition is then transformed into several types of visual portrayals (graphs, tables, animated diagrams). Other computer tools incorporate similar processes. They allow the user to experiment by changing values or restructuring the depiction and often generate visual results (See Sidebar 3.1). This give-and-take kind of an environment encourages an iterative approach, as opposed to a one-shot methodology. Illustrative programs include: spreadsheets, outline processors, Logo language, simulation construction kits, databases, etc. These computer tools can analyze complex systems that extend beyond normal cognitive limitations.

Visualization Tools for Scientists

Many scientific journals that describe new insights and discover ies are filled with articles of scientists who have used computers as visualization tools to assist them in gaining new insights. For example in a recent Discovery magazine, Frank Happner (Wickelgren, 1990) described a computerized model of birds in flock. The result was a mathematical model describing the chaotic behavior of birds in a flock-- the psychology of flock behavior. Another article in the same issue described a computer model of corn growth (Hively, 1990). The scientist who designed this model stated "My goal.... is to understand what makes a plant tick." (p. 74) What makes computers a useful medium to investigate corn growth is that "...the process we're monitoring obey well-known laws we can express as equations" (p.75).

Sidebar 3.1

Sidebar 3.1 Visualization Tools for Scientists

One reason computer tools became appealing to educators was their potential for encouraging shifts in thinking (Olson, 1988). Papert (1980) took a "Whorfian" perspective in asserting how the educational programming language of Logo imbues learners with a way of thinking:

> The process reminds one of tinkering; learning consists of building up a set of materials and tools that one can handle and manipulate. Perhaps most central of all, it is a process of working with what you've got. (p. 173)
>
> ...By building Logo in such a way that structured thinking becomes powerful thinking, we convey a cognitive style, one aspect of which is to facilitate talking about the process of thinking. Logo's emphasis on debugging goes in the same direction. (p. 180).

The tools that are available influence thinking, and this has implications for computer tools. Pea (1985) postulated that a major role for computers was to stimulate reorganization of mental functioning. The notion was that the tools that are available influence how learners use them and ultimately influence learning.

Computers differ from other forms of media. Traditional text presents orthographic symbols and/or pictures that are static. This stability enables the reader to read back over difficult passages. Television is a relatively transient medium but provides pictorial images that activate rich epistemological structures. Transient in the sense that an image that appears on the screen will eventually disappear off the screen (although playback and freeze-frames are possible). Computer tools tend to be less orthographic and less stable than most books but are less transient than a medium like television because of user control and non-linearity. The computer's value is not only in its ability to depict symbol systems, but also its ability to process procedures created through symbolic portrayals. This ability to process information facilitates the transformation and juxtapositioning of symbol systems. A multimedia environment potentially combines the best features of the above media by making available both a concise portrayal and access to a richer description. Nevertheless, the research into this kind of a tool is still too immature to make generalizations (Ambron and Hooper, 1988; Dede, 1987; Kozma, 1991).

Kozma (1991) identified an important criterion for using a particular medium:

> But learners will benefit most from the use of a particular medium with certain capabilities if the capabilities are employed by the instructional method to provide certain representations or perform or model certain cognitive operations that are salient to the task and situation and that the learners cannot or do not perform or provide for themselves. (p. 182)

In other words the computer tool should provide unique educational possibilities. Computer tools have been thought to have multiple benefits for the learner. Speaking specifically of computer simulations, Goodyear et al. (1991) identified typical arguments conceived to justify computer implementation:

> ...simulation-based learning is usually expected to motivate, to invite active and deep processing of subject matter, to allow for systematic exploration, for fruitful failure, and for unlimited practice, all of which should contribute to better learning outcomes, reduced learning time, or both. (p 274)

3.1.2 Cognitive Benefits

The following section lists the benefits of portrayal tools that encourage changes to internal representations. Identification of attributes that influence student thinking will facilitate effective pedagogical application of the tool and inform developmental efforts. By way of disclaimer, what follows is a rather diverse description of learning. The intent is to provide a relevant backdrop for investigating learning with portrayal tools.

3.1.2.1 Internalization

Symbolic output is the sole determiner of thought. This was the hypothesis of Benjamin Whorf (1956), he suggested that language directs how individuals construct their representations. For example, Eskimos have many descriptive terms for snow, and the Hopis have multiple descriptions of flying objects. However, despite differences in language, people are able to learn how to communicate with each other. This suggests that Whorf's strong hypothesis is probably false. However, the theory at the other end of the spectrum from the Whorfian hypothesis seems equally unpalatable. Kozma (1991) referred to this theory in his review of learning with media. This theory as espoused by Clark (Kozma, 1991) suggests that the means of communication (media) per se does not influence learning, it is merely a vehicle for delivery. However media often influences the way the message can be delivered and thus will influence learning (the media is the message).

Bruner (1966), like Whorf, assumed that children's ability to develop symbolic portrayals is a function of their use of symbolic language. Again, there are no strong suggestions from research that this is the case. Vygotsky (1962) also theorized that language determines thoughts. In Vygotsky's theory, internalization is fundamental to a child's development (Daehler, M. W. & Bukatko, D., 1985). His suggestion was that during development thoughts and inner speech are separate. Over time, through exposure to social language, internalization of language takes place; thoughts and inner speech become intertwined (Vygotsky, 1962). Piaget (Ginsburg, 1988) spoke of imitation as being an important aspect in the development of semiotic functioning, the processing of mental symbols. Socially stimulated internalization requires shared attention between the modeler and the learner (Ratner and Stettner, 1991). An important aspect of this act of internalization is motivation, as well as the overall role of emotion. The implications are that the affective domain has a role to play in the effectiveness of internalization.

Hawkins (1974) captured the essence of internalization:

> ...the child should learn how to internalize the function which the adult has been providing. So, in a sense, you become educated when you become your own teacher. If being educated meant no longer needing a teacher - a designation I would recommend - it would mean that you had been presented with models of teaching, or people playing this external role, and that you have learned how the role was played and how to play it for yourself. At that point you would declare your independence of instruction as such and you would be your own teacher. What we all hope, of course, is that as the formal, institutional part of education is finished, its most conspicuous and valuable product will be seen to be the child's ability to educate himself. (pp. 53-54)

Although Hawkins focuses on independent learning this involves social constructivism. Vygotsky (1962) and Rogoff (1990) both suggested that internalization of a social tool like language has cognitive benefit. By changing the nature of the social tool to a computer, then there is the possibility of internalizing processes associated with that tool. "By changing the environment man can regulate his own behavior and control his own psychological processes." (Tikhomirov, 1974, p. 374) This suggests that external mediation results in internal mediation. An example of this are those individuals in the Orient who used the abacus, but now find it more efficient to use a mental abacus (Glass and Holyoak, 1986). Similarly, portrayal tools can prompt organizing structures in the mind (Holley and Dransereau, 1984). Olson, Bruner (1974), and Salomon (1988) suggested that portrayal tools provide opportunities for manipulation of the content, and this manipulation becomes internalized.

In summary, there are quite a number of educational theorists who speak of the importance of internalizing the external environment.

Pea (1985) advocated a Vygotskian perspective that suggests symbolic technologies function to restructure cognition. Polin (1991) agreed and cited studies conducted by Margolis, a Soviet researcher, demonstrating computer tools that model reality can function to link content and students' cognitive processes: Students making transformations of a computer model reflect on changes to the representation of content and back to the model in an iterative fashion, providing a means for seeing the differences between thinking about the content and the content itself.

An externalized portrayal is the result of selected ideas being mapped out onto an external medium. Despite the translation process, internal representations might be incongruent with external portrayals. This sets up conflict that challenges current representations. In other words, the external portrayal may lead the learner to question the mapping between the content and the internal representation of the content. Computers provide opportunities for manipulating a model of the content, and this manipulation becomes internalized (Kozma, 1987; Salomon, 1988). Brown (1967) and Winn (1987) agreed that it is possible to internalize a tool. This might take place because a computer tool affords higher order processing that encourages cognitive revision.

The computer provides a new form for internalizing processes (Kozma, 1987). The computer has the unique capability to display dynamic situations graphically. As a consequence, the computer may change the way information is organized in mental representations. Speaking specifically of computers as portrayal tools, Tikhomirov (Olson and Bruner, 1974) contended that "computers are tools which alter man's psychological processes. Man alters external things; but afterward, these alterations influence his internal psychological processes" (p. 21). The contention is that when a manner of viewing information proves valuable, the mind begins to organize other things/experiences using that perspective. This takes place because there are features or attributes in perception that become linked to internal perspectives. Thus an internalized representation or perspective is activated when an appropriate problem is encountered. Computer tools influences the internal perspective and in turn influences subsequent learning.

3.1.2.2 Bias of the Tool

One of the theories of this research is that the bias of the tool influences learning. The bias of a tool may become internalized. A bias is identified by the perspective the tool imposes. This perspective is represented by the dimensions of the information salient in the depiction. All symbol systems are endowed with a bias; no symbol system can be said to be isomorphic with mental structures. When students translate their ideas into an external medium, it must be done through a symbol system. A symbol system that has limited powers of communication activates selected types of knowledge. For instance the writing process itself influences thought. Personal experience suggests that ideas become altered through translating those ideas into written form. Sometimes the way the words come together suggest a slightly different meaning from what was intended but none the less useful. Portrayal tools provide the means to change the frame of reference, thereby allowing particular explanations. "Frame of reference" suggests the activation of alternative knowledge structures that can be used to organize information in specific ways. Speaking of representations as portrayal tools, Rubinstein (1986) stated:

> ...the representation is a framework for thought, and it may provide new insight that did not exist before; it may suggest new alternatives, new connections, or cues to information not retrieved before; or it may help us identify the need for unknown information. (p. 6)

Olson and Bruner (1974) claimed:

> It follows that symbolic activities such as drawing an object, describing an object, or photographing an object require somewhat different information about the object. To the extent that these new forms of cultural or symbolic activity require previously undetected information about the world, the media of expression and communication are explanatory devices -- a point of immense importance to an understanding of the child's acquisition of knowledge. (p. 146)

Media are explanatory devices by virtue of their ability to activate knowledge structures. The knowledge structures that become activated reflect media's bias. Reimann (1991) noted the importance of bias in his work on simulations. He set forth that different forms of code produced by the computer foster different cognitive processes:

> Hypotheses can only be built on what is encoded and focused on at any given time. We may think of the encoding rules as providing a vocabulary to describe states of the world. The rules used by the learner to represent the domain establish a specific view of the environment: a descriptive bias. (p.63).

It is believed that the tool's bias influences learning. Driver (1989) pointed out that conceptual change may be domain and context dependent. Winn (1987) concluded that "graphic forms encourage students to create mental images that, in turn, make it easier for them to learn certain types of material." (p. 159) The nature of the learning task is one of the key factors in determining graphic form usefulness. This is an issue that Lambiotte et al. (1989) alluded to: different mapping conventions lend themselves to describing different types of underlying structure. For instance, a causal diagram lends itself to describing feedback loops. Causal diagrams are probably less than useful in describing hierarchical relationships where a tree mapping devise might be a better choice of tools.

The tool that is used colors what is viewed as being important. This bias of the portrayal tool is a nontrivial issue; this is a significant affordance that assists learners to gain new insights. It is like using a red filter to view a picture. With this filter only red elements of the picture are seen, so perception of the picture is quite different from normal viewing. Spatial portrayal tools are analogous to this filter: these tools change the perspective for viewing a system.

van Joolingen (1991) described the bias of tools with the term "experimental frame". This is seen as a filter which identifies relevant information to include in the modeling process. The experimental frame limits the field of view of the modeler to certain aspects of the real system. A tool incorporates a new paradigm as part of the bias of the tool. The student then is in a position to bring this new framework to bear on the content structures that are activated. In this way portrayal tools have the potential to uncloak previously ignored dimensions of the knowledge and to induce conceptual change through a shift of framework (Presson, 1987). For example, an outline processor predisposes cognition to organize information in a hierarchical manner. When the processes are activated with appropriate content structures, the structures that organize information hierarchically operate on the content to provide the person with a new organizational view of the information. This new perspective may provide insights by visualizing relationships or revealing counter-evidence that conflicts with current conceptions. The STELLA environment contains a variety of portrayal forms: graphs, equations, diagrams, tables, etc. Each of these portrayals emphasize particular dimensions of dynamic systems and thus hold potential as a learning device.

It has been theorized that scientists' tools for verifying and testing theories provide metaphors and concepts for scientific discovery (Gigerenzer, 1991). For instance, it has been noted that viewing the mind as an "intuitive statistician" becomes conceivable because statistical tools provide a new metaphor for theories about thinking, and become acceptable because use of statistical tools has become wide spread. Gigerenzer called this the "tools-to-theories" heuristic of discovery. In essence, the analogy of the tool becomes a basis for the discovery of new theories. Portrayal tools influence the type of data produced and the explanations sought (Hanneman, 1988). Meadows, (in Randers, 1976) in speaking about different paradigms used to generate models, noted: "In a real sense the paradigm biases the way the modeler sees the world, thus influences the content and shape of his models." (p. 24)

Analogies are a form of perspective-taking that have been used to bridge student thinking from alternative frameworks to conventional scientific conceptions, Clement (1989) noted that explanatory models allow scientists a fresh perspective for visualizing ideas through analogical thinking. In this study, the STELLA model is the explanatory model that will provide students with an analogy for seeing new structures hidden behind dynamic systems. In a sense it provides students with an "analogical anchor" (Clement, Brown, and Zietsman, 1989). Analogical anchors have been used to move intuitive conceptions toward scientifically acceptable conceptions. Through thinking about the content in a metaphorical way (flows and accumulations in STELLA) a framework is now available to stimulate shifts in conceptions. STELLA is an analogical anchor with built-in goals of identifying causal loops and seeing the structure of a system as the cause of the behavior.

3.1.2.3 Spatial Advantage

Spatial tools like STELLA will probably not benefit all individuals equally well. There are some individuals in some contexts who will benefit from use of portrayal tools. However for the most part, students don't get formal instruction in schooling on how to construct or decode graphic forms, yet there is evidence to suggest that we can improve these skills with practice (Arnheim, 1985) (See Sidebar 3.2). The reasons for this condition may be a cyclic one. A lack of graphical form instruction results in students who lack graphical expressive skills. These students develop into teachers who, in turn, lack graphical instructional skills. So the cycle continues. Students are not learning how to deal with graphical forms of portrayal so they are ill prepared to make interpretations on graphical portrayals. Taylor and Cunniff (1988) contend that for certain applications graphic portrayal of concepts are superior to textual portrayals, at least for some learners. This is not an argument to do away with textual or print materials, rather the graphical aspects could provide additional portrayals that would enrich a student's understanding of the content. Papert states "Individuals can -- and in some cases must -- follow very different learning paths" and "Some children are crippled by mismatch with the intellectual style of the curriculum". Speaking of the children described in Weir's book, Papert goes on to say "her prime example of mismatched learners is the category of spatial thinkers -- children who can achieve a high quality of intellectual work when they are allowed to use more spatial ways of thinking..." (Weir, 1987, page x-xi, Forward). Winn (1987) indicated that portrayal tools give a graphic advantage by influencing the form of expression and how that information gets processed. Spatial tools like STELLA provide learners opportunities to take advantage of spatial cognition.

> School Bias
>
> Olson (1985) has argued that schooling is biased toward verbal versus graphic forms of communication.
>
> *Sidebar 3.2*

Sidebar 3.2 School Bias

3.1.2.4 Multiple Portrayals

Computer tools are noted for performing impressive operations on the symbolic rendering in the memory of the computer. As an illustration, STELLA transforms system behavior into multiple abstract graphic forms that are thought to be more understandable and accessible (Ogborn, 1990). A better understanding of an object is achieved as a person moves around it, establishing different perspectives. In the same way Narode(1987) noted that portrayal tools provide students with multiple forms of depiction that might be effective at exposing the complexity and depth of an issue by conceptualizing it in new ways. Dickson (1985) suggested that computer technology represents an effective means of encouraging cognitive transformation, by allowing users to move back and forth between different symbol systems. The computer provides a tool for translating between symbol systems and may result in easing the shift from one form of portrayal to another (Salomon, 1985). STELLA excels in translating information from algebraic expressions and diagrams to graphs, tables, and animated icons. Since the computer provides a tool for the quick translation between symbol systems, Salomon (1985) suggested that this will also enrich a student's metacognitive awareness. This level of thinking is supported by a system that can transform one form of depiction to another. The main point being that multiple portrayals activate alternative knowledge structures and because the computer can translate rapidly between different forms of information it encourages juxtaposing activated knowledge structures.

3.1.2.5 Underlying Structure

STELLA relies on analogical processes to link representations of the content with the plumbing metaphor. Illumination of problems often involves reformulating initial representations through analogical thinking. For example, the theory of light was reframed by using the analogy of a wave. Brown (1989) ascribed success in analogical problem solving to seeing the underlying structure of the analogy. Gick and Holyoak, (1980) found analogies to be a useful tool in reformulating representations using the classic convergence problems; the solution involved thinking about dividing up a source and moving it to the destination from different directions (Dunker, 1945). They found that the use of the "general-analogy" increased success on the "radiation-problem", but distant analogies of a more abstract nature were less effective unless the underlying scheme was identified. Analogies help individuals identify the underlying structure of the systems/problems.

The research into novices and experts also sheds some light on the importance of seeing the underlying structure. Chi (1981) noted that experts see the underlying structure making them superior problem-solvers. Novices tend to have less structured knowledge and less pertinent knowledge, while the knowledge of experts is richly structured with more pertinent knowledge. The expert's structures encompass more powerful principles, while novice's structures just contain schemas of objects. Experts focus more on underlying principles and the organization of concepts (Gilhooly, 1988; Chi, Glaser, and Rees, 1981). This suggests that being cognizant of the underlying structure of knowledge is important in various domains.

Gick (1985) found that diagrammatic cues were effective in analogical problem solving. Portrayal tools may be useful in bringing to the surface the underlying problem schemas in a more concise manner (Lambiotte, et al., 1989). A graphic portrayal acts as model by focusing on the main effects because there is not room to display the entire domain. For instance, STELLA diagrams provide model constructors with schematic diagrams. Schematic diagrams have been used to portray in a concise manner the underlying structure of knowledge for efficient search, recognition, and inference. (Lambiotte, et al., 1989; Larkin and Simon, 1987).

Once a STELLA diagram has been constructed, the information can be referenced in a random access manner. This is in contrast to consciously searching through declarative memory that requires sequential access. Visual portrayals involve parallel processing that enable an entire image to be brought in and represented in our minds. The visual spatial relations made up of nodes and linkages in STELLA communicate an entire system in a simplified manner, usually in one image that depicts the underlying structure. Seeing the underlying structure has been identified by researchers as being important in problem-solving situations (Chi, 1981; Brown, 1989; Glass and Holyoak, 1986).

White and Gunstone (1989) suggested that conceptual change requires deep processing, as a result of being able to see the underlying schemas. Deep learning involves an understanding of how each node relates both to near and distant nodes (Kahn, 1985). Deep meaning allows individuals to make better connections with analogous problems in memory. Graphic tools can facilitate construction of connections highlighting a system's underlying structure.

3.1.2.6 Realism versus Abstraction

Gaining expertise in a field of endeavor seems to be associated with the development of abstraction in order to see the underlying structures. (Hayes, 1989). Kahney (1986) and Gilhooly (1988) both indicated the importance of abstraction in the problem-solving process. Abstracting meaning affects transferring problem-solving schemas to new situations (Glass and Holyoak, 1986). Perhaps the utilization of externalized portrayals can facilitate abstract thinking. For instance, graphic forms often do not need many words to describe ideas since information is captured in the symbols and their spatial arrangement (Lambiotte, et al., 1989).

Without the huge knowledge base of the expert, the novice has little to draw on. There is no way to totally replace the need for a knowledge base that is required to make informed explorations. However a portrayal tool may assist novices to think more flexibly with the knowledge they have. Flexibility may come from being able to recast problems in a new form. The abstract notational system of graphical portrayals may yield expert-like thinking about the problem through uncovering the underlying structures of the problem.

Elements of abstract graphical form may not be isomorphic with content. For instance, the physical relationship of content may be isomorphic to spatial relationship on the graphic form (as with a topographical map), but the notation representing locations may not have any correspondence to the real objects (as with a dot representing a city). One of the features lost with abstract portrayals is detail, but this provides graphic tools with one of their advantages: ease in processing. It is a tradeoff between the value of a rich and a concise description. It is possible to combine both a rich and a concise description but that might take away from the advantages of the abstract portrayal. For instance, with simulations, a system has been simplified for the purposes of understanding. Adding complexity and detail back into the system may detract from the purpose of the tool.

There is also a tradeoff involved in using generic forms (circles and boxes) rather than icons or actual pictures. Although diagrams with pictorial

images tend to activate richly connected representations, there could be a lack of common meaning. International symbol systems are an example where images do share meaning across cultures (See Figure 3.1, Universal Symbols). However, even if a standardized set of icons for every idea or concept could be conceived, it might not be easy to get common agreement. Brown (1967) argued that it would be extremely difficult to have an image for many abstract ideas. For instance how can you have an image for the concept of "knowing"? Individuals may reconstruct images that provide specific instantiations of the concept, but to have one image that subsumed all the subtleties of the idea of "knowing" is difficult to conceive. This is not a quantity issue, but a semantic problem. The point is that it may be difficult to match realistic images to abstract concepts but we can easily match abstract concepts to a generic images. For instance a box labeled "knowing" could take on referential meaning. With a reduced set of elements, (boxes, circles, and arrows) the conventions are kept simple and are more readily accepted by others. STELLA uses such a set of conventions. Using words as labels helps disambiguate the meaning of generic symbols but does not absolutely identify meaning.
Another reason that pictorial icons are ineffective is the cost of maintaining a pictorial library. Creating a library of icons or even looking up an icon every time there may be a change in conceptions would be inhibitory to the process of constructing a portrayal (even with a computer).

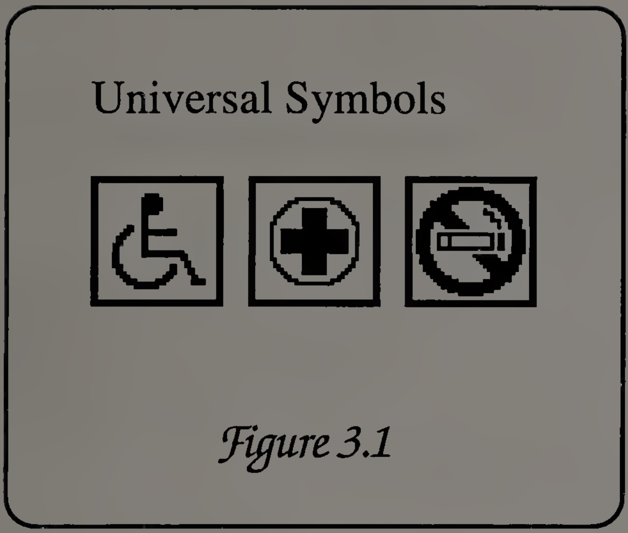


Figure 3.1 Universal Symbols

A related but separate notion of simplification is that a portrayal tool eliminates influences that are of minor consequence, so the focus is on the primary influences in the system. Modeling tools have a way of eliminating noise, leaving out known data for the sake of explanation (Kahn, 1985; Olson and Bruner, 1974). Through modeling, information is eliminated from the representation of the real world to make it understandable and manageable. This filtering takes place through the bias of the graphic form. There is a sifting process whereby the more salient ideas are incorporated and the ideas that lack activated strength are left behind or hidden in the graphical nodes.

Subtractive abstraction (Arnheim, 1974) brings up the important issue of deciding what is left in and what will be included. The STELLA manual (Richmond, Peterson, & Vescuso, 1987) calls this "elegant simplification", just having the essential information in the explanation. Novak (1984) suggested that this is an art. As Lambiotte et al. (1989) suggested there is probably a tradeoff between the information conveyed and the amount that can be processed while retaining the gestalt sense of what the portrayal conveys. The learner should ultimately determine what is included or excluded but an informed instructor can provide guidance and probing questions that help the learner select out pertinent variables for portrayal.

Too much information for the sake of realism is sometimes counterproductive (Arnheim, 1974). Good examples of this abound. In some situations, a simulation that comes close to realistically modeling a complex system is not as valuable for learning the major influences in a system as a simplified version For instance, children use this principle in their drawings; they don't include all the details, just what they think is important to them at the time. The degree of abstraction or realism depends on the goals of the individual and the context of the learning situation.

Simplification also affects cognitive load. It frees cognition to concentrate on more salient features of the information. The process of constructing depictions is a selective process. People do not attempt to represent everything, so the skill of selective construction is a process that has been used previously. It comes as no surprise that simplification seems to be an important characteristic of using portrayal tools (Winn, 1987) (Brueker, 1984).

Portrayal tools naturally use chunking techniques by using symbolic abstractions. Chunking has been well documented in facilitating recall (Glass and Holyoak, 1986). Chunking involves aggregating elements that seem strongly connected. An abstraction has a way of aggregating pieces of information under one idea or one symbol. The result is viewing aggregated ideas and considering how these separate clusters operate together. This form of simplification relates to cognitive load. It frees cognition to concentrate on just the more salient features of information. A single node displayed in a depiction may represent a number of ideas that coalesce into a single notion for the sake of understanding.

Duchastel (1991) noted that self-constructed simulations can develop from a more global or simplified view of the system, then, as understanding increases, a learner can progress to a more complex version. STELLA modeling expedites construction of increasingly complex models because it encourages embellishment of self-constructed models.

Arnheim (1974) cautioned that symbolic manipulation needed to be supplemented with experience in content. It is difficult to manipulate an abstracted depiction of knowledge without being able to reconstruct a representation from experience. Learners need experiences with the content to make sense out of the abstract nature of portrayal tools. Portrayal tools need to be but one avenue of exploration.

3.1.2.7 <u>Building Bridges</u>

One fundamental aspect of portrayal tools involves tapping prior knowledge and communicating that to oneself and to others. Researchers have used portrayal tools (such as conceptual maps) in reading comprehension (Brueker, 1984; Holley & Dansereau, 1984; Lambiotte & Dansereau, 1989; Novak, 1984). Conceptual mapping is thought to be analogous to the interconnectedness of nodes in mental representations. This comes from an information processing perspective (Holley and Dransereau, 1984). Portrayal tools are useful for expressing prior knowledge and making it available to conscious control. A common argument is that graphic portrayal tools have the potential to take advantage of the way memory works. Comprehension (Heimlich, 1986) involves building bridges between new knowledge and old, so being able to inspect ideas laid out in a diagram should be helpful in the construction of bridges. Bridges in the mind represent relationships between knowledge structures. In STELLA bridges from one kind of information to another can be depicted with arrows illustrating linkages between related items.

3.1.2.8 Cognitive Efficiency/Spatial Advantage

Work with conceptual maps has implications for STELLA because both use schematic diagrams to illustrate relationships. A conceptual map is a set of concepts represented by graphical objects (circles and arrows) in a meaningful spatial arrangement. Novak (1984) likened concept maps to road maps. Conceptual maps visually display pathways of meaningful connections between concepts. Graphic forms provide a means of inferring connections. The graphic form enables visualizing connections that may have eluded logical relations. Novak (1984) observed that students and teachers using conceptual maps were able to see new relationships and connections. Perhaps these connections lay dormant in tacit knowledge structures and require a different perspective for them to be activated. Portrayal tools provide another vantage point to investigate a problem. Some writers (Lambiotte, et al., 1989) have suggested that graphic organizers can function to remove the barriers imposed by conventional linear thinking. Graphic portrayals lend themselves to a search of relevant relationships while an outline emphasizes linear organization of information. The constructor of a map can focus on a node and ask a series of questions. These questions are in a sense potential connections because the designer can visualize the graphical connection and then ask whether or not it makes sense. Through graphical portrayals new connections are just an imaginary line away. For instance, consider a student who understands that predators are somehow related to prey in an ecological simulation. By visualizing linkages, a graphical portrayal now makes it possible to think about potential relationships (such as linkages between predator and prey deaths or between prey and predator deaths). Having the components of the system visually displayed in space evokes imagined connections (See Figure 3.2).

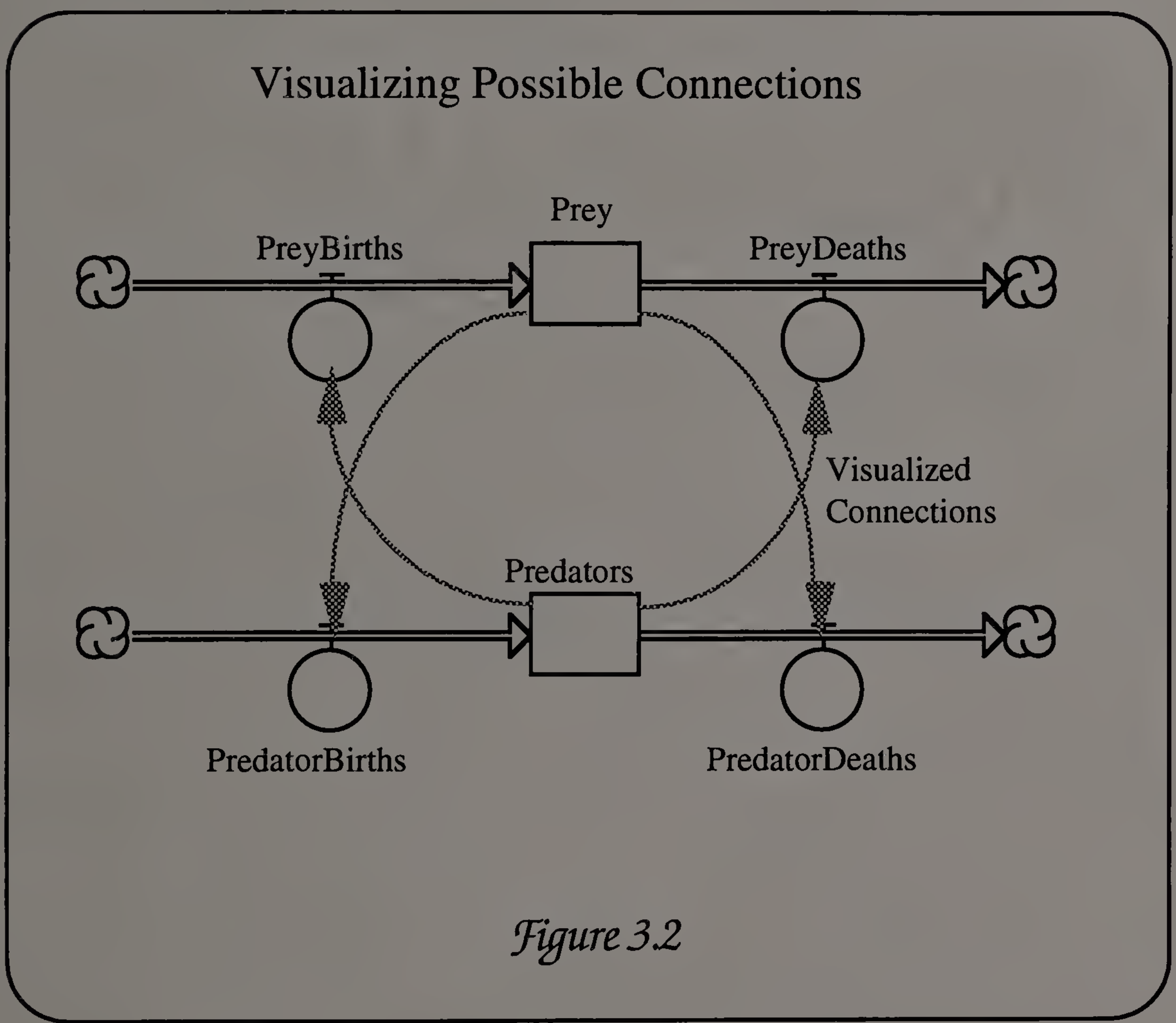


Figure 3.2 Visualizing Possible Connections

There is an intuition that seems to be pervasive (at least among visual learners) that graphic forms are somehow more efficient or understandable than textual information. This may be preferentially true for those with high spatial aptitude (as determined with Educational Testing Service's Kit of Factor

Referenced Cognitive Tests). Nonetheless, Lord (1985) postulated that visuo-spatial aptitude can be learned and is not limited to innate abilities. He viewed this aptitude as being important for education to develop.

In most cases the same learning can be achieved through some means other than portrayal tools. Yet an issue is the cognitive cost: the time and effort required (Levie, 1987). Symbol systems impart cognitive efficiency that is not achieved through language expression. There are many ways of expressing a representation, but one may be more efficient than another. Larkin and Simon (1987) noted that when portrayals are informationally equivalent, the differences in processing make a distinction in efficiency. A graphic form may lend itself to describing certain aspects of knowledge. For instance, it may be more efficient at highlighting relevant parts of knowledge; this saliency makes inferences easier to generate than in other symbolic forms. Differences in search and explicitness could account for differences in processing where cues in graphical portrayals are in an adjacent location, reducing the need for extensive search. A graphical portrayal provides a structure for search, recognition, and inference. (Larkin and Simon, 1987).

Larkin (1989) hypothesized that a diagram reduces search and facilitates quick "perceptual judgments" that otherwise require difficult logical inferences. The suggestion is that if there is a match between the form of depiction and the kinds processes that are acting on them, cognitive efficiency will be enhanced. A display can also facilitate the reconstruction of goals or annotations lost due to shifts in focus.

Spatial cognition is an issue in this study because the portrayals used by the computer require spatial processing. Distinct spatial forms have distinct meaning (Olson, 1983). Meaning is the criterion learners use for selecting representations used in generating descriptions. Meaning is dependent on the nature of the display and context. Olson (1974) claimed that "media converge as to knowledge conveyed, but diverge as to the skills they assume and develop" (p. 17). This statement suggests that new skills may have to accompany the effective use of media for communicative purposes. One of those skills involves spatial processes. Spatial skills involve reasoning about an object's orientation and location in space. These spatial skills are required to interpret and predict using STELLA's spatial portrayals.

Lambiotte, (1989) suggests that learners use a Gestalt perception in analyzing graphic forms. For instance, graphical portrayal tools are able to communicate, through visual spatial relations, the sequential, topological, geometric, or hierarchical nature of information. Spatial constructions take advantage of subtractive abstractions by imparting the ability to rapidly access various parts of the knowledge structure. Visual portrayals involve parallel processing that enables an entire image to be brought in and represented in our minds. This is in contrast to serial processing, characteristic of print and audio. Spatial forms often consumes less time to process than the verbal equivalent (Brueker, 1984). For instance, look at the adjoining diagram (See Figure 3.3). Given this illustration, there is an immediate sense of A influencing B, or A flowing to B. The exact meaning can be detected from context or with disambiguating labels, but there is an immediate impression about likely meaning. Perhaps it is this Gestalt perception that provides an advantage in graphic forms, that is, the ability for all the information to be scanned concurrently.

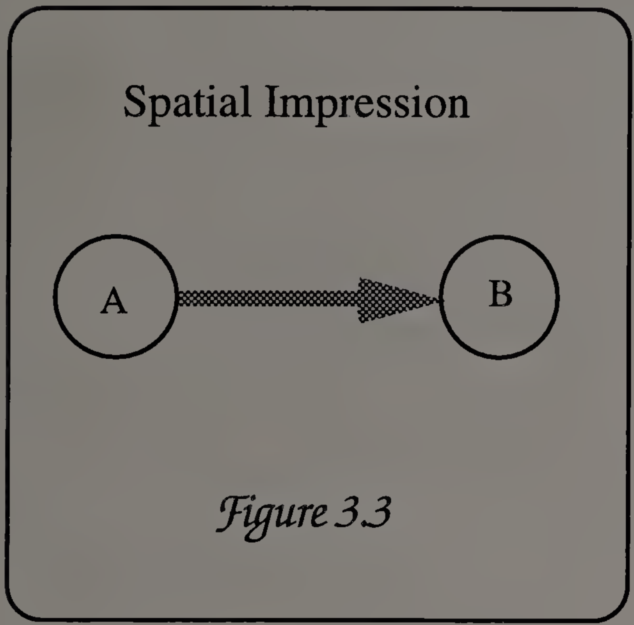


Figure 3.3 Spatial Impression

Spatial arrangement can indicate complexity, subareas, gaps, and pathways and or boundaries (Lambiotte, 1989). This metaknowledge can then guide the process of asking questions (Forman, 1989). Winn (1989) found that students can understand the pattern of relationships by using spatial distance to communicate how closely animals are connected in predator-prey relationships. Pinker (1985) noted that imagery can be called upon to deal with difficult problems. Difficult problems frequently involve many factors that can't all be maintained in working memory.

The work on cognitive mapping seems to be somehow analogous to the topic at hand. The word "mapping" is interesting because it implies a correspondence, normally between representation and portrayal. "Cognitive mapping" (Anooshian and Siegel, 1985) means being able to use an internal representation of locations to get around. Since there is a sense of location to almost everything that is learned, these experiences might act in an analogical way to help understand semantics derived from spatial portrayals. For instance, learners use landmarks in creating representations of locations. This seems comparable to the use of important nodes for determining spatial orientation in a conceptual map or STELLA diagram. During way-finding a person familiar with an area might become oriented to their surroundings by identifying a landmark. On a spatial portrayal, identifying an important node will reorient a person to the location of focus (in relation to other factors). The way certain landmarks are key to way-finding is analogous to how nodes are used in graphical portrayals for spatial orientation. Selected nodes probably stand out or are seen as important in making connections to other factors. In addition, there is a fair amount of inferencing taking place with unseen locations during way-finding activities. This parallels the inferences about semantic organizers because much is unstated verbally, and inferences have to be determined to take into account information not provided.

One of the points of this discussion of way-finding, is that other disciplines can be brought to bear, and some of the issues raised in the way-finding literature are profitable to explore in understanding spatial tools. Further, experiences with the world can map onto the use of portrayal tools and can act as a basis for understanding of spatial tools. These experiences and knowledge are part of the tacit knowledge base activated when dealing with the portrayal tools.

3.1.2.11 Analogical Thinking

Portrayal tools can act as spatial metaphors. Metaphors have often been used to introduce novel ideas such as computer literacy (Peelle, 1984). Spatial metaphors liken the representation of content to the graphical portrayal.

Goodyear et al. (1991) noted that learning a new device requires mapping attributes of a familiar device onto the attributes of a new device. This may create some inaccurate initial representations yet is a way to construct a representation to work from. A diagram highlighting important ideas identifies structural isomorphisms between different domains of knowledge. This in turn might stimulate analogical transfer. There is evidence that suggests that being able to identify structural similarities is an important aspect of being able to find a solution to analogous problems (Brown, 1989; Holyoak and Thagard, 1989). STELLA uses a plumbing metaphor as a learning technique to understand model construction and behavior.

3.1.2.12 Model Building

Building STELLA simulations involves constructing models. Since mental models are rarely static, external forms of depiction need to be malleable. Computer modeling lends itself to modifications of conditions because of the ease of editing and transformational abilities of computer tools.

Ost (1987) recommended that modeling should be a part of the curriculum. He asserted that "models and modeling are part of the fabric of science" (p. 367). While modeling, learners discover how to cope with new theories. There are individuals who believe that models are a ubiquitous part of the learning process; any learning involves creating models or theories (Springer, 1990). Kahn (1985), speaking specifically of computer simulations, said that these tools assume a potentially useful role in helping students understand what a model is. This is because learners' conceptions are externalized and viewable. Seeing the world as being governed by laws is significant to scientific understanding (Olson, 1988). The computational approach that STELLA has adopted encourages students to account for scientific phenomena. STELLA encourages experiential learning and discovery through virtual viewing of system behavior. In this way STELLA models may inspire development of coherent theories.

Novak (1984) reported an unanticipated positive benefit of using portrayal tools: intellectual honesty. This honesty about knowledge stems from an understanding that knowledge and the structure of knowledge is generated from self perspective. There is a relationship between the externalized form and the internal representation of knowledge. "It is the ability of modeling programs to make explicit and visible the model the student has constructed which makes modeling potentially such a powerful tool" (Kahn, 1985, p. 114). This correspondence between representation and portrayal fosters intellectual honesty.

A person who has not had to think rigorously about the interrelationships between concepts may benefit by expressing those in some portrayal tool. Making relationships explicit through spatial portrayal makes them accessible for criticism, because other possibilities are now conceivable. Driver (1989) agreed that there is value in bringing our theories to the level of conscious control. Getting ideas out in some externalized form helps commit students to certain ideas. This nurtures an integrated theory that can then be tested, challenged and revised.

Model construction and conceptual change work together. The model externalizes the ebbs and flows of a system providing a basis for qualitative understanding. It is this qualitative understanding that will help students solve new problems (Niedderer, Schecker and Bethge, 1991). This is opposed to traditional forms of instruction that focus on textbook problem-solving and quantitative reasoning. The qualitative approach is important since experts have been observed performing qualitative analysis before they engage in quantitative analysis (Chi, Glaser, and Rees, 1981). Niedderer, Schecker, and Bethge (1991) characterize students' representations as having a chasm that separates rules that are memorized from concepts that are understood:

> This explains why formal quantitative knowledge acquired in science instruction, e.g. the proportional relationship between force and acceleration, does hardly affect the conceptual level. Unless the conceptual differences between students' mental models and the scientific views are made explicit and are recognized by the students, rules and equations form a distinct layer of examination knowledge. (p. 86)

They go on to suggest that STELLA's iconic portrayal promotes a qualitative understanding. For example they list the following equation:

v(d) = SQRT{2/0.09*[(Fsp-Ffr)*d-c/2*d2]}

The STELLA equivalent is illustrated in Figure 3.4, below:

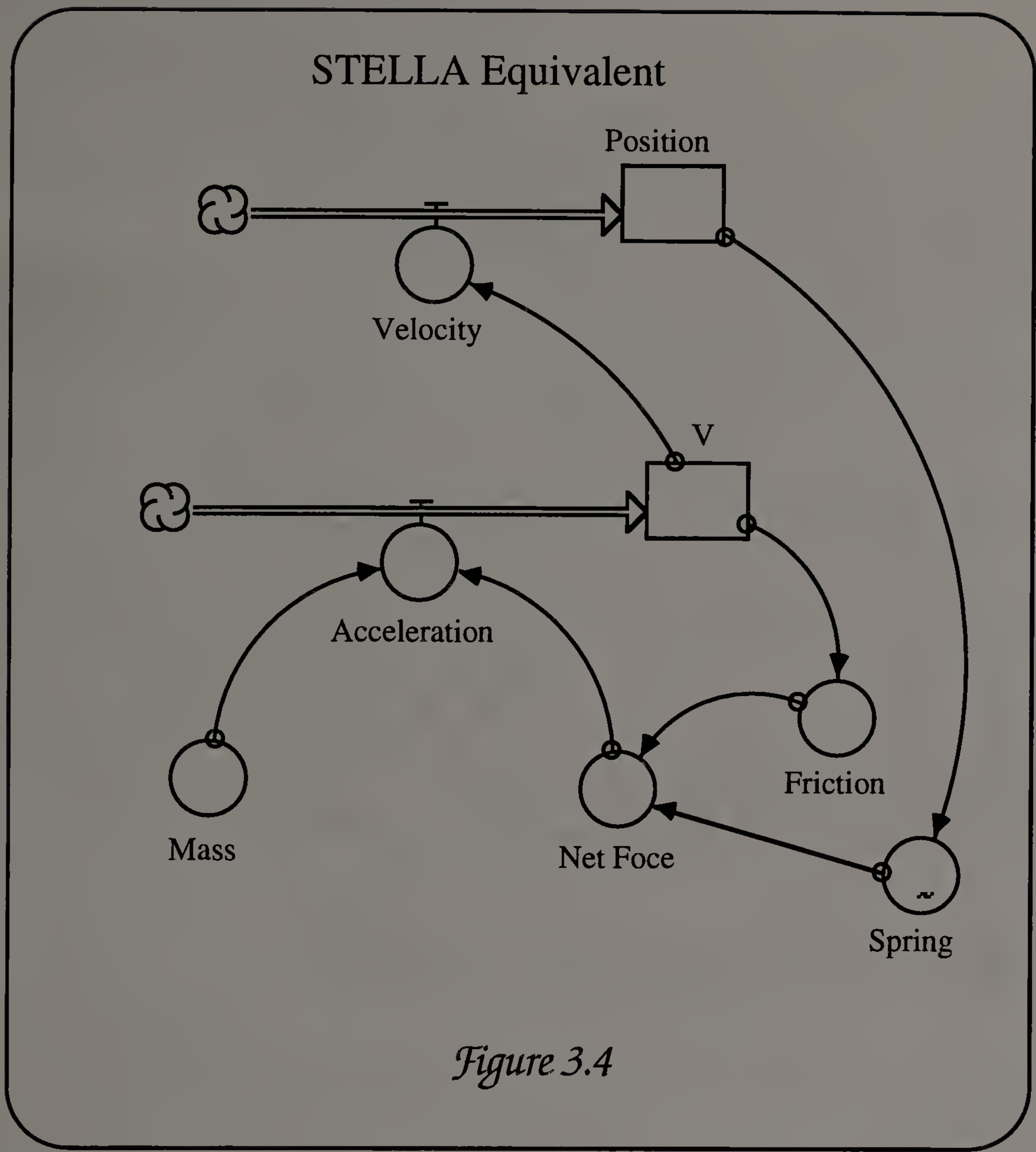


Figure 3.4 STELLA Equivalent

There are numerous differences between the two forms of depiction. One is that the STELLA model is two-dimensional emphasizing relationships rather than exact computation. Another difference is that the STELLA's graphic icons highlight rate and accumulation rather than the operations that will be performed on variables as depicted by the notation of mathematical equations. It is possible to illustrate a STELLA model on paper or on the chalk board of a classroom but that model is not active. On a computer creating linking arrows to the various variables automatically generates equations behind the scenes. These equations form part of the differential equations that STELLA uses to produce real-time results, making the computer version active.

There is a critical difference between memorizing equations and constructing qualitative STELLA models. The memorization of equations is a task that students are often engaged in without qualitative understanding. Another difficulty is that often not enough information is available to form precise quantitative models. The semi-quantitative nature of simulation construction kits like STELLA facilitate the construction of qualitative relationships in the absence of known quantitative relationships. Randers (1976) advised that modeling should not be used for quantitatively forecasting but for increasing qualitative understanding by testing consequences of different options. In the scientific community the legitimacy of computer models for forecasting future events is hotly debated but the issue for this discussion is the implications for learning.

From an instructional perspective researchers recognize the potential value of computer models for constructing increasingly more involved models. Kozma (1991) advocated a pedagogical model that incorporates the development of progressively complex model construction. One potential benefit of building a simulation is that each step can have a physical component (Ogborn, 1990). Understanding can be increased incrementally and is reflected in model construction by gradually building up previous models (Duchastel, 1991). In this way the STELLA model reflects students knowledge.

Perhaps graphic forms could be thought of as extending experiences. Portrayal tools have the ability to bring together actions and consequences so that a student can view a sequence of temporal events at one glance (graph). In this way students gain a holistic sense of the content that might not be available through normal experience (Olson and Bruner, 1974). Dede (1987) surmised that some kinds of portrayal tools can provide surrogate experience (microworlds). We know that important learning comes through experience. With STELLA, students can create models of their own thinking. This constructivist approach has significant implications. It might make students more motivated. When we discover something, it becomes our own. Through self-constructed STELLA portrayals, students can confront their own conceptions. In discussing the implications of modeling tools, Forrester (1968) suggested that:

> The representation need not be defended as perfect, but only that it clarifies thought, captures and records what we do know, and allows us to see the consequences of our assumptions, whether those assumptions be perceived as right or wrong. (pp. 3-5).

STELLA is an example of a portrayal tool that extends experience by encouraging experiential learning and discovery through interaction and virtual viewing of system behavior.

3.1.2.13 Theory from Pieces

As mentioned in Chapter 1, diSessa (1988) postulated that students should be encouraged to integrate fragmented ideas. The utilization of different symbol systems may reconcile knowledge previously existing as unconnected pieces (Kozma, 1991). STELLA might bring together disparate ideas into an integrated whole. It could act as a platform for presenting discrete ideas concurrently, making it easier to seek relationships between them.

Developing graphical models and making explicit relationships could stimulate construction of coherent theories. The reason STELLA might work in this manner is that incoherent ideas operationalized in STELLA generate output inconsistent with expectations. The resulting conflict stimulates a reassessment of external portrayal and internal representations.

3.1.2.15 Freeing Cognitive Energies

Constructing STELLA models may yield a deeper understanding of knowledge structures. This may happen by making knowledge structures available for inspection in an external medium which frees up cognitive energies. Cognitive energy is presumed to activate a limited number of knowledge structures. The thinking is that energy devoted to one kind of thinking may reduce the amount of energy available to perform other tasks. Working memory is limited, and the amount of cognitive energy is finite (Glass and Holyoak, 1984). It has been demonstrated that people have difficulty evaluating four or more variables simultaneously (Hayes, 1989). A person can create new connections quickly with mental imagery, but images have to be continually refreshed to be maintained. In addition, as image complexity increases, the difficulty in maintaining the image increases. External forms of depiction provide an almost unlimited source of virtual memory (Brueker, 1984). Portrayal tools have been suggested as diverting cognitive energy to higher processing (Goetz, 1984). Hayes (1989) noted that external portrayals can reduce the load on working memory and reveal new relationships. Hawkins, Mawby, and Ghitman (1987) proposed that a good notation system should free us to concentrate on higher order skills or more advanced problems. Friedoff and Benzon (1988) suggested:

> When we visualize through the use of external means such as computers, we restructure a problem so that more of it is processed by the preconscious part of our brain - the visual system that is our silent partner. In this way, consciousness can be devoted to the highest levels of analysis (p. 13).

Complex situations might involve so many factors that they can't be maintained in working memory (Meadows and Robinson, 1985). External depictions may relieve this problem by becoming an extension of working memory. Liberated cognitive energies can be diverted to metacognitive processes which monitor actions, consciously orchestrate processing, and challenge ideas. These kinds of processes are vital for stimulating shifts in thinking. This is a primary reason why portrayal tools are valuable. Assuming that metaknowledge is built into mental schemas, then when these schemas are being called upon during problem solving, the time is perfect for modifying and updating them (Weir, 1987). In this way STELLA's graphical portrayal may be a way to stimulate cognitive change.

3.1.2.16 Source of Reflection

Logo represents a computer tool that has had considerable attention given to it, particularly its metacognitive value (Clements, 1986; Burnett, 1986; Emihovah & Miller, 1986; Weir, 1987). Logo has similarities with STELLA, so thinking about Logo may have implications for STELLA. Psotka (1985) wrote an opinion paper on metacognition and Logo. He suggested that students are theory-builders by use of imagination and new rules. Since the act of debugging and self-reflection are closely associated, using a programming language such as Logo can encourage both debugging and reflection in the same context. Logo's graphics help bridge between the symbol system of the computer and mental representation. Communicating with the computer is viewed as an outward expression of how communication takes place with ourselves. Finally, procedural knowledge and declarative knowledge seem to be mirrored in the debugging process, either as we modify data or procedures. These insights concerning Logo are equally applicable to STELLA.

STELLA involves describing, building, modifying, or otherwise using models. This kind of explicitness provides a means of reflecting on thinking processes. To an extent the STELLA model becomes a mirror, reflecting mental representations of the content and cognitive processes. Sheingold (1987) mentioned that computer portrayal tools acts as a mirror, reflecting back on cognition. Levie (1987) concurred that portrayals can reflect back on mental representations and cause changes. Mason (1992) indicated that conceptual maps can act as metacognitive tools to stimulate reflection on learning. Novak (1984) pointed out that tools like concept mapping may be a way of seeing knowledge structures. Brueker (1984) agreed that graphic tools provide a unique tool for exposing the structure of knowledge. Being able to see the nature of knowledge may be the first step in understanding how to approach learning. In particular, externalized portrayals may stimulate students to understand that the concepts they have affect how they perceive the world. Portrayal tools enable the visualization of structured knowledge and can aid in reflecting on its meaning.

Goodyear et al. (1991) indicated that discovery learning environments have the potential for realizing metacognitive skills. These skills are fostered through an environment that reacts to student actions by selecting, testing, analyzing, and modifying approaches based on feedback. In addition, a tool that can generate quick translations between symbol systems enriches a student's metacognitive awareness (Salomon, 1985). This awareness is fostered through transformational possibilities that juxtapose different depictions of the same phenomenon.

STELLA causes a pause that stimulates challenges and can become a platform for rethinking ideas. Forman (1987) suggested that a good educational tool encourages the user to pause for reflection. Rubinstein (1986) suggested that portrayal tools slow learners down from moving too quickly into solutions before they have adequately represented the problem. Slowing down and being more deliberate about specifying factors of influence in a system help to combine new ideas or pull old ones apart. Driver (1986) pointed out that altering preconceptions takes time -- time to think, time to challenge, time to question, and time to discuss. The methodical approach encouraged by portrayal tools stimulate individuals to slow down and consider a problem much more closely. This promotes reflective thought. STELLA lends itself to this kind of deep analysis. Specifying relationships and mechanisms is STELLA's way of encouraging users to pause for reflection. There may be times when slowing the learner down is not a profitable activity but generally speaking this kind of thought-intensive activity is ignored in traditional schooling. Many educational systems place a high degree of value in accomplishing tasks in reduced time. The philosophy is: the more that can be accomplished in the shorter time, the better even if that means only a superficial level of understanding. This approach may have its redeeming outcomes through mastery of a variety of factual information and this kind of knowledge may be required to move to a higher level of exploration. However, personal observation of activities in the classroom suggest that in many situations students infrequently have the opportunity to move beyond a superficial level of exploration to a more intensive study that lends itself to rigorous thinking and to deep understanding.

Hewson and Thorely (1989) pointed to the importance of students seeing their own processes of conceptual changes. Graphical portrayal tools could provide the means for doing this (Goetz, 1984). Lawson (1989) advanced the idea that many times shifts in thinking are not only made obscure to the researcher, but often to the student as well. These shifts are often embedded in tacit processes. Portrayal tools could make these changes more explicit, allowing students to gain metacognitive insight into their thinking processes.

3.1.2.17 Explicitness

Hanneman (1988) suggested that tools like STELLA comprise a formal language for expressing theories. Such a language has its own syntax and vocabulary (see chapter 2). Hanneman postulated that it is the ability to be precise and specify relations that make these kinds of tools useful. It is the specificity and precision that enables the construction of a model which produces certain behavior. A tightly structured system makes it easier to state ideas explicitly; it does not admit ambiguous rules. Kahn (1985) agreed that to understand the world, knowledge structures need to be made explicit. However there are tradeoffs using a formal language like STELLA, it may not be rich enough nor flexible enough to capture every aspect of the scenarios to be modeled.

The work on social cognition also points to the value of explicitness. Glaser (1991) suggested that the role of social cognition should be a means of making student thinking explicit: “Thus, school instruction might well consider how teaching practice can make apparent the forms of students' thinking, in ways that can be observed, transmitted, discussed, reflected upon, and moved toward more competent performance and dispositions for reasoning." (p.135) If this is the role of social cognition, other instructional devices such as STELLA can be beneficial by playing a similar role.

STELLA requires the user to be explicit in the way information is represented by specifying the limits, conditions, and relationships between variables over time. This portrayal tool encourages a rigorous investigation of a problem. Rigorous investigation can be accomplished by making ideas explicit and by designing mechanisms for those ideas (Forman, 1987, Olson, 1985). The rigor helps focus thinking and identify relationships that are based on imprecise assumptions (Meadows and Robinson, 1985). STELLA is an environment which fosters this. STELLA models must be organized, precise, and internally consistent. Natural language can be an ambiguous way of describing knowledge (Holley and Dransereau, 1984). Holley and Dransereau (1984) argue that spatial tools can make relationships unambiguous. STELLA makes relationships unambiguous by encouraging the user to specify relationships (both graphically and algebraically). Commitment to a form of portrayal is important. This keeps the modeler honest because specifying mechanisms commits the person to an idea. Choosing STELLA as the tool for portrayal helps students to commit to a form of depiction. Of course there is the negative side of commitment that is discussed under the topic of prediction (section 3.1.3.9).

Portrayal tools make students' thinking explicit in ways that allow for monitoring both by students and researchers or instructors (Narode, et al., 1987). An externalized portrayal of student preconceptions provide the teacher with valuable assessment information. Alesandrini (1987) reported that these abstract tools are useful for revealing to teachers student preconceptions. Munby (1991) demonstrated how a graphical display such as a concept map can be used to diagnose student conceptions of chemistry. Novak (1984) likewise documented how he utilized concept mapping to analyze conceptual change. For example, students' graphic forms that lack important components in their maps cue the instructor about students' understanding and suggest possible instructional strategies. Barlex and Carre (1985) theorized:

> "There is a need to look behind students' words and drawings if we want to understand how they have tried to shape some personal meaning. It is important to do this because children come to school already in possession of important ideas about science." (p. 47)

There is a gulf between instructors' representations of students' cognition and students' representations. Instructors and researchers are viewing a translated image of what is going on inside the mind as students render their mental constructs with portrayal tools. Externalized conceptions provide a basis for making inferences about student thinking.

3.1.2.18 <u>Question Generation</u>

Explicitness serves as a framework for asking questions. Questions often follow from being precise about how relationships exist. This explicitness makes ideas accessible to criticism much more than mental models (Meadows & Robinson, 1985). In STELLA user-defined mechanisms make it possible to study instructions which are executable and viewable in real time. If an assumption is missing, is not made explicit, or is logically inaccurate then it usually becomes apparent in feedback to the user. In STELLA this comes in the form of error messages, graphs, tables, or animated diagrams. The process of analyzing data results in hypothesis testing which involves asking questions of the system. Reimann (1991) proposed that appropriate tools (simulations) also encourage inductive approaches. STELLA is a tool that encourages the generation of questions that foster both deductive and inductive learning. For instance, deductive learning might be supported when the model's output reinforces students externalized theories. Inductive processes might dominate when output is recognized as being contradictory to held views.

3.1.2.19 Semi-Concrete Depictions

The STELLA elements themselves may hold additional cognitive benefits. The boxes, circles, and arrows provide a "semi-concrete" way of depicting the abstract and making the abstract manipulative. Concrete objects are those that do not portray something else and have a one-to-one correspondence between manipulations of the object and sensory feedback. Whereas an abstract symbol has little resemblance to its referent and manipulations of the symbol may only represent one aspect of the referent. There seems to be continuum from concrete to highly abstract. Semi-concrete is the term used here to describe the nature of the STELLA depictions because it is concrete in the sense that the learner can manipulate the graphical depictions (icons and arrows) yet they depict abstract ideas (like death rate, population, or concentration, etc.). Ideas that were formerly just abstract like death rate are now rendered with symbols (circles, boxes, and flows) that can be rearranged in a visual medium adding a sense of concreteness.

Novak (1984) suggested that through the use of graphic tools (conceptual maps) learners can visualize concepts, their relationships with other concepts, and their hierarchical associations. Narode (1987) indicated that graphical depictions make abstract ideas more concrete. Many of the ideas that are portrayed with graphic forms are abstract and don't have equivalent pictorial images. Kozma (1991) indicated that computers:

> ...can graphically represent not only concrete objects but also formal, abstract entities, entities that novices do not normally include in their models. (p. 197) ...with computer models, arrows and other symbols can behave in ways that are like the behavior of forces, velocities, and other abstract concepts... Furthermore, learners can manipulate abstract symbols and observe the consequences, successful or otherwise, of their decisions. (p. 198)

Abstract problems that have visual analogs via portrayal tools, might be better solved using imagery (Pinker, 1985). This is possible because learners create cognitive linkages between an abstract concept and a symbolic code in the medium. This makes it available to a host of processes otherwise not available. For instance variables represented by symbolic codes in the medium can be relocated, linked to different variables, animated, and graphed. These possibilities may not have been considered had the abstract concept strictly been available for mental transformations.

3.1.2.21 Social Cognition

Benefits also come through sharing graphic depictions with others. Vygotsky (1962), Rogoff (1990), and others theorized that learning comes through social and language interactions. Graphic organizers can act as a bridge between what we know and what we want to communicate (Pehrsson and Denner, 1989). Some depictions do not lend themselves to self explanation. This in fact may serve a useful function by encouraging students to communicate knowledge. Pehrsson and Denner (1989) suggested that through metacognitive processes, learning can take place by watching others. Social interaction is not only a source of reproductive action, it can be the source of creative insights (Rogoff, 1990). As graphical portrayals are shared with others, new relationships or concepts are fleshed out that were not considered through individual inquiry. Sharing of portrayals give students a chance to see problems solved from a number of different perspectives (Stevens and Collins, 1980). Friedoff and Benzon (1988) pointed to the potential influence on social cognition:

> The computer makes it possible for groups of individuals, even if they are separated by great distance, to collaborate in visual exploration whether in the artistic, design, or scientific spheres. The computer democratizes visual thinking (p. 16).

Burnett (1986) identified the importance of sharing on metacognition. He spoke in reference to Logo, that students should be free and encouraged to share their results or problems with others. This sharing takes metacognition a step further than just translating ideas into models. Sharing, stimulates students to translate their models into verbalized communication. Since students in this study, share common ground, STELLA building blocks, there is a mutual language that will be understood.

Normally portrayal tools are thought to be geared for individual use. As identified above, there are benefits that will be gleaned from communicating portrayals to others. Niedderer, Schecker and Bethge (1991) indicated that STELLA models have implications for the negotiation of models through social construction. Portrayal tools such as STELLA facilitate the sharing of conceptions in a concise yet informative way.

Social cognition and emotions have been suggested to be inextricably linked to one another (Ratner and Stettner, 1991). Thus the social context influences the affective domain that in turn has implications for cognitive change.

3.1.2.24 Problem-Solving Devices

A problem can be defined as the gap between current understanding and a goal state. STELLA, therefore, has a built-in problem. This problem is characterized by the gap between students' representations and externalized portrayals. Reconciling these differences into a coherent theory is the goal state.

It has been demonstrated by numerous researchers that the initial representation of a problem is important in finding a solution (Greeno, 1986; Luchins, 1942). Preparation for finding solutions constitutes understanding the problem which involves weeding out irrelevant facts from the relevant information. Portrayal tools can have a role to play by facilitating a useful representation of the problem.

Production of possible solutions is one avenue that might prove useful for portrayal tools. In many problems there will be multiple correct solution paths. Portrayal tools can help by displaying pathways and connections. These tools supply the user with alternatives because of the way information is depicted. In addition, the translation of ideas into portrayals, like STELLA elements, breaks down knowledge into its constituent parts which is a fundamental aspect of problem-solving (Hayes, 1989).

3.1.3 Potential Problems

Utilizing computer tools like STELLA precipitates problems which require consideration. The following sections list and describe learning barriers that students might encounter.

3.1.3.1 Complexity

Computer modelers, Meadows and Robinson (1985), spoke of the problem of others interpreting their simulations:

> The models typically hide extremely simple theories under heaps of numerical gadgetry. Their methodological paradigms constrain creativity and limit comprehensiveness as often as they lead to insight (p. 370).

Others have also encountered the problems inherent in complex simulations. Another modeler, Hanneman (1988) explained:

> ...mathematical formulations of complex problems often exceed the capacities of their creators and consumers to understand and explicate them. ...complex coupling among even a small number of variables can rapidly exceed our capacity to solve such systems or comprehend the meaning of the solution if one is found. (p.25)

These are harsh words to come from individuals who are themselves modelers. Modelers must be able to work around these problems or else they would cease to consider modeling useful. The negative attributes of modeling are also potential sources of insight and understanding such as creating mechanisms, imposing the bias of a tool, and making explicit personal theories, etc. This study does not explore the value of interpreting constructed models by an audience, rather the benefits to the modeler's cognition.

Although STELLA can communicate in a simplified manner and depict an entire system in one image, the possibility of excessive information exists. Students might fail to create reasonable boundaries for their models and consequently depict too much. Consequently, models can become encumbered with extraneous information clogging cognitive processes.

Limiting boundaries to maintain simplicity is a solution to overly complex models, but Wilson (1992) argued that reducing the complexity of the simulation eliminates the very purpose of studying with a model. Wilson contended that the computer's power resides in its ability to translate complexity into an easily understood graphic image. This may be true, yet to understand the abstract graphic form, mapping has to occur back to the complexity of the content. The degree of complexity required for insight is a tradeoff with the simplification required for understanding. The previous discussion is an issue of richness versus parsimony. Lambiotte et al. (1989) concurred that there is a tradeoff between the information presented and the amount that can be processed while retaining a gestalt sense of what the portrayal communicates.

The latitude inherent in most simulations can potentially lead to trouble. One observation is that students can exhibit unsystematic modes while interacting with simulations (van Berkum, and de Jong, 1991). To counter this, researchers note the need for social scaffolding when learners interact with complex simulations (Duchastel, 1991).

Goodyear et al. (1991) concluded that simulations are generally too complex but can be improved by supportive environments. Effective instructors can have a tremendous impact on learning by creating models of students' cognitive attributes. Personal observation suggests teacher interns who are effective provide opportunities for students to express themselves. This is used by the interns to form models of student cognition. This knowledge informs effective instruction when students have insufficient resources to surmount a learning obstacle on their own (Hawkins, 1974). In order to make informed intervention the instructor must have a theory of how transformations of student knowledge takes place. This model may be implicit or explicit, but nonetheless it guides interaction with the student. Work from Intelligent Tutoring Systems (ITS) supports this contention. ITS are based on the assumption that it is possible to computationally translate ideas concerning cognition functions into a system that provides instructional interventions. For instance, Brown and Burton (1978) developed BUGGY, a computer program that diagnoses student difficulties by developing models of student misconceptions in basic mathematics.

Another problem is that learner control can lead learners into cul de sacs of learning. A learning cul de sac fails to bring the learner closer to scientifically acceptable conceptions. Not that all cul de sacs should be viewed pejoratively, some involve more interesting learning terrain than others. Considering time constraints, an informed instructor can ward off an inefficient trip down a dead end by challenging students or suggesting a more profitable avenue of exploration.

3.1.3.2 Reconstruction of Memory

Another argument against simulation construction is that models are not sources of new knowledge but only provide platforms for the reconstruction of memory (Meadows and Robinson, 1985). Hayes (1989) identified this same obstacle:

> "There is still another objection sometimes raised against computational science: that we cannot learn anything fundamentally new from a simulation. The argument runs as follows: all a computer can do is reshuffle its inputs in various ways and eventually return some permutation of them; thus whatever answer comes back from the computer must have been imminent in the data to begin with" (p. 87).

The counter argument is that if the results of a complex system are so obvious, it would not be necessary for scientists to conduct experiments. The results would be self-evident in the setup of the experiment. Ignoring confirmation studies, the results of many experiments are not known a priori because of the complexity of systems. The reconstruction process through the lens of a system dynamics paradigm (e.g. STELLA) may lead to new outlooks or new insights. Wilson (1992) stated: "Because simulations, if programmed correctly, are not trapped by preconceived notions of what is expected, they can generate unexpected results." (p. A23) In a sense modeling is constrained by internal representations; model construction can only flow from a mental model. However simulating the model might produce results that are incongruent with internal representations. These conflicts that lead to cognitive dissonance represent a powerful learning attribute of the modeling process.

3.1.3.3 Models as Reality

Another difficulty is perceiving simulations as isomorphic with the content. Olson (1988) pointed out that students' lack of distinction between reality and the computer depiction is a source of problems. Taking models too literally makes it difficult to differentiate between the models and representations of reality (Ost, 1987). Models by their very nature are not isomorphic with the content but simplifications. Furthermore, a simulation may produce output that is at odds with mental representations.

Models are designed to focus on certain dimensions of information. The process of constructing portrayals is a selective process: not everything from representations gets portrayed. Portrayal tools may have a role to play here as well. Through making models of the world explicit instructors can help learners juxtapose the portrayal with the content. This in turn helps learners understand that models are constrained views of the content, and are not the content per se.

There are three typified views of mapping between representations of the content and model as illustrated in Figure 3.5. Illustration I depicts a mapping between the model and the content. The model and the content are viewed as separate entities but the mapping identifies those aspects of the representations that are semantically analogical. This is a healthy relationship for modeling because a student can ask questions about the model that can then be asked about the content. The content and model are not seen as isomorphic. Illustration II depicts no mapping at all because the model and content are misunderstood as being isomorphic. In this view the student thinks what happens to the model occurs in the real world. This is inappropriate because students cannot differentiate between the model and reality; when the model runs amok, reality must be amok too. Illustration III depicts no correspondence at all between the content and model. This results in manipulation of the model without any regard for linkages with the content; running a simulation for its own sake without contemplating applications to the real world. diSessa (1988) warned that tools used out of context fail to demonstrate the power of the tool. He noted that this problem is often encountered in math when teaching and learning focus on the tool rather than on applications. For instance, many instructional practices are geared to teach mathematical algorithms without any experience with how these algorithms solve everyday significant problems. Studies support this contention from the physics domain (diSessa, 1988). In the case of simulation construction kits, this would be evident by using the program merely for its own sake without emphasizing linkages to a content domain. Although decontextualization is not a criticism of the tool per se, it is a problem in utilization. Students may also exhibit a mosaic of previous views or switch back and forth between different views, depending on the context.

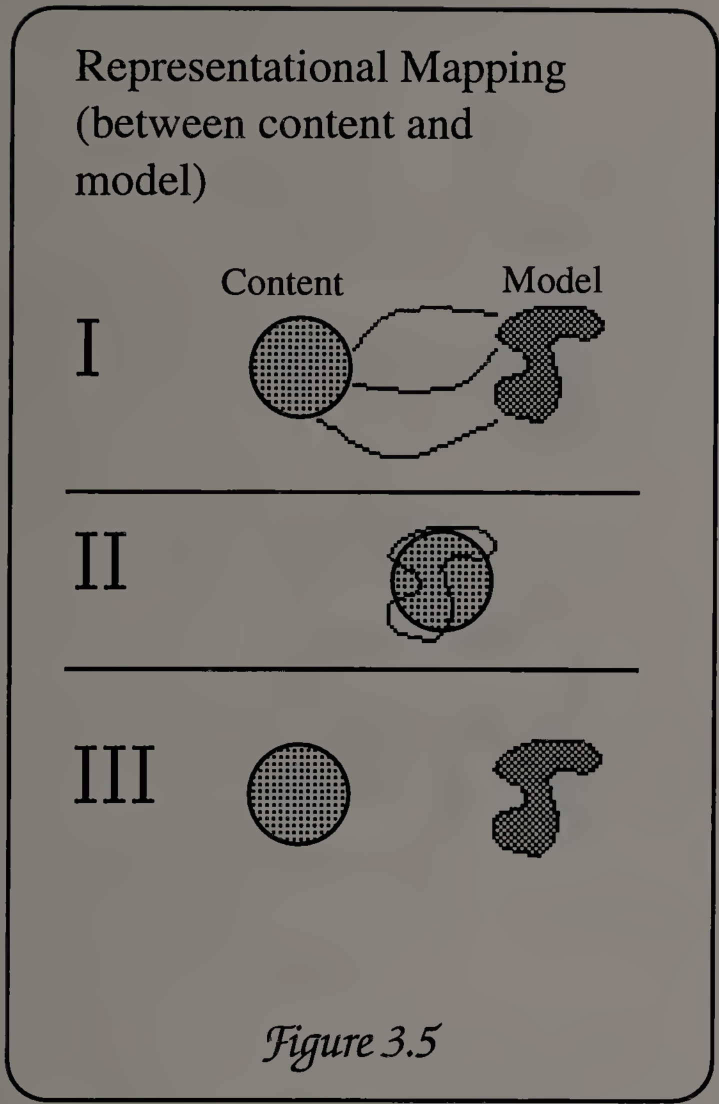


Figure 3.5 Representational Mapping

Kozma (1991) noted that an important part of learning involves understanding the relationship between symbol systems and the real world. Students can learn how a symbol systems works in a microworld but that knowledge may not transfer to the real world. Research such as that done by Brasell (1987) provided evidence of this problem. The researcher found that if there was a real-time correspondence between the production of a graph and the movement of an actual object, then understanding of the meaning of the graph increased drastically. It is difficult to manipulate an abstracted depiction of knowledge without being able to reconstruct a representation from experience.

Knowing how to judge the proximity between internal representations and external depiction is a valuable skill. Pehrsson and Denner (1989) urged that the role of educators should change from that of the imparter of knowledge to a facilitator, helping learners understand how to judge the "goodness of fit". They described it as "proximity", which is achieved by having students view a model mapped to content as depicted in Illustration I. STELLA might enhance this skill by providing an environment that is executable, juxtaposing simulation output with expectations of the content.

Pehrsson and Denner (1989) indicated that in order for graphic processing to be a tool in the learner's repertoire, it needs to be a part of meaningful learning. Meaningful learning suggests learning in a context. A skill taught in isolation remains in isolation. Studies into workshop effectiveness or staff development bear this out (Freer, 1987; Snyder and Anderson, 1968). The implications are that STELLA thinking needs to be integrated into a variety of contexts and given important problems to portray.

3.1.3.4 Cognitive Resistance to Change

Many of the potential benefits described previously make the assumption that students will be able to make appropriate interpretations of the outcomes of a simulation. One of the stumbling blocks facing students is the inability to recognize a problem. Without recognition of a problem with mental models there is little chance for cognitive dissonance and, hence, cognitive restructuring is not likely to happen. This has been a well-documented attribute of student thinking where the goal has been to overcome misconceptions (Driver, 1986, 1989; Karmiloff-Smith, 1988; White and Gunstone, 1989). Alternate frameworks are notoriously resilient to change and often the relevance of a discrepant event is ignored (Driver, 1989; Goodyear et l., 1991; Nussbaum, 1989). On the other hand, portrayal tools such as STELLA may confront current theories with strong counter evidence because multiple forms of portrayals underscore different dimensions of information. For instance, if a graph does not challenge a student's current thinking, then an animated diagram or table might.

3.1.3.5 Inability to See Benefits

Failure to "see" the benefits of graphical forms may be a reason why visual arguments are not more appealing, and why the research results aren't more convincing. Not knowing what to look for may result in cognitive blindness. There is no guarantee that the instructional goals and the goals of the learner will be one and the same (as in the instrumentalist approach). If students are not adequately provided with guidance and models of depiction, then the effort of construction may have little impact. Without a vision of what the tool can do, the benefits might go unrealized.

3.1.3.6 Time Expended versus Benefits

Time has repeatedly been cited as a potential problem with use of graphic forms. Both learning and using these tools are time-consuming. Not all knowledge is gained equally fast. Perhaps there are levels of knowledge, some kinds of knowledge are acquired easily while other knowledge takes more time and energy. Rather than posing a question regarding time expended, a more productive question can be framed addressing the conditions under which the tool will be worthwhile.

3.1.3.7 Hidden Information

Larkin (1989) noted another kind of problem. Display-based systems highlight certain kinds of information and hide other kinds of information. Errors could be generated because the display hides the state of the information that is crucial for coming to an informed decision. For instance, in STELLA a graph may not make discrete values salient. To complicate the problem, within STELLA, confrontational portrayals are not intuitive to a neophyte; only subtle cues suggest which form of portrayal will challenge thinking. That metaknowledge is constructed through experience with the tool. Novice users struggle, but a skilled instructor can make informed interventions so that students' thinking does not go unchallenged.

3.1.3.8 Lack of Knowledge

There are four kinds of knowledge students might lack that impede learning in STELLA. First, is a lack of interpretation knowledge. This may lead to an ineptitude for decoding vital information (Larkin, 1989); for instance, graph misinterpretations. Second, may be inadequate experiences with the domain knowledge. Without experiences and knowledge of the content, mapping to abstract symbols will be difficult, if not impossible. Third, deficit knowledge may be metacognitive. Goodyear et al. (1991) indicated that although exploratory environments have the potential for fostering metacognitive skills, some students may lack the organizational skills to see these benefits. Fourth, an additional knowledge deficit is not understanding the tool, disabling students from effectively translating representations into portrayals. Hanneman (1988) noted that the meaning of systems such as STELLA are embedded in the conventions of the program. To understand the workings of the model one must also understand the conventions used to define the model.

3.1.3.9 Prediction

Embodied in the development of STELLA models is the role of prediction. There are some concerns about having students make predictions. One view is that a student may be unwilling to relinquish his/her view because it is embedded in self-constructed knowledge structures. This is not without support from research (Nemirovsky and Rubin, 1991). Iran-Nejad (1990) likewise identified this hindrance:

> Ongoing schemata are inordinately stable. ...Prediction based processes are locked inside the ongoing schema and are driven by its stability. They assimilate facts that could otherwise be considered as contradictory. They, therefore, make the construction of a new schema less, rather than more, likely. (p.585)

However, this does not exclude contradictory information from being recognized. Not all schemas are stable; some may be transitory.

Prediction is a given with model construction. It is hard to conceive that students would not develop beliefs about a model's behavior through the model construction process. Further, it is thought that asking students to make predictions will stimulate the formation of theories. Theory production has been shown to be useful for learning and outweighs the hardship of relinquishing conceptions later. For instance, Karmiloff-Smith and Inhelder (1975) reported that children need a theory to be able to recognize counter examples. They concede that children tend to retain their initial theory as long as it is seen as viable. However, they also say that "it seems possible for the child to experience surprise and to question his (theory) only if the prediction he makes emanates from an already powerful theory expressed in action" (p. 209). Having some sort of theory is usually better than not having one at all. Abandoning established theories (unlearning) is a fundamental part of learning. While students have good reasons for hanging on to their theories, seeing the limitations and problems with the current theory and embracing new ideas is fundamental to progress.

Prediction is an important aspect of forming inferences about scientific discoveries (Reimann, 1991). Making predictions has important implications for becoming mindful of the internal structure of the system. If a student is asked to make a prediction, some thought is put into formulating a line of reasoning that brings together disparate thoughts, exposing the cognitive model. Consider for a moment the consequence of not making a prediction. Students would not have an opportunity to express their thinking that might cloak alternative perspectives. Without prediction there may be some inclination for students to just go along with the output of the model and form their theory purely on the output of the model as opposed to the structure of the model, or to continue to patch it without really debugging. Glaser (1991) noted that better learners are those that anticipate the consequences of an action. Speaking specifically of computer simulations Olson (1988) observed that students need opportunities to identify patterns and this can be accomplished by predicting the result of an experimentation. He finds that the younger students (grade 4) make predictions by guessing, but the older students use knowledge about emerging patterns to guide their predictions.

3.1.3.10 Problem Disclaimer

Regardless of encountering problems, tools such as STELLA can be potentially useful for restructuring cognition. Inevitably the previously listed problems will be encountered in the course of model-building. These problems exist and cannot be rationalized entirely away. Implementation will determine to what extent these problems detract from the learning experience. The benefits of STELLA will be a function of how it is implemented. Sheingold (1987) noted that technology does not stand on its own; it needs to be thoughtfully integrated into learning environments. This reality is described in a vivid way by Piller (1992) who divulged the stark reality that exists in selected educational environments that were visited and described. There is gross disparity between educational settings. At one end of the spectrum teachers share a higher vision of learning that involves innovative and exciting ways to teach. In this environment, technology is viewed as a useful tool for accomplishing intriguing activities. At the other end of the spectrum learning is viewed as mastery of skills. This pedagogy rarely goes beyond memorization of facts. In this environment technology is limited to drill and practice and stifles the very aspects of learning that technology should foster.

As Goodyear et al. (1991) pointed out, a unified theory to explain learning with simulations does not exist. Such a theory would inform instruction and would enrich the vision of learning with portrayal tools. This review of the theoretical underpinnings of learning moves towards a more coherent theory. The following review of related research will also add to an understanding of this environment and its influence on cognition.

3.2 Related Research

Although an extensive body of research done with simulation construction software, let alone STELLA, does not exist, any study into learning has potential implications for this study since this study focuses on changes to cognition. What follows is a survey of selected domains that are relevant to understanding a STELLA environment. Relevancy is achieved by identifying research studies that share similar characteristics of the STELLA environment. Sources of investigation include work on development, way-finding, conceptual maps, metacognition, microworlds, problem-solving, spatial skills, spatial aptitude, tool interaction, simulations, and simulation construction.

3.2.1 Developmentally Appropriate Symbols

Children working at Piaget's concrete operational level can manipulate and understand portrayal tools. Novak (1989) reported that students in the seventh and eighth grade were adept at learning concept maps. Through subjective observations, students at this level picked up on the technique of concept mapping better than college level students. Alarez and Risco (Novak, 1989) reported using concept mapping successfully at the primary grades. Young children even at the primary grade levels can understand and benefit from the use of portrayal tools. However, STELLA construction combines other abstract notions that make it a more demanding environment. For instance, a student not only is required to construct a schematic diagram of the model but to define the relations with algebraic expressions and interpret portrayals. It is not unreasonable to consider the use of this tool at the elementary level if an instructor can provide considerable scaffolding.

3.2.3 Comprehension Effects

Some studies indicate graphic forms enhance comprehension effects (Heimlich and Pittelman, 1986). These studies suggest that semantic maps are useful in eliciting better comprehension by bridging the gap between prior knowledge and new information. Alesandrini (Winn, 1987) reported that by having students draw diagrams they perform better in science understanding. Lambiotte et al.(1989) reported a meta-analysis of 23 studies of graphic organizers on postreading comprehension. The results ranged from moderate to negligible. They rationalized the relatively weak evidence by suggesting that in many studies the linkages are not labeled, resulting in ambiguous meaning. In other textual comprehension studies Holley and Dransereau (1984) found that efficiency with the tool increased with use and that the experimental group was no better at recall of detail than the control, but had better comprehension of the main ideas.

Novak (1984) cited research study done by Kingstein in 1981 that found improved student understanding of ecological concepts through the use of concept maps. A study reported by Winn (1987) found that when one group of students was asked to construct a map of a text and the other group was not, the map-makers did significantly better on comprehension tests. Winn revealed that "the act of constructing a graphic is what is important for improving comprehension, not simply the presence of the graphic" (p. 190).

A detailed account of one study illustrates how many of these studies are conducted and will establish a basis for addressing concerns: Lehman, Carter, and Kahle (1985) did a study involving two instructional treatments: one used concept mapping and vee diagramming and the other, a written outline approach. The study involved 250 subjects from 2 high schools. The researchers used achievement tests designed to measure higher order learning (designed by experts). They found no significant differences, even though the pilot study did show significant results. The description of the study leads to speculation that the researchers were involved in the instructional aspects of the pilot study and then turned the instructional aspects over to regular teachers in the main study. If this was the case, perhaps the failure to produce significant results did not lie in the tools as much as in the teachers, their beliefs and instructional methods. No mention was made of teacher training or encouraging teachers to model good mapping techniques. One concern with the research as reported was the topic of implementation, which was not discussed. It is important to know how a particular tool is used because this influences student use and perception of the tool. The researchers noted that the two groups covered the same material over the course of a semester. Another concern is in regards to the amount of learning time given to introduce and utilize the graphical tool. Without sufficient time for overcoming the initial barrier of unfamiliarity, the benefits can go unrealized. There may have been the traditional pressures to cover the same amount of material, negating the values of intensive methodical investigation. Further, the achievement tests may not ferret out the benefits of the graphical tool. Without knowledge of cognitive benefits of the tool, using an achievement test of higher order skills may be a hit or miss approach. These concerns do not discredit the research but rather illustrate issues that deserve consideration.

3.2.5 Encoding versus Reconstructing

Winn (1989) ascertained that graphic tools influence information encoding. Baker and Santa (cited in Glass and Holyoak, 1984) reported that procedures for encoding information affects its recall. However, other research findings indicated that the best use of graphic tools is in post reading condition where the tool is used to assist in reconstructing the important ideas. This seems to be consistent with the findings of Kardash, Royer, and Greene

(1988) on perspective taking. In this study the researchers introduced a perspective to activate schemata and found that perspective taking is much more effective after the presentation of a prose passage than before. The reason for the reference to this research is that using graphical portrayal tools may very well be a kind of perspective taking. Darch, Carnine, and Kameenui (1986) declared that graphic organizers as text comprehension tools are more useful after a passage has been read than before. They also found that children with graphic organizers are able to reconstruct more ideas. With the generation of additional ideas there is a preferential chance of seeing connections. This is an advantage that STELLA may impart by being a vehicle for revitalizing representations through depicting relationships.

3.2.6 Spatial Skills

The alternative portrayals explored in this research require spatial aptitude. There is some contention over whether this is innate or something that can be influenced by education. Lord (1985) cited research studies and provided data from one of his own studies that suggest visuo-spatial aptitude can be learned. He goes on to cite other research that indicates the importance of visuo-spatial aptitude in academic disciplines, particularly the sciences.

Presson (1987) and DeLoache (1989) found that young children have difficulty orienting themselves in space when a map is not directly aligned with the target. This seems to be connected to the egocentric perspective that young children have. Formal thinkers are able to change their perspective relative to the orientation of the map. The conclusion that Presson drew is that as development occurs children become less tied to their immediate surroundings and view the map as separate with multiple meanings. This seems to align with the development of other kinds of formal operations that require coordinating multiple aspects of a task (Ginsburg, 1988). Presson used the conflict between primary and secondary spatial abilities to suggest that certain spatial perspective tasks are more difficult than others. Students failed to separate model as symbol (secondary) from model as object (primary) in spatial orientation tasks. (Primary spatial processing involves dealing with information that is available through sensory manipulation. Secondary spatial processing involves separating the interpretation of the information from its direct relation to sensory input). Presson (1978) concluded:

> Thus children err with the standard appearance questions because they rely on the immediate framework of the surrounding room as an implicit frame of reference to provide (a primary) meaning to the symbol. The error is more of a realistic error than an egocentric one. (p. 93)

The conflict between primary spatial processing and secondary processing highlights difficulties students have with STELLA. See the theoretical discussion of this subject in section 3.1.3.3.

Winn, Li, and Schill (1991) revealed that tree diagrams reduce response latency in determining kinship relations. These findings suggested that spatial depictions facilitate search and computation. The spatial arrangement of relationships was deemed to be a significant factor for learning. These researchers suggested that the perceptual inferences involved in spatial cognition are more easily generated than the logical inferences required by textual information. Familiarity with the diagram's terms and conventions also make a difference by allowing students to use more effective strategies.

The RAAGS (Representational, Analogical, and Abstract computer Graphics for Science) system is implemented on Apple IIe computers using a graphics tool called Mousepaint (Alesandrini, 1987). The students are encouraged to use the graphic tool to illustrate concepts. The researcher reported that students (seventh grade) find it difficult to create their own abstract portrayals. Informal assessment indicates that abstract portrayals are the most difficult for students to generate as compared to realistic or analogical.

3.2.7 Attributes of Portrayal Tools

Although there is not extensive research into the kinds of coding systems that are optimum for portrayals there are a few studies that discern attributes of mapping that facilitate comprehension (Lambiotte et al, 1989).

Mason (1992) conducted a two year study that investigated the use of concept maps with prospective science teachers. One concern was that students' undergraduate experience primarily draws on the regurgitation of terms and algorithms rather than establishing relationships and qualitative understanding of concepts. The researcher expressed concern that these intern science teachers will perpetuate this form of learning and teaching in their own classrooms. To counter act this the researcher used group discussions, journals entries, presentations, quantitative and qualitative analysis of student generated concept maps, and peer review to assess students' thinking. These student interns demonstrated the effectiveness of concept maps by reflecting the hierarchical and interconnected nature of science. Concept maps were also attributed as a source of reflective thought that stimulated thought provoking questions.

Greeno (1986) provided students with a computerized graphical system for representing math word problems. In this research the students were asked to use a semantic network to break down math word problems. The researcher found that students were able to make explicit normally implicit processes. Students were also able to represent information more abstractly. Greeno's research (1986) suggested that the graphic form causes learners to reconsider the problem in light of the structure of the tool.

Willis and Fuson (1988) carried out a similar study to that done by Greeno. The researchers implied that most traditional approaches to teaching addition and subtraction problems involves focusing on the solution strategy and ignores the children's representation of the problem. The researchers used a method of learning that involved children drawing schematic diagrams that corresponded to the semantic features of the problem before proceeding to a solution strategy. They discovered a significant improvement over a control group that used traditional worksheets and reviews. A correctly filled in diagram was highly correlated with coming to the right answer. Diagramming helped students identify classes of problems. Thus this portrayal process was an important step in determining an appropriate solution strategy. It was not just the diagram per se that was important but the degree to which the diagram differentiated between types of problems. This approach was deemed useful in revealing students representations of problems for instructional purposes.

Kotovsky and Simon (1990) performed a number of research studies exploring difficult problems (Chinese Ring puzzle). By creating digitized portrayal of moves (on a computer) they found that problem difficulty decreased immensely. They concluded that:

> In these problems, the limited processing resources the subjects initially bring to the problems are consumed by the task of discovering the nature of the move, to the point where they cannot do the planning, place-keeping, or other simple processing that allow a solution to be found." (p. 183)

This finding along with other findings suggests the importance of alternative forms of portrayals in solving problems and points to the value of using computer generated depictions.

It is observed that in traditional instruction in polynomials, students learn rules that govern graph production. Unfortunately, when students encounter a situation not covered by the rules they revert to guess work. Dugdale, Wagner, and Kibbey (1992) provided a computer tool that transformed student constructed polynomial equations into graphs. They noted that students using this tool tend to establish a qualitative understanding of the equations rather than relying on memorized rules. In addition, this environment required mindful engagement by encouraging students to question contradictions and relate current output to previous output.

Burnett (1992) reported research through the process of self-reflection. He accomplished this by self-documenting his thinking while using computer tools. He used two computer programs, LogoWriter and Mathematica. These tools create spatial portrayals of trigonometric equations. He explored the component parts of these equations independent of the whole. Through this process he came to a better understanding of the behavior of the entire equation. He suggested that discovery learning is not linear. In addition:

"...learning is often bumpy, and education's efforts to smooth the ride may be misplaced." (p. 1) He contended that cognitive processes inherent in discovery are fundamental to what "real learning" is and this process imparts considerable motivation.

Yerushalmy (1991) cited numerous studies into multiple portrayals. These studies suggest multiple portrayal software has the potential to enhance math understanding, develop a more coherent concept of math principles, transfer math concepts to new situations, and facilitate solving nonstandard questions. The potential problems are that these tools might generate misconceptions and not enhance solving standard math problems. Yerushalmy (1991) carried out a study on 35 eighth grade students utilizing a program entitled ANALYZER that provides multiple portrayals of algebraic functions. The forms of depiction included in this program are equations, tables of values, and graphs. Through observations and paper-and-pencil tasks the researcher found that in some instances the visual portrayal does not provide the information necessary to come to certain kinds of learning (change in coefficient and resultant rise over run). Other portrayals are better at coming to these ideas (table of values). Another discovery is that portrayals that are semantically linked do not necessarily stimulate linked understanding in the learner. Yerushalmy suggested that a more didactic approach might be suitable for communicating the notion of linkages between portrayals. The ANALYZER program was thought to help student understanding of graphs as a whole and to understand graph transformations through manipulations of equations. Further, students were not overwhelmed by alternative portrayals. Students' understanding did improve over the course of the research, but no comparisons were made with traditional methods.

3.2.8 Ability - Tool Interaction

There are students who have an aptitude for taking advantage of spatial portrayals. Numerous studies (Snow and Cronbach, 1984; Winn, 1987) indicated that graphic forms assist low-ability students more than high ability students (see Figure 3.6). In many of the above studies ability was defined by verbal abilities. Low-ability students were found to benefit most from graphic portrayal tools. This supports the contention that education is doing a disservice by using language as the dominant symbol system in schooling (Taylor and Cunniff, 1988).

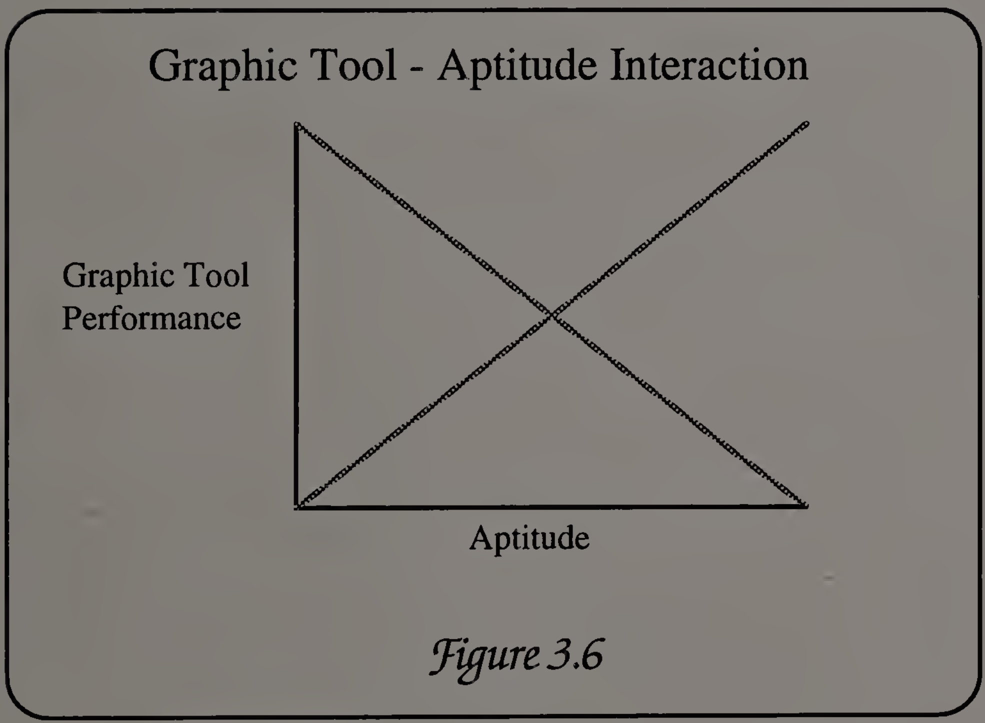


Figure 3.6 Graphic Tool - Aptitude Interaction

Rewey et al., (1991) found that expert created k-maps (knowledge maps) with scripted cooperation (social interaction) benefited low ability students most without affecting performance of high ability students. In contradiction, Winn (1989) found that using certain types of graphic forms (for instance, chart forms), reversed the interaction with ability; high ability students did better. The rationale is that high ability students are more prepared to process the information provided.

Koran and Koran (reported by Winn, 1987) conducted a research study of water cycle diagrams. The findings indicate the use of diagrams resulted in better inductive reasoning and general intelligence (Reference Tests for Cognitive Factors, ETS) in seventh graders than eighth graders, and assisted low ability, but not high ability students. The suggestion made is that there is developmental interaction at work and that older or developmentally advanced students do not need the assistance of the spatial arrangement of a diagram. One has to question if just a year's separation makes that much of a difference; perhaps there are other undocumented factors at work.

Holley and Dransereau (1984) found from their studies that networking (conceptual mapping) techniques are more useful for low GPA than high GPA students in college. The rationale they provide is that the high ability students already are using organizing strategies and the new strategies interfered (Winn, 1987).

Goodyear et al. (1991) identified some concerns about attribute treatment research. One concern is that attributes may work interactively with other attributes that are not identified in the research. Other attributes that might play a part are motivation, anxiety, self concept, locus of control, cognitive style, field dependence or independence (global versus analytic), cognitive complexity (degree of differentiation of cognitive structures), reflectivity/impulsivity, risk-taking, convergence/divergence, instrumentalist tendency (mark seeking), etc. (Goodyear et al., 1991). An additional difficulty is that learner attributes might be transient in nature. Another concern is the predictive nature of aptitude treatment interaction; individuals may respond differently than the generalized results of averaged comparisons. The bottom line is that it is difficult to draw any hard and fast generalizations about ability-tool interactions.

3.2.9 Context Tool Interaction

Cognitive change may be a function of the environment. This has particular implications for portrayal tools since the tool influences the environment. Studies by Winn (1987) suggested that there are situations where a more realistic portrayal is effective. He also indicated that recall of information depends on the task. He compared a detailed circuit diagram with a more abstract diagram. The detailed diagram assisted students more with the sequence and the less detailed diagram preferentially helped students with placement. Winn concluded that graphic portrayal tools were useful for emphasizing those attributes that were made salient in the information.

Holley and Dransereau (1984) pointed out that mapping tools work best for summarizing longer sections of text because the portrayal allow the students to see the macro structures. They also found that text book type articles lend themselves better to these techniques. This is not surprising since the concepts in textbooks are typically more easily identifiable and the relationships more explicit.

3.2.10 Problem Solving

Novak (1989) reported that in seventh and eighth graders concept mapping improves novel problem solving (problems of a variety not encountered before) , but there was little correlation with classroom scores. Novak (1989) described a number of studies demonstrating that students using concept maps in college math courses performed better on problem solving tasks and had more confidence in their abilities.

A research study by Mayer, Dyck, and Cook (reported by Winn, 1987) involved instruction on concept mapping skills. They found no significant differences on verbatim recall. However, there were differences involving identification of relationships among concepts and doing problem solving questions that went beyond the material presented. In this situation "going beyond the material" means solving problems that could not be solved by recalling from material presented in class.

Sternberg and Weil (reported by Winn, 1989) indicated that student success on syllogistic problem solving improved by arranging comparisons with Venn diagrams. Taylor and Cunniff (1988) described a study involving a graphic programming language compared to a more textually oriented language. They found that the graphic programming tools are more effective in communicating meaning regardless of visual aptitude. This determination was based on reaction time and accuracy of comprehension to the code displayed in both forms.

There are few studies that exhibit evidence for students' internalizing problem-solving approaches of portrayal tools. However, Winn (1987) reported studies indicating that students are able to internalize cognitive strategies that are modeled in the medium. In one study children chunked information better because of their experience with graphic forms. Greeno's research (1986) implied that given external graphical forms of expression, the construction of internal representation can be fostered. In this study learners were provided with a graphical mapping tool to solve math word problems. The research cited above suggests that portrayal tools can assist in problem solving situations.

3.2.11 Metacognitive Effect

There has been considerable research into Logo and its impact on metacognition -- with mixed findings. There are similarities between Logo and STELLA. Logo, like STELLA, invites constructions by the student; the resulting constructions are executable, and often involve spatial understanding.

In one study, Emihovah and Miller (1987) analyzed teachers' discourse and found that the teacher-student interaction changed with the use of Logo. The number of exchanges between the student and teacher increased (versus directed instruction from the teacher), and more particularly, the number of exchanges initiated by the student increased. These findings are not surprising, given that the researchers were comparing the experimental group to the conventional classroom. The experimental group consisted of 2 pairs of students (5 year olds), conceivably the small group would encourage sharing of ideas regardless of the environment. They also wanted to show that students observing the teacher modeling metacognitive strategies can transfer self-regulating behavior (versus other-regulated) to other situations (cognitive abilities exam). The studies failed to demonstrate transferability based on their criteria.

Clements (1986) performed a study involving the effects of Logo on metacognition. He based his research on the componential theory (Sternberg) and used a control group, a CAI group, and a Logo group (72 children, first and third grade). The Logo group scored significantly higher in comprehension monitoring and metarepresentation. As a follow-up study, Leher (1987) performed an experiment involving 3 types of environments: Logo, Story Machine and Estimation (software), and a control group. He based his study on Vygotsky's theory of learning. The idea is that students, left to their own devices will not gain deep mathematical understanding. According to this theory, the instructor provides "scaffolding" so students can reach higher levels than they could without assistance. The research paradigm maintained the variable of the teacher and the type of instruction (other studies do not account for this problem). They accomplished this by using the same teacher and similar strategies for all the environments, thus any differences the software make could be identified. At the end of a 5 month experimental session the 3 groups were exposed to a posttest consisting of the game "Tower of Hanoi". In some ways (meta-components, meta-representation) the results failed to replicate Clements' findings, but on comprehension monitoring there was significant agreement. Since these findings specifically related to the particular problem they used as the posttest, it would be interesting to find out how stable these results are over different metacognitive measures. The findings indicated that Logo stimulates the translation of constraints into goals. The Logo group also demonstrated better efficiency over time, making fewer mistakes to get the right answer over repeated trials, but the difference was not significant.

Emihovich (1986) proposed a similar experiment. The researcher based the study on Vygotsky's perspective that the computer is a tool to think with. Three issues comprised the focus of the study: 1) the content of what children are asked to learn, 2) the social context, and 3) the theoretical principles that explain learning. Logo is seen as a microworld for exploration, giving students a sense of enfranchisement. The thinking is that the nature of an interactive, self directed environment would negate a curriculum that has all students working on the same task at the same time. The theory suggests that higher mental orders progress from external to internal by social interaction. Adults help a child regulate this process by externally exposing children to higher order skills. Logo lends itself to this way of thinking: because children talk to the turtle, it is a form of verbal communication that stimulates internalization. This is accomplished through mediated instruction by the instructor using metacognitive strategies. The researcher indicated that although the study of transfer is important, even if there is no evidence for transfer there is value in being successful, and Emihovich felt as though Logo provided students with this experience.

Seidman (1987) in a meta-analysis reviewed a number of studies dealing with the issue of transfer of cognitive skills from programming. The reviewer pointed out that many of the studies include meta-courses as an adjunct to the programming experience. All the experiments that he reviewed note that programming in and of itself is not enough, and that the instructor's role is thought to be vital. He noted that there is a need to match learners to different environments -- implying that different levels of intervention would be preferential for different learners. Some learners do well in a self-initiated environments while others do not. The reviewer also noted that introducing new ways of thinking often happens without consideration for the "cognitive baggage" students bring to the environment.

The metacognitive research indicates that it would be overly optimistic to expect a tool like STELLA to stimulate transfer of metacognitive skills in studies similar to those cited. Nevertheless, the results of these studies also suggest that metacognitive skills can be fostered by environments that are in many ways similar to STELLA.

3.2.12 Research on Simulations and Microworlds

Studies on simulations and microworlds have implications for this dissertation. There is a subtle distinction between simulations and microworlds. Simulations are typically more constrained and governed by a domain. In typical simulations the parameters that can be modified are limited, and exploration is constrained by a predefined sequence. A simulation also has a form of correspondence with some external system. Microworlds allow students to freely explore an environment that may not necessarily have close correspondence with an external environment. As a simulation moves towards a construction kit, the distinction between simulation and microworld blurs. A simulation construction kit provides freedom for defining the scenario being modeled and flexibility for defining the operations of the model and thus looks more like a microworld.

Olson (1988) used a computer simulation called “Flame Life” with elementary students. He noted that students and teachers in his study perceived an actual experiment with the “real thing” to be more valuable than the simulation. However the simulation might be complementary to actual hands-on experience. The researcher noted that:

> Rather than see the simulation as a way of modeling and exploring a system - easy or difficult - the teacher saw it as a substitute experiment to be used when the real thing wasn't possible... In the view of the teacher, the simulation is more like a film of the real thing, rather than a model of it which can be explored in a classroom in ways that the real thing cannot. (p. 76)

He observed a number of interesting behaviors from taped sessions and interviews with elementary students. Some students keyed on superfluous information such as the numbers themselves. Students were strongly influenced by their beliefs, and this influenced their willingness to test alternatives. Their attitude was: "Why should I put effort towards proving the obvious?" Even when confronted by patterns that suggested problems, they sometimes chose not to consider alternatives. Students generally focused on recent data, rather than combining this with previous data. In addition, students were sometimes too quick to quit collecting data when more iterations were required to see patterns. In this regard students tended not to test the whole range of values. Students demonstrated that the concrete aspects of the simulation were more appealing to think about. Students generally had difficulty realizing that the reactants of a chemical reaction are conserved. Students also floundered in identifying the crucial factors within the system -- those influences that are the major contributors to system behavior. Students repeated values during experimentation to determine if they would get stable results and did not use systematic testing procedures. Students generally lacked strong investigative skills.

The conclusion is that students learn not just from being taught but through the reconstruction of knowledge. Olson emphasized this point by cautioning:

> We simply cannot assume that they take the problem the same way the simulation designer does... Thus how the simulation is embedded in ongoing teaching is critical both in terms of concepts that are developed in relation to the simulation and in terms of teaching strategy. (p. 79)

In a follow-up study with older students (grade 4-6) Olson (1988) observed that students appreciated the value of computer simulations. Students noted that one can quickly do trials and obtain a graph. The older students (grade six) also placed less trust in the computer and recognized its limitations, as opposed to the younger students (grade four). Olson concluded that the way computer simulations can contribute to conceptual change is through a learning environment where the teacher is interested in the possibilities that the computer holds for exploring questions. The computer can provide confrontations, but the teacher is the one that helps put those challenges in perspective.

Reimann (1991) reported an observational study with college students (n=8) on a simulation program called “REFRACT”. This simulation facilitated students’ investigation into the physics of optics (surfaces, lenses, and rays). The program also gathered information on student interaction. After designing an experiment, students predicted the result. One interesting finding was that some students had a preference for quantitative output from experiments while others preferred graphical output. This seems to reinforce the idea that some students are visual learners. A major roadblock to student success with this simulation was difficulty determining the relevance of variables. Relevance in this case was the covariation between variables. Students had difficulty finding variables that covary. Students also displayed difficulty systematically controlling the variables; they tended to change several variables, sometimes confounding the results. One student repeated trials. It is interesting to note that some students described phenomena in pictorial terms. Reimann suggested that forms of portrayal are not "informationally equivalent"; that the same information cannot be gleaned from either representation. Portrayals are not "computationally equivalent" either, suggesting that inferences easily drawn from one portrayal may not be drawn from the other. This study suggested graphical and numeric portrayals will result in different learning process and outcomes.

White and Horwitz (1991) reported significant improvement in the qualitative understanding of Newtonian physics by an experimental group of grade six students compared to control groups. This was achieved with a set of increasingly sophisticated microworlds that allowed students to explore the physics of movement on a computer screen. One factor contributing to the success of this microworld was that portrayals make abstract concepts more concrete. The other major contributing influence was attributed to asking students to generate alternative description of laws, this illicited a metacognitive view. The researchers also noted that providing opportunities to see discoveries applied to real world situations helped to make transfer possible. In a redesigned program students built on their own understanding and made great strides towards overcoming misconceptions. "The computer allowed students to create external or concrete representations of their current understandings and to examine them, apply them, and confront their limitations." (p. 27)

Polin (1991) reported research done by Margolis (a Russian researcher) that involved a computer simulation of the classical lever over a fulcrum with differing loads. The results of this study were not encouraging. Less than 35-40 percent showed transfer of learning. The researcher suggested that this is not surprising because the tool did not allow for a very important precondition of externalization to take place. This is a way of connecting the learners ideas with those of the tool. This lack of externalization is thought to be the reason these initial studies fail to show significant results on transfer. The computer simulation used a particular way of depicting the mechanism for altering the states of the simulation which did not conform to the student's view.

Goodyear et al.'s (1991) meta-analysis on simulation effectiveness suggested that over all, the results have been mixed. These researchers concluded that the primary cause of difficulty was the complexity of the task. Most simulations involve a multitude of options requiring prior knowledge of the domain and use of the program, monitoring and orchestrating the learning process, and the courage and motivation to pursue an investigation. Yet the large exploration space or high model complexity are relative to the attributes of the learner (knowledge base and attentional capacity). Students with sufficient background knowledge were more successful with simulations than those that weren't unless they were bolstered by instructional support. They cited studies indicating that the learning of underlying principles was enhanced if the relationship between variables was salient. In such programs where relationships were not salient, students still learned how to control the system but without an understanding of the underlying relationships. Protocol analysis of one simulation study indicated that students did not use systematic investigation, did not make explicit predictions, and required more prerequisite knowledge. The authors cited a study which found that learners had difficulty with simulations that developed over time and were single-minded when looking for the effects of a change. Students also exhibited learning degradation when faced with failure; the students tended to abandon planning behavior, took less risks, failed to generate hypotheses, and developed a bias toward confirming evidence. Further, students tended not to analyze trends nor gather additional data. In some instances, users of simulations used fragmentary knowledge structures that were not coherent and sometimes at odds. However, this may represent the initial stages of true learning. Users were also observed developing intuitive forms of knowledge rather than making use of evidence from the data. Thus the complexity of simulations, students' knowledge structures, and cognitive processes play part in the success or failure of simulations.

Smith (1991) used the Alternate Reality Kit with students and found that there was a tradeoff between the "literal" aspects of the metaphor and the "magical" aspects that depart from the metaphor; special functionality provided by the computer. Through observing students working with this system the author found that learners required little explanation with features that were close to the metaphor while special functionality required more mediation.

Yerushalmy (1991) noted that linked portrayal systems in computer tools enhanced students' understanding of algebra using programs like Green Globs and Geometric Supposer (Sunburst). Yerushalmy also emphasized that enhanced understanding is a function of appropriate use.

Kozma (1991) described a pedagogical paradigm for progressive model development. Progressive model creation leads the learner from simple models to more complex models. Students using a microworld designed to facilitate model progression scored significantly better than the control group on transfer items. Kozma (1991) cited research with this kind of environment that involved depicting abstract concepts with semi-concrete symbols. More recently this type of microworld was described by Gorsky and Finegold (1992) and was used to successfully confront students' naive conceptions of force, acceleration, and velocity. The system they developed created student profiles based on student interaction that then became the basis for confrontationary interventions.

3.2.13 Research on Simulation Construction Kits

There are few documented efforts that investigate STELLA and learning. Toval and Flores (1987) described the use of a program similar to STELLA that they developed. This program is a component of a computer literacy program in Spain. They did not specify any instruments that were used to collect data, but did suggest some benefits. One notable idea is "the modeler gets almost without noticing, a deep and exhaustive knowledge of the subject matter that is being modeled" (p. 301). In addition they noted that this environment encourages learning strategies, criticism, student interest, cooperative learning, and a systematic investigation of the problem.

Through the Technical Education Research Center (TERC), Zuman and Weaver (1988) reported initial studies comparing test scores before and after exposure to STELLA. Topics included: exponential growth and decay, feedback loops, and graph interpretation. STELLA students showed significant improvement on questions dealing with change over time (exponential growth and decay), feedback loops, and graphing. However in questions involving algebra skills (traditional algebra problems) there was no significant change. In observational data, some students were able to recognize that different problems share common structure.

Mandinach (1989) described an ongoing project called Systems Thinking and Curriculum Innovation (STACI) that uses STELLA in numerous content areas. She made comparisons with traditional approaches and found that traditional students used more precise terminology and only understood simple graphs. The STELLA students were adept at breaking a problem into component parts and used a verbal description of change over time rather than focusing on terminology. She also did another study comparing students' metacognitive behaviors. She documents: "Apparently, not having a systems course was detrimental; having some systems was advantageous" (p. 13). She also held interviews after the fact, and summarized one girl's comments:

".... the systems thinking approach enables her to organize and check her work mentally and focus on important concepts despite her dislike for STELLA" (p. 19). She also noted that "...some students who had previously been less than successful in science courses espoused the approach as a means by which to overcome past difficulties" (p. 31). Her other findings suggested that STELLA stimulates cognitive involvement as measured by self-regulation instruments.

3.2.14 Research Conclusions

Despite the given theoretical perspective, there is mixed support from previous research that STELLA affords shifts in cognition. Many researchers attempt a race-horse kind of a study comparing graphic forms with textual forms. Many of the studies mentioned previously used pre- and post-tests. Although there is a lack of strong evidence to support graphic portrayal tools, the mental processes that the tool purportedly stimulates have been shown to be effective in learning. These tools hold promise, but the research fails to unequivocally confirm that. Without an understanding of the value of a tool, it will be difficult to make comparisons which may not take into consideration what is of most worth for that tool. As pointed out by Glaser (1991), performance will continue to be a useful form of assessment, but research into the transition between states of knowledge requires attention. Describing students' interaction with STELLA through time will add to the overall picture of how this kind of an environment influences thinking. Studying students interacting with STELLA will identify cognitive change and isolate attributes of the environment that stimulate those changes. That is the intent of this research study.

CHAPTER 4

RESEARCH STUDY

Discussing face value and impressions of a tool are useful, but analysis of students' activity structures reveal practical value. This study juxtaposes actual student activity with perceived value of portrayals to determine the usefulness of STELLA for fostering dynamic thinking. This study will provide an in-depth description that will generate new research questions and hypotheses for future studies. The goals of this study are understanding, description, discovery, and hypothesis generation.

4.1 Research Questions

The following text outlines the conceptual research questions selected for this study. The overall conceptual hypothesis of this study is that the STELLA learning environment can elicit shifts in students' assumptions about complex dynamic systems. These shifts will be viewed from a number of vantage points which include identification of assumptions, barriers to dynamic thinking, diagram progression, sequence of assumptions, and portrayal efficacy. These issues are reframed into the following questions :

1. As students interact with STELLA can changes in student cognition be identified?

2. By capturing the context of cognitive change can features of the STELLA environment that stimulate cognitive change be inferred?

3. Are there patterns in the learning sequence?

4.1.1 Assumptions

Students' dynamic assumptions can be classified into categories. These categories or levels of thinking are identified by student activity. To better differentiate between levels of dynamic thinking a listing of assumptions follows. These assumptions were identified either in the STELLA manual (High Performance Systems, 1990) or became apparent through observing student operations.

4.1.1.1 Identification of Stocks

Identification of stocks is characterized by students' being able to see those factors in the scenario that can be viewed as something that accumulates or depletes over time. Students are able to translate appropriate processes from their knowledge of content into STELLA stock icons and demonstrate that they understand those symbols with their protocol.

4.1.1.2 Identification of Flows

Identification of flows is characterized by students' identifying rates as a separate factor in the scenario. Students are able to translate appropriate processes from their knowledge of content into STELLA flow icons and demonstrate that they understand those symbols with their protocol.

4.1.1.3 Interdependence of Variables

A dynamic perspective would be identified by students' expressing an understanding of relationships between variables. Students' lacking this view discussed variables as if they were unrelated and did not make any connections between them.

4.1.1.4 Feedback

One-way causality is an alternative assumption which describes events in terms of a factor causing changes in another factor without any regard for feedback (see Figure 4.1 and 4.2,). Students with this assumption think in terms of independent causal factors and static relationships instead of interdependent relationships that fluctuate over time. (For an explanation of STELLA's symbol system refer to Chapter 2)

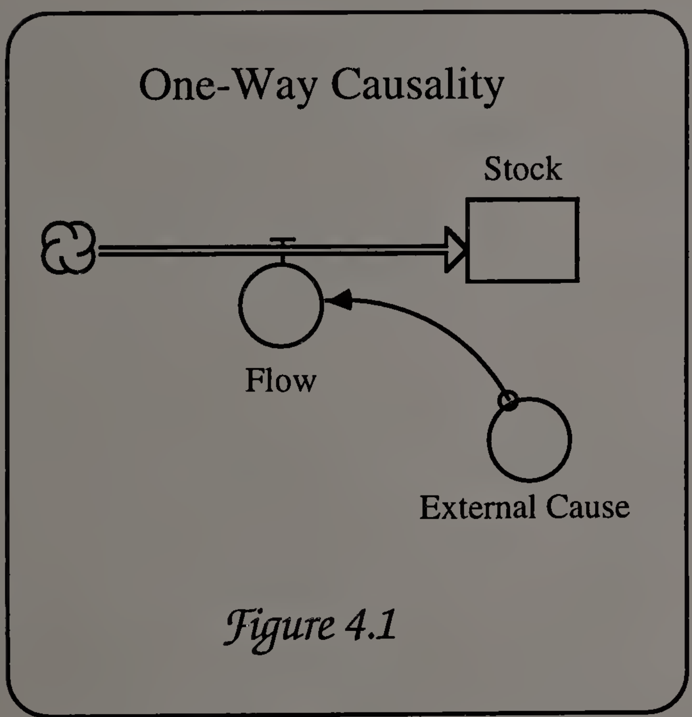


Figure 4.1 One-Way Causality

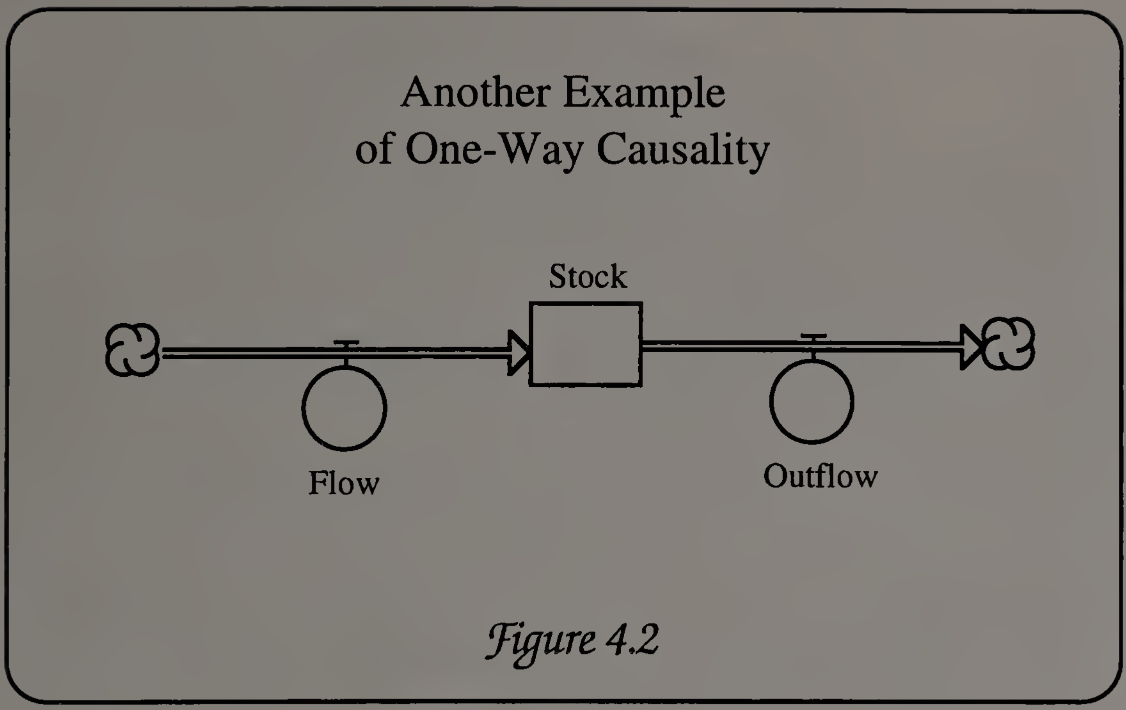


Figure 4.2 Another Example

The creation of a diagram that directly links a stock to its own flow would be evidence of simple feedback thinking. Figure 4.3 illustrates this with a connection between the “Stock” and the “Flow” and the “Flow” then directly influences the “Stock”.

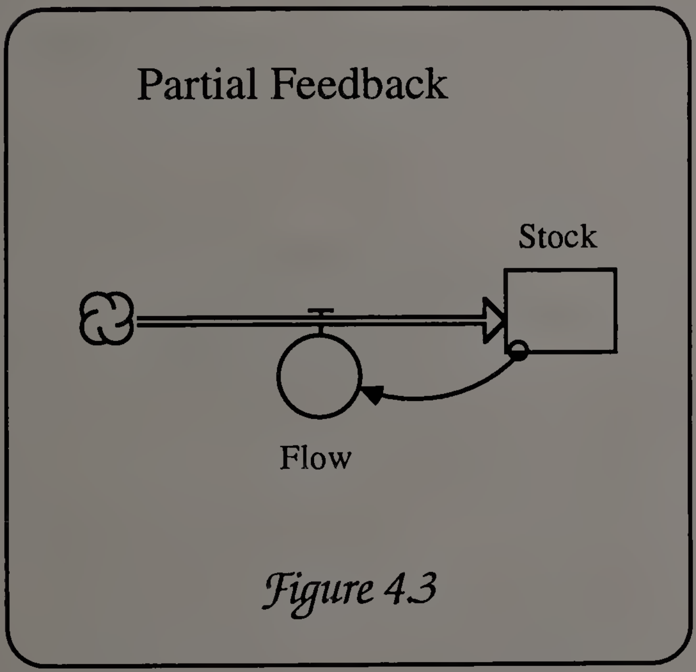


Figure 4.3 Partial Feedback

Partial feedback accommodates those cases in which the major factors in the simulation are only partially linked with causal loops. For instance in Figure 4.4, the variable "Stock" influences "Outflow" and "Outflow" affects "Stock" (by virtue of being an drain) but there is no causal loop with "Inflow". The term "partial feedback" implies incomplete necessitating judgment based on context.

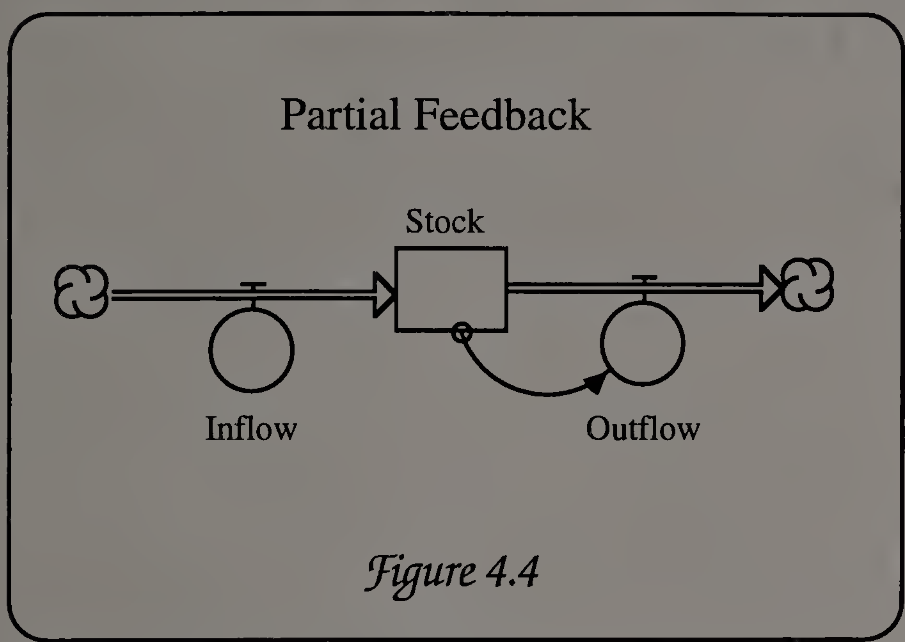


Figure 4.4 Partial Feedback

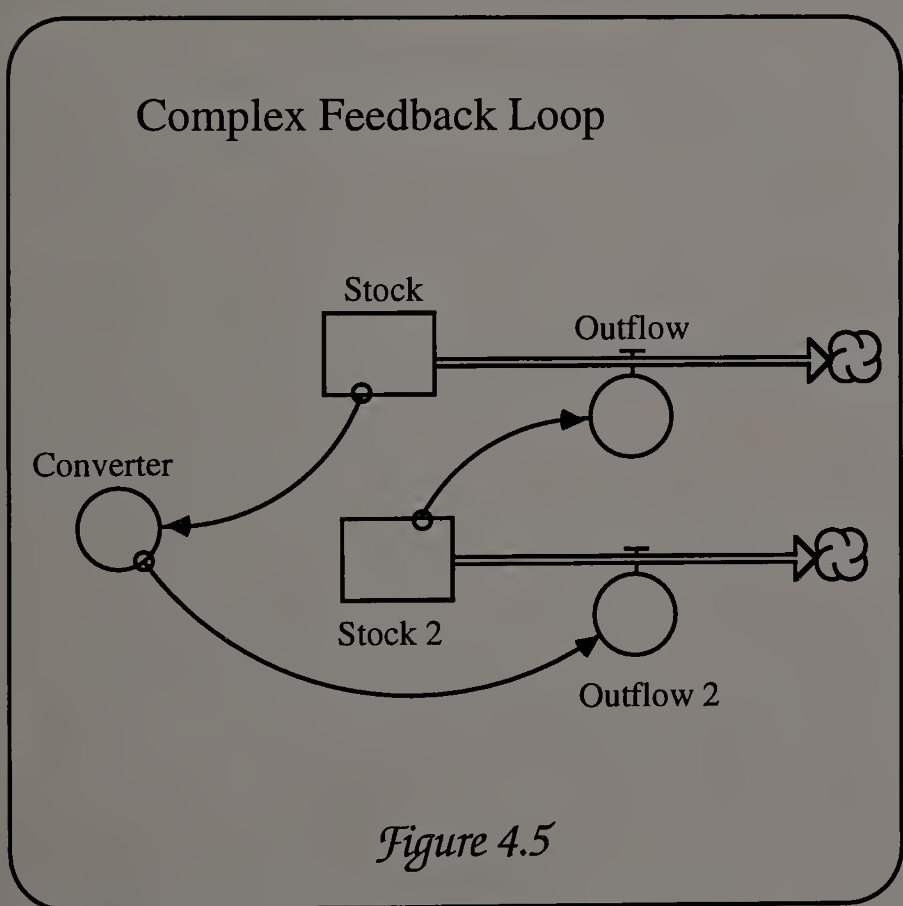


Figure 4.5 Complex Feedback Loop

Another level is complex feedback thinking. This is defined by the creation of a feedback loop in which a factor is indirectly related to itself through another stock or flow. For instance in Figure 4.5, the variable of "Outflow" influences "Stock" that influences "Outflow 2" that affects "Stock 2" and finally completes the loop by linking back to influence "Outflow". Students demonstrating this level of thinking construct models that structurally have feedback loops and discuss relationships as being dependent on each other through causal loops. (See Chapter 2 for a discussion of Converters)

4.1.1.5 Shifts in Dominance

The dynamic perspective suggests that systems exhibit shifts in dominance between the various flows in the model and would see dynamic behavior as the result of interdependent feedback loops. Students exhibiting this dynamic assumption will describe a stock's behavior as the result of a positive or negative feedback loop dominating over another; these compensating causal loops generate dynamic behavior. The alternative assumption is demonstrated by focusing on just one flow for the cause of behavior. In this case the student looks at feedback loops as being independent from each other and not affecting the dynamics of another loop. Students with this assumption will describe a system's behavior in terms of just a single feedback loop with no account of how it dominates over another loop in the system.

4.1.1.6 Delay

The identification of delays in the influence of variables suggests a dynamic understanding of the model. An alternative assumption is confirmed by student protocols that indicate that changes in one variable will have instantaneous influence on all other factors.

4.1.1.7 Goal-seeking

Students able to identify and describe goal-seeking behavior are able to identify a fundamental aspect of most system structures. Interesting dynamics are often the result of competing goal-seeking behavior. Students exhibiting this kind of thinking will describe how a system is attempting to reach an equilibrium. Whereas students unable to identify and describe goal-seeking behavior where it exists illustrate the alternative assumption.

4.1.1.8 Internal Structures as Cause

Dynamic perspective ascribes the structure of the model as the source of behavior. This is evidenced by students making changes to the structure of the diagram, or the logic of the underlying relationships in attempts to change the nature of a model's behavior. An alternative assumption views behavior of a dynamic system as derived from an external force. This alternative framework is evidenced by experimenting with the value of a factor that does not, in fact, change the basic shape of behavior. This category is inclusive to all the other assumptions and thus is difficult to isolate as a separate category of student operations. Even though this category will not be used to classify student thinking it is useful to identify it as an overall view that would be cultivated if students progress through the other assumptions.

Dynamic assumptions and alternative assumptions are thought to be mutually exclusive but there may be situations when combinations of assumptions exist. In other words, students may have alternative assumptions in one context and dynamic assumptions in another context, concurrently holding two competing views. Even referent systems that have the same basic structure may elicit different levels of dynamic thinking. Another possibility is that assumptions are transitory.

4.1.1.9 Order of Assumptions

Determining the emerging order of assumptions will be a useful exercise. This information will foster conceptualization of instructional interventions that assist students to attain the higher levels of dynamic thinking. Thus one of the outcome so f the research will be analyze the order of assumptions that students exhibit as they construct STELLA models.

4.1.2 Barriers to Dynamic Thinking

A qualitative study of this type can investigate additional research questions that arise from the data because the methodology does not limit the nature of the data collected. Normally an experimental study has questions and instrumentation well defined but the instrumentation is usually designed to acquire specific and narrow information about the original question. A qualitative evaluation by the nature of its instrumentation provides a flexibility that accommodate emerging data types. One type of emerging data was student errors. There are at least two kinds of basic errors: translation errors and interpretation errors.

4.1.2.1 Translation Errors

Students can incorrectly translate their mental models into computer models. These errors can be categorized into translation errors in graph construction, diagram layout, and algebraic expressions. Problems translating mental models into algebraic expressions have been identified by researchers (Clement, Lochhead, & Soloway, 1979; Maternowski, 1980). These studies indicate syntactic types of errors exist. For example, order maps on to the equation. In addition semantic types of errors exist. For example, relative size maps on to the equation. Studies on graphing suggest problems such as drawing a graph as a picture rather than an abstract portrayal and confusing slope with height (McDermott, Rosenquist, & van Zee, 1987; Schultz, Clement, & Mokros, 1986). Translation of ideas into STELLA diagrams has not received attention in the literature and will be explored in this study.

4.1.2.2 Interpretation Errors

There are two types of interpretations: one that interprets output of the model and another that interprets the model itself. Interpretation errors of the model involve problems with understanding the model's structural aspects as well as the underlying equations. Interpretation errors of model output involve difficulties understanding graphs, tables, diagrams, and animation. Interpretation errors of tables (Maternowski, 1980) and graphs have been documented in the research (Brasell, 1987; McDermott, L., Rosenquist, M., & van Zee, E., 1987; Schultz, K., Clement, J. & Mokros, J., 1986). These errors seem to follow the same kind of misconceptions as translation errors (listed above). None of the background research read focused on the interpretation errors of STELLA diagrams or animated diagrams. These errors will become part of the data used to analyze student protocols.

4.1.3 Benefits of STELLA

Certain terms communicate specific aspects of the notion of "benefits" of the STELLA environment for cognition. One term is "efficacy": the power to have an effect. In this context, efficacy means the power of the portrayal tool to have an effect on learning. "Affordance" is a related term but refers to specific features of the environment that give forth or afford some educational benefit to the user (Forman, 1987; Olson, 1983). Affordances of portrayal tools have been covered extensively in Chapter 3 (see section 3.1.2). What follows is a brief explanation to make explicit the linkages between those benefits and the STELLA environment. The thought processes activated by manipulating a STELLA display may encourage cognitive restructuring. For educators, knowing the aspects of STELLA's displays that stimulate shifts in thinking will make implementation more effective in educational settings. Below affordances are classified into categories that correspond to features of the STELLA environment:

1. Translation bias

   STELLA manifests a translation bias through the plumbing metaphor that will activate dynamic aspects of students' knowledge. The dimensions of the information highlighted by STELLA encourages students to think in terms of rates and accumulations (refer to Figure 4.6). This selective activation process might be the means of identifying aspects of the content not previously recognized. Consequently STELLA could stimulate students to ask questions about their own epistemology as they link dynamic perspective with knowledge of the content. These questions might arise from inconsistencies in students' epistemology that STELLA makes salient.

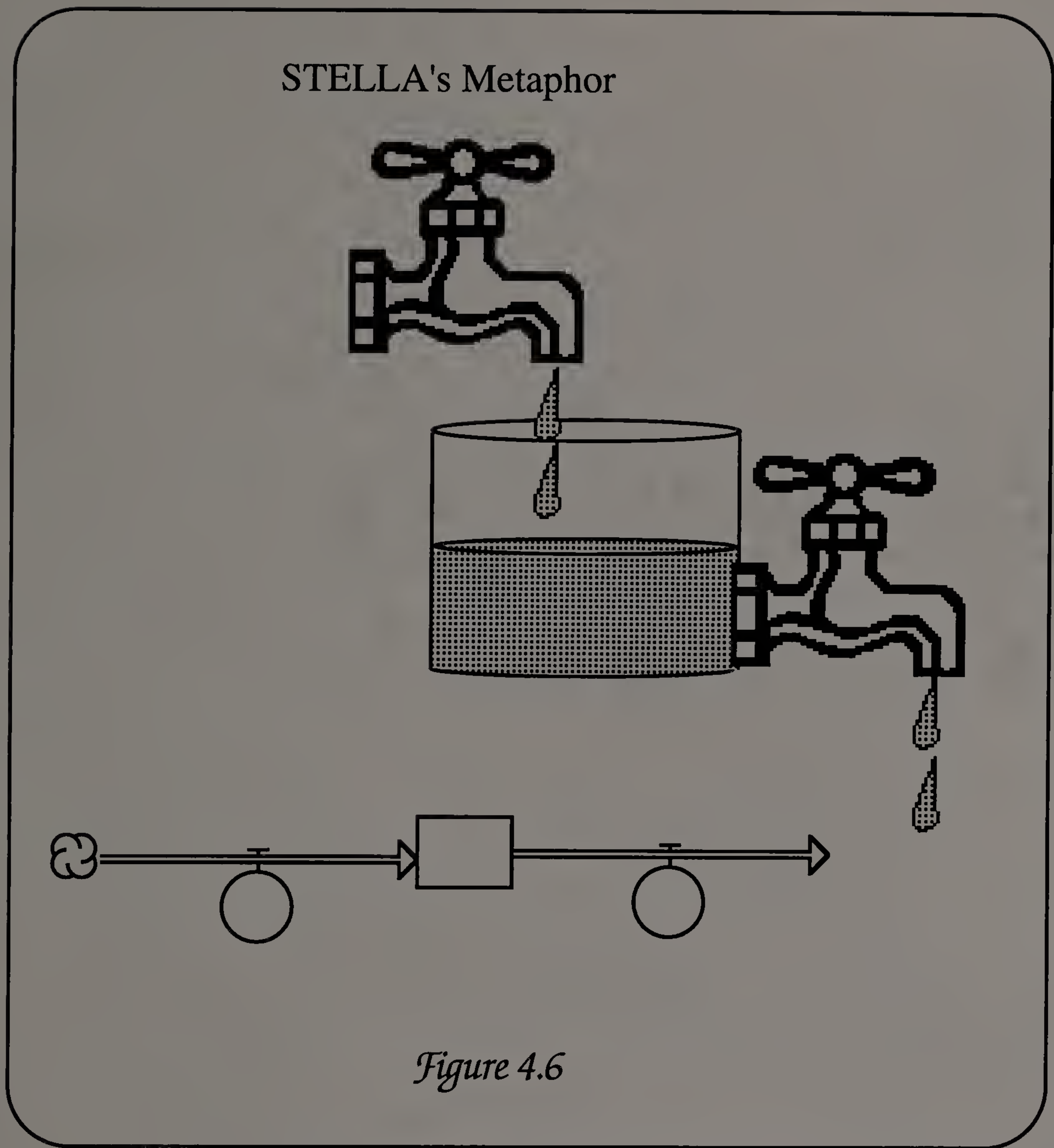


Figure 4.6 STELLA's Metaphor

2. Diagrams

The diagrams focus student consciousness on the flows, accumulations, and relationships. Viewing ideas expressed through the diagram might help students to see relationships that were not apparent in their knowledge structures. Figure 4.7 illustrates the way students might construct a predator and prey system. Prey and Predators in this model are depicted by separate flows, the visual portrayal provides visual anchors from which to make experimental connections. Visualizing possible connections stimulates logical testing for coherence. For instance students may recognize that predators influence prey populations but do not associate that relationship with the death rate of prey. Likewise students may not have thought about the relationship between "Prey" and "PredatorDeaths" had the diagram not made it relatively easy to visualize.

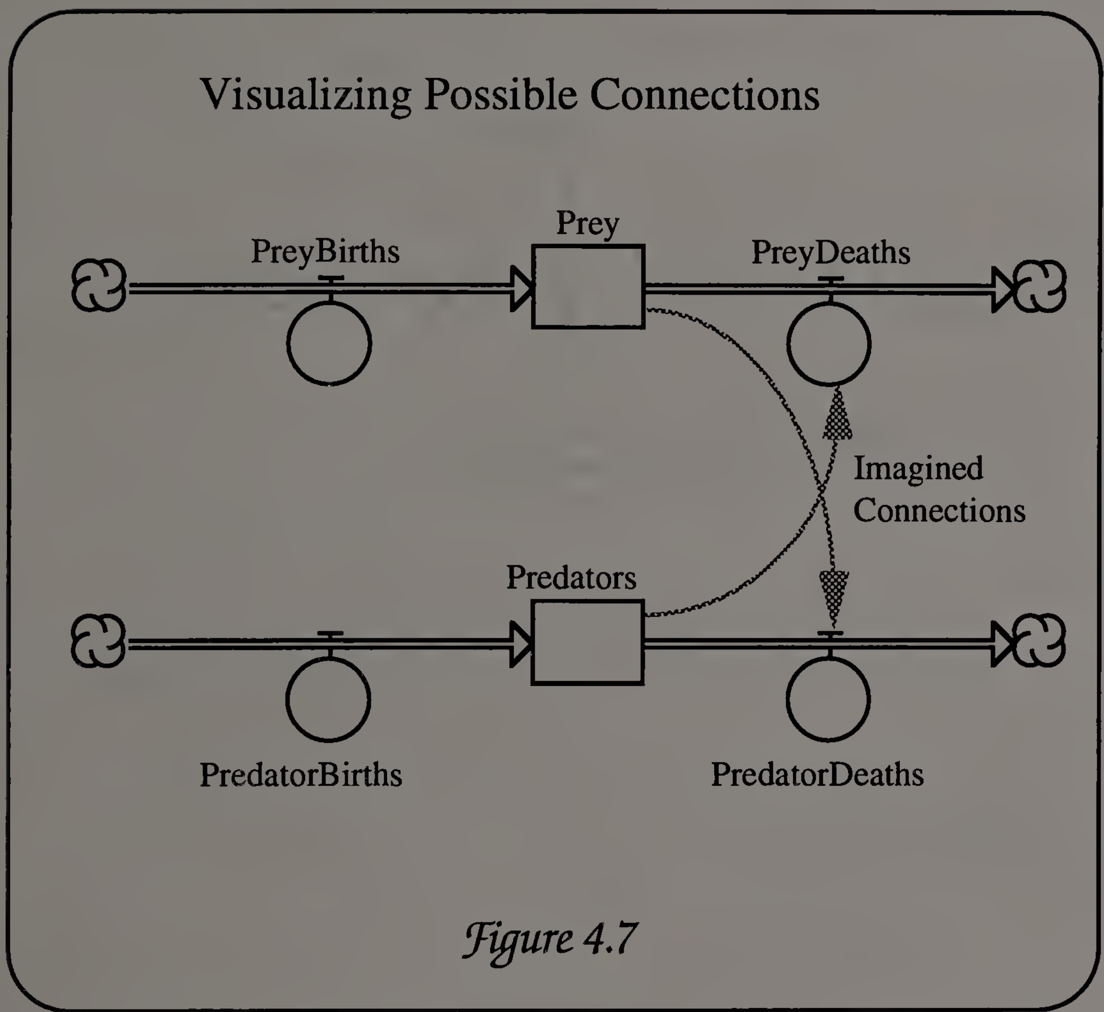


Figure 4.7 Visualizing Possible Connections

3. Animated icons

STELLA's animated portrayals are close to students' experiences. Students have encountered containers that fill up or drain (see Figure 4.8). Viewing a simulation through an animated depiction links this previous knowledge and experience to abstract dynamics via semiconcrete visualization and animated icons. For instance in the dials on the flows (BECOMING & BREAKDOWN) move clockwise as the rates increase and move counter clockwise if the rate decreases. The levels in the stock raise or lower depending.

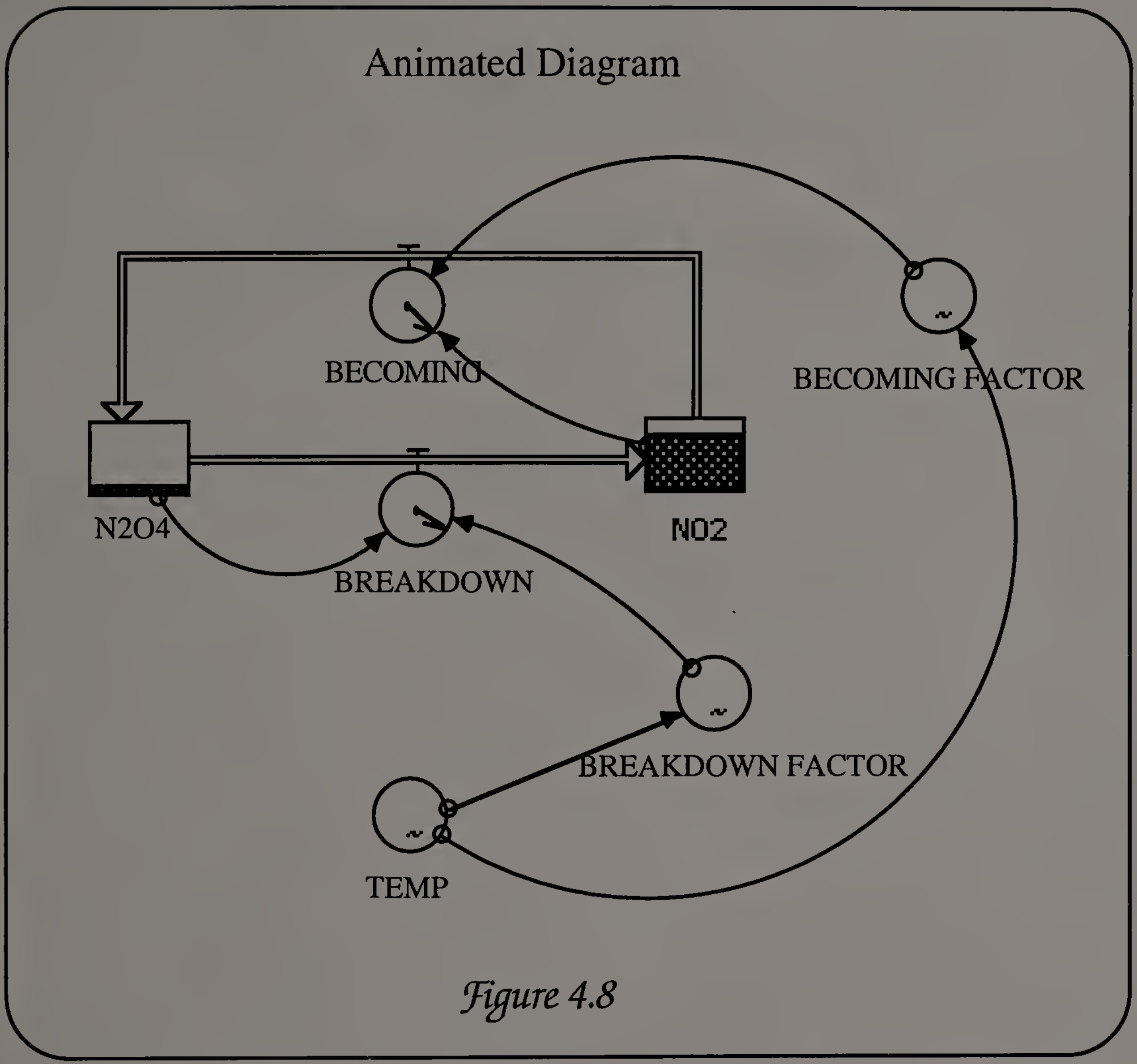


Figure 4.8 Animated Diagram

4. Graphs

Despite the abstract nature of graphs they are a common tool familiar to students. Students will be asked to draw their own graphs that reflect their predictions concerning system behavior. The STELLA graphs will then be used to compare student predictions with model output. The cognitive dissonance generated by discrepancies between student predictive graphs and STELLA graphs will be another source for student questioning. For instance in Figure 4.9 the student reconciles the difference between his/her prediction and the model's output.

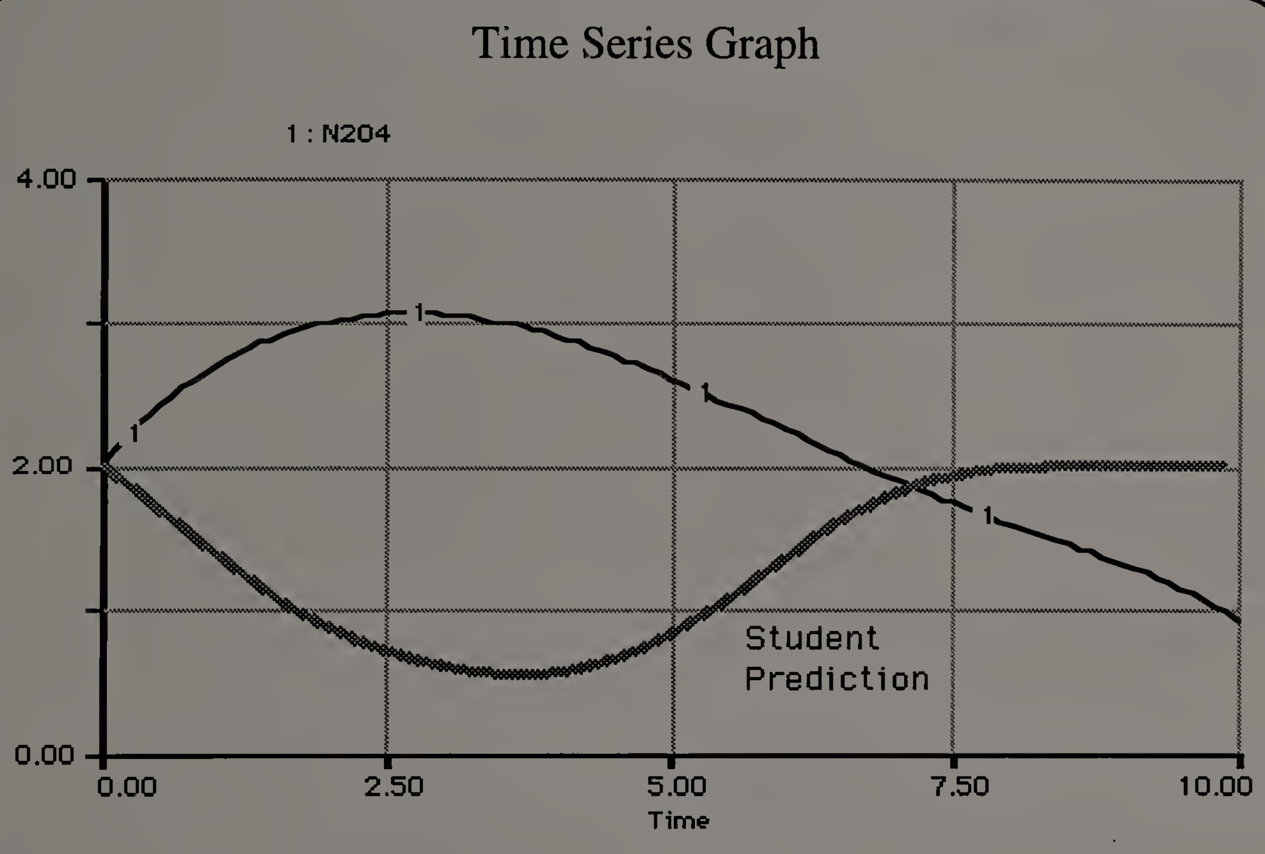


Figure 4.9

Figure 4.9 Time Series Graph

5. Tables

Tables will stimulate students to focus on the reasonableness of values, identify patterns, or to assess the execution of STELLA's equations. Figure 4.10 depicts a table of values resulting from simulation output. Students can view this information and determine if the values are reasonable and ascertain how the values are being generated. For instance at time zero the difference between BREAKDOWN and BECOMING is 0.8 and that if that value is added to the current value of NO_2 that becomes its new value at time one. This is one way students can identify patterns from the table of values.

Table of Values

Time	0	1	2	3	4	5
N2O4	2.0	1.2	0.8	0.6	0.5	0.4
NO2	2.0	2.8	3.2	3.4	3.5	3.6
BREAKDOWN	0.9	0.5	0.4	0.3	0.2	0.2
BECOMING	0.1	0.1	0.1	0.1	0.1	0.2

Figure 4.10

Figure 4.10 Table of Values

6. Equations

Equations define how relationships exist and the value of variables in the system. Viewing and modifying algebraic expressions underlying STELLA operations will underscore the consequences of altering variables. Students can then construct linkages between equations and system behavior. Students can change an algebraic expression and view the consequences on model output. Note that students only create the expressions for the flows and define the initial values of the stocks, STELLA automatically provides the expressions for the stocks. The view on Figure 4.11, provides a complete listing of expressions for the entire model, most students will only view one expression at a time.

Equations

```
N2O4(t) = N2O4(t - dt) + (BECOMING - BREAKDOWN) * dt
   INIT N2O4 = 2
  INFLOWS:
 BECOMING = NO2*BECOMING_FACTOR
  OUTFLOWS:
 BREAKDOWN = N2O4*BREAKDOWN_FACTOR

NO2(t) = NO2(t - dt) + (BREAKDOWN - BECOMING) * dt
   INIT NO2 = 2
  INFLOWS:
 BREAKDOWN = N2O4*BREAKDOWN_FACTOR
  OUTFLOWS:
 BECOMING = NO2*BECOMING_FACTOR
```

Figure 4.11

Figure 4.11 Equations

4.1.4 Cognitive Change

Identifying students' dynamic assumptions, barriers, and affordances will combine to build a foundation to answer the most significant question for this research. The pivotal question for this study is: How does cognitive change take place? Specifically, how does cognitive change occur within a STELLA environment and what are the implications for cognitive theory and education?

4.2 Research Design

The overall intent of this research is to study cognitive change in a particular computer learning environment. The decision to use qualitative methodology is captured in Kuhn's (1984) statement:

> In particular, researchers interested in both learning and development have begun to explore the use of new "microgenetic" methods as a means of obtaining detailed observations of the change process as it occurs. These methods differ markedly from the classical training study methodology discussed earlier, in that the focus is on the change process itself rather than on a comparison of pretest and posttest performance. (p. 173)

This study is designed to evoke evidence of cognitive change. The approach categorizes student operations and links those operations to cognitive categories. Cognitive change is inferred from changes to student operations. These changes are associated with features of the environment that have inferred roles for stimulating cognitive change.

4.2.1 Methodology

The methodology used in this study utilizes a Vygotskian approach. In this view tools carry perspectives that will be acquired as learners interact with them and see them in use. Thus, conceptual change is seen as something that must be within a learner's grasp, referred to as the "zone of proximal development" and facilitated by the modeling of mentors (Case, 1978; Rogoff, 1990; Vygotsky, 1962). Thus the role of guidance will be an important aspect of the research methodology for this study.

This research sets forth a qualitative study, one that describes how students interact with STELLA. This investigation is intended to identify regularities in student operations and changes to those regularities.

A controlled experimental design might compare STELLA students with a control group that do not experience STELLA. Such controlled experiments tend to isolate various attributes of the environment, attempting to identify features of the software that produce testable results. Factoring out attributes of STELLA may result in differences in cognitive processing. This divide and conquer approach loses the gestalt perspective (Rock and Palmer, 1990). Therefore different information may be gathered by a research design that isolates variables. On the other hand, there may be a synergistic effect from the juxtaposition of different symbol systems and procedures that are embedded in STELLA. This investigation will bring in as many variables as possible to paint a holistic picture of students' cognitive processes.

Nevertheless there is still a need to control factors by setting boundaries. In this research, controls ensure that the STELLA learning environment is what will be studied, and not something else. The controls are in the setup and design of the research. The setup involved identifying STELLA as the tool for students to work with and potential topics for students that had not been covered in school. The description of the study recounts students' interaction with STELLA. This provides evidence or lack thereof for STELLA's role in student thinking.

4.2.2 Selection of Participants

An appropriate level for subjects in this research was determined to be grade 11. There were several reasons for this choice. First, STELLA requires algebraic understanding, so higher grade levels were considered assuming more experience. Grade 12 would have been the logical choice to maximize mathematical experience, but during the spring semester of their last year, seniors' minds might be preoccupied with other things (exams, graduation, college/university, etc.). Several high schools within commuting distances in western Massachusetts were approached about access to students and appropriate hardware facilities. Permission was obtained from two local high schools. In both cases a segment of a science class was set aside and a verbal presentation given by the researcher on the purposes, methodology, and potential benefits of the study. A total of four classes (about 20 students per class) were given the presentation. There were about 8 students that expressed an initial interest, but once the researcher tried to enlist them to spending an hour or two each week, many indicated they had other commitments or were not prepared to spend the time. The researcher ended up with four volunteers, two girls from one class and a boy and girl from separate classes from another school. The reasons for their volunteering was not explicitly ascertained, however they all expressed an interest in learning how the computer could model real world situations. The original intent was for students to work together in pairs. The two girls from the same class worked together. The other two students could not work out conflicts in their schedules so they worked independently of each other.

4.2.3 Student Background

The four students will be designated S1 through S4 to maintain anonymity. S1 was a spontaneous female subject, age 16, who used verbal mediation continually as she worked on the STELLA models with S2 as a pair. S1 seemed to be having more of an internal discussion with herself at times than with her partner, and it was difficult for her not to dominate the discussion. She was a aware of this and discernibly restrained herself at times. Her high school subjects were English, Phys. Ed., French I, II, & III, Biology, Chemistry, Earth Science, Latin, World Culture, US. History, Geometry, Algebra 1 & 2, Introduction to Business, and Chorus. Her overall GPA was B but she received an A in math and Bs in the sciences. Her career goal was nursing.

Her computer experience involved 3 years of home use on a word processing system. She had no previous experience with computer simulations.

S2 was S1's partner, a somewhat shy and reserved seventeen year old female. She often allowed S1 to dominate the discussion and was quick to agree when S1 made any predictions or suggestions on how things worked. It was as if she was there because she was friends with S1, and at times gave the impression she was not mindfully engaged (not paying attention to the discussion). The researcher attempted to counter this behavior by asking S2 her opinions or predictions first before S1. Despite this problem, at times she discerned issues that S1 failed to perceive. She had taken English, Math, Chemistry, Biology, Earth Science, World Cultures, U.S. History, American Government, Chorus, Phys. Ed., and French I & II. Her overall GPA was a B-. Her science grades were Cs and received a B in math. She had no career goals. She had two years of word processing experience at school, but had no previous exposure to computer simulations.

S3 was a popular girl, age seventeen. She was described as a "top notch" student by her teachers. She had taken American Government, U. S. History, Algebra, Advanced Math, Geometry, Latin, and French. Her overall GPA was an A. She received A- in both the sciences and math. Her career goals included psychology and education. She had no previous computer experience but caught on quite quickly and was soon proficient in STELLA. She worked on her models individually.

S4 was a quiet and somewhat reserved seventeen year old boy who was somewhat hard to hear at times because he was soft-spoken. His high school courses included Chemistry, English, Algebra, Music, and American Government. His over all GPA was a B+, while he received an A in Math and a B in the Sciences. His computer experience involved using a word processor and games at home for the past 3 years. He had a month of computer programming at school and had experienced several real time simulation programs (flight simulator and a helicopter simulation) as well as adventure games. His career goals were to be a musician or an artist.

4.2.4 Instrumentation

Parental permission was obtained for all students participants. An initial questionnaire was designed to gather relevant background information from students .

Before students began to create models on their own an assessment was made to determine if students were ready. Written descriptions of five scenarios were given to students which they attempted to translate into STELLA diagrams. This assessment instrument does not evaluate the full range of skills required for STELLA interaction. Nevertheless, this assessment determines if students were prepared to initiate model construction. All that was expected from students was the demonstration of translating ideas into stocks and flows with a general idea for how to use connectors and converters. The intent of this assessment was not to look for a perfect match between the student's model and the researcher's model. The researcher's perceived view of the system might be quite different from the student's view. In many cases the difference between the researcher's models and the students' models were missing relationships. Two students' responses to the assessment are included and are representative of the other students. Since the hypothesis of this research is that STELLA will influence students to reconsider their models, these results were exactly what was hoped for. The results of this assessment confirmed the researcher's judgment that the students were generally ready to proceed with the construction of a model.

The main data-gathering method the researcher used during model construction was observation. This was not always a passive observation but a clinical interview (Clement, 1984; Ginsburg and Opper, 1988; Robert, 1984) This involved the researcher posing questions concerning specific instances of student behavior or computer output. The questions attempted to stimulate student verbalizations and encourage students to think. These probes were intended to foster communication of students' mental models and challenge their thinking without providing solutions. The researcher also encouraged students to verbalize their thinking (e.g. "What are you thinking now?").

Internal validity was established through "triangulation" (Merriam, 1988): use of multiple sources and multiple methods to substantiate inferences. Inferential jumps will be based on reports of selfreflection, manipulation of the computer model, gestures, the use of predictions, justification, and verbal interaction with other students or the researcher. A historic log of STELLA models was maintained to track modifications. Validity of conclusions drawn by the researcher should be corroborated by the reader. The reader can participate by calling upon his/her own experiences to make judgments. The researcher has attempted to provide a rich description so that others can make their own judgments as to the applicability of the findings here. According to Merriam (1988) external validity is recast with speculative hypotheses.

4.2.5 Procedures

At the first session the researcher administered the initial questionnaire to obtain general background information on the students.

Training on STELLA involved the following topics:

- Introduction
- Features of the software
- Generic processes
- Conceptualization; system dynamics
- Guidelines for constructing models
- Testing Strategies

The last three topics were covered using example models. The researcher modeled the process of constructing a simulation, then helped the students with the construction of a simple model. A more detailed account is included below under the heading Training sessions.

After students were somewhat familiar with STELLA the researcher videotaped students constructing and testing their models. During student interaction with STELLA the researcher carried on a clinical interview. At the end of the sessions the students were asked to identify aspects of the STELLA environment that were beneficial and problematic.

4.2.6 Time Frame

Sessions for all students began March 4, 1991 and lasted through June 7, 1991.

S1 and S2 met with the researcher twice a week for about 35 minutes (after school) for a total of 22 sessions. This resulted in approximately 770 minutes of contact time, although S1 missed several sessions for health reasons.

S3 generally met once a week during a study hall. Unfortunately due to a number of unforeseen events, such as a half day, an assembly, and a doctor's appointment, only eight-45 minute sessions were completed for a total of 360 minutes contact time.

S4 began with a 45 minute session once a week for 6 weeks, then increased to two sessions a week (during a study hall). 14 sessions were held with this student for a total of 630 minutes.

4.2.7 Training Sessions

In the first session, the researcher offered a rationale for using STELLA. STELLA was suggested as a means for simplifying and portraying ideas about complex systems. At this point, a preconstructed example of tree harvesting was introduced as a simple example. The researcher explained the variables and how they were connected to each other. Students attempted to predict a variety of outcomes while changing just a few of the parameters. This highlighted the interdependent nature of STELLA. The resulting graphs of changes confronted students' prior conceptions of how this system functions. The objective of this exercise was not only to introduce how STELLA works but also to provide a rationale and motivation for the construction of models.

Other topics covered in the first sessions included a discussion of STELLA building blocks: stocks, flows, converters, connectors, and clouds. The plumbing metaphor was used to help students relate STELLA to something familiar.

Different arrangements were presented that illustrated both conserved and nonconserved flows. The researcher instructed students on the procedures for constructing simple time series graphs.

All the menu items were discussed and illustrated, although some items on the menus were never used again. The rationale for this approach was to provide students with a sense for the possibilities; they could always ask for directions if they wanted to take advantage of an unfamiliar feature.

The researcher modeled the process of model construction using the ozone example.

Generic structures (derived from the STELLA manual) in the form of diagrams, equations, and graph output were illustrated and discussed with students. Working models of these generic structures were discussed and manipulated by students. Printouts illustrating these generic structures were available for reference during model construction.

Students were then encouraged to produce their own model of a rat population. Sidebar 4.1 provides a description of the scenario. The researcher was involved in the construction process even though students were encouraged to build the model themselves. The researcher intervened when students expressed frustration, when they asked for assistance, or when it became apparent that students were embarking down a line of reasoning that might prove unproductive.

> Rat Scenario
>
> A number of rats are placed in a cage. You have control over the feeding rate. Can you construct a model that shows the dynamics of this population?
>
> *Sidebar 4.1*

Sidebar 4.1 Rat Scenario

Finally, students were asked to create a model with as little assistance as possible. Initially students were encouraged to identify topics from their courses that would lend themselves to STELLA. S1 and S2 identified The Great Depression. It was a good topic, and it could have been put into STELLA, but the large number of factors that the students wanted to include made it prohibitive particularly for novices. The other students also had difficulty selecting appropriate topics, so in order to save time the researcher provided a list of appropriate topics. The list of possible scenarios included cocaine's influence on the nervous system, global warming, lead poisoning, chemical dump, osteoporosis, and chemical equilibrium (this was a topic suggested by S1 and S2's teacher). This list of topics was provided to S3 and S4 along with a brief verbal description. S1 and S2 conferred with their chemistry teacher and decided to explore the chemical equilibrium scenario. S3 and S4 both chose the cocaine scenario (independent of each other). A description of these scenarios as seen by the students is in.

4.2.8 Researcher Involvement

The researcher was a participant-observer or "researcher participant" (Merriam, 1988). In this role the researcher interacts during the entire process of model creation and testing. Here the researcher interacted but also attempted to remain neutral concerning the translation of student ideas. In other words, the researcher withheld comments concerning the validity of ideas expressed by students. The researcher only attempted to confront students' ideas with their own constructed models by suggesting different views of the data. The researcher also rendered assistance with technical aspects of the program, with student interpretation errors, or when the current line of exploration looked fruitless. The researcher also interjected probing questions that challenged student thinking in attempts to unveil thought processes. Instructional probes have been used as effective means of evoking useful problem representations (Glaser, 1991).

4.2.9 Student Involvement

Students read the written description of the scenario they chose to model. They were then asked to construct a model of that phenomenon. Students were encouraged through the course of the research to express their thoughts. They were requested to generate questions about their models and justify their answers. The students created the models, although the researcher did on occasion make suggestions, provided counter-evidence, or used probing questions. During the course of the study students were frequently asked to make predictions about model behavior under a given set of circumstances (see a discussion on the role of prediction in the theoretical chapter, section 3.1).

4.2.10 Videotaping Sessions

The decision to start videotaping was somewhat arbitrary. Certainly the researcher could not wait until students had mastered the STELLA environment, otherwise shifts in student thinking may have been missed. However, the researcher did not want to tape interaction that was primarily just instruction nor begin taping before students were comfortable with the researcher. The taping sessions began on the fourth week of sessions after students had begun constructing their rat models before they began construction of their own models. The camera was placed directly behind the computer and was focused on the screen of the computer. When necessary the researcher verbalized gestures and expressions that were not captured by the video tape or directed students to make gestures on the screen (probably once or twice a session). Students didn't seem to express any apprehension about being videotaped. It appeared to be a relatively unobtrusive means of collecting data.

4.2.11 Limitations

This study is not without limitations: There is an inherent problem with most case studies. The research would provide stronger conclusions with a larger number of cases. Since the participants were volunteers, this introduces a bias. The research setting was not isomorphic with a typical classroom. The researcher worked separately with one pair and two individual students. Although a skilled instructor would probe a student in a similar fashion as the researcher, the amount of time and energy is probably disproportionately weighted on the researcher's side. A critical issue is time.

Considerable time was spent each session refreshing students' memories. Had the students been able to meet every day or even every other day, there would not have been the need to spend so much time reviewing models. Another limitation was that the researcher was only given a designated period of time to meet with students. This developed into a problem because the students often could not finish during the designated time. Since the researcher was anxious to obtain as much of their reasoning, less time was spent having students reflect on their experience. However, these are realities that school teachers have to grapple with, so this made the study more like a typical school environment.

The clinical interview may appear to be a confounding variable. Will the observed behavior be a result of the interview process or the STELLA environment? An argument might be mounted that suggests STELLA is not what is being investigated but rather STELLA in conjunction with a clinical interview approach. This contention has merit. There are two aspects of the clinical interview that might influence student thinking. First encouraging students to verbalize their thinking might affect cognitive processes. Hayes (1989) notes that thinking aloud has been used as an instructional procedure to help students grapple with problems. Second, questions or comments made by the researcher might affect student thinking. Indeed as mentioned previously technology does not stand on its own; neither does STELLA. In many instances students in this study needed assistance in manipulating the tool. Furthermore with guidance the STELLA environment confronts student thinking. The rationale for an interventionist approach was to challenge students' thinking. Without mediation from a skilled instructor students' thinking might go unchallenged. In many instances the researcher attempted to provide students with a portrayal of the data that would either confirm or refute their theories. The degree of obtrusiveness from these interventions is relative. Any intervention is obtrusive. Providing STELLA can be considered an obtrusive intervention, so an interview increases the relative degree of intervention. However, STELLA without mediation from an instructor renders the results less valid because educational settings commonly involve an instructor who makes interventions. The clinical interview represents the kind of instructional intervention that a skilled instructor would probably use. Thus, in this study the clinical interview is considered part of the learning environment and adds to the "ecological validity" (Kuhn, 1984) of the study; the degree to which it approaches the kind of environment that exists.

CHAPTER 5

ANALYSIS OF SELECTED PROTOCOLS

All of the student protocols were completely transcribed and analyzed. The entire set of student protocols will not be included because of their voluminous nature. The analysis includes selected sections of protocols that show noticeably strong effects. Extracting the relevant sections of protocols is intended to show salient aspects of students' dynamic thinking. Other transcribed protocols are available by contacting the author. Conventions used to document student protocols are described in Sidebar 5.1.

Notes for Quoted Protocols:

In quoted protocols parentheses will indicate that either a reference to an object was obvious from the context or a gesture was used to point to it. Throughout student protocols the variable labels from STELLA models will be identified with capitalization.

Sidebar 5.1

Sidebar 5.1 Notes for Quoted Protocols

This descriptive study will reveal how students interact with STELLA. However, speculative hypotheses that imply further research will also be included. To accomplish this an analysis of selected protocols was done. This detailed analysis of students' protocols sought to flesh out a model of students' cognitive structures by categorizing their operations. Certain types of operations were theorized to be attributes of students' knowledge representations. This is not to say that students' mental models are completely available for inspection, but merely that aspects are exposed through externalizations. With aspects of mental models inferred, evolutionary changes were tracked. This technique involved categorizing students' protocols as an index of shifts in thinking. Student operations were coded into assumptions, affordances, and errors. Patterns were identified with tables and diagrams that illustrate the sequence of progression in dynamic assumptions.

Patterning is a way of demonstrating reliability. Pattern identification within individuals and across individuals yields important inferences. The validity of conclusions will be determined through the process of corroboration: banding together sources of information that point to common conclusions. More confidence can be placed on reasonable inference as the amount of circumstantial evidence increases.

One of the propositions this dissertation holds is that students are encouraged to change their view of dynamic systems by exploring selfconstructed models. Shifts in thinking will be demonstrated by the structure of students' diagrams, gestures, and verbal protocols. Moreover, it is hoped that patterns in the interaction with STELLA can point to internal cognitive processes. Mappings inferred between behavior and cognitive processes will impart insights into learning.

Notationally, wavy line diagrams will be used to convey transformations to mental constructs. Wavy line diagrams map students' mental constructs to behavior and foster interpretations. The example in Figure 5.1 was taken from a pilot study. This technique of analyzing student protocols is adapted from Clement (1977, 1979), Driver (1983), and Easley (1978).

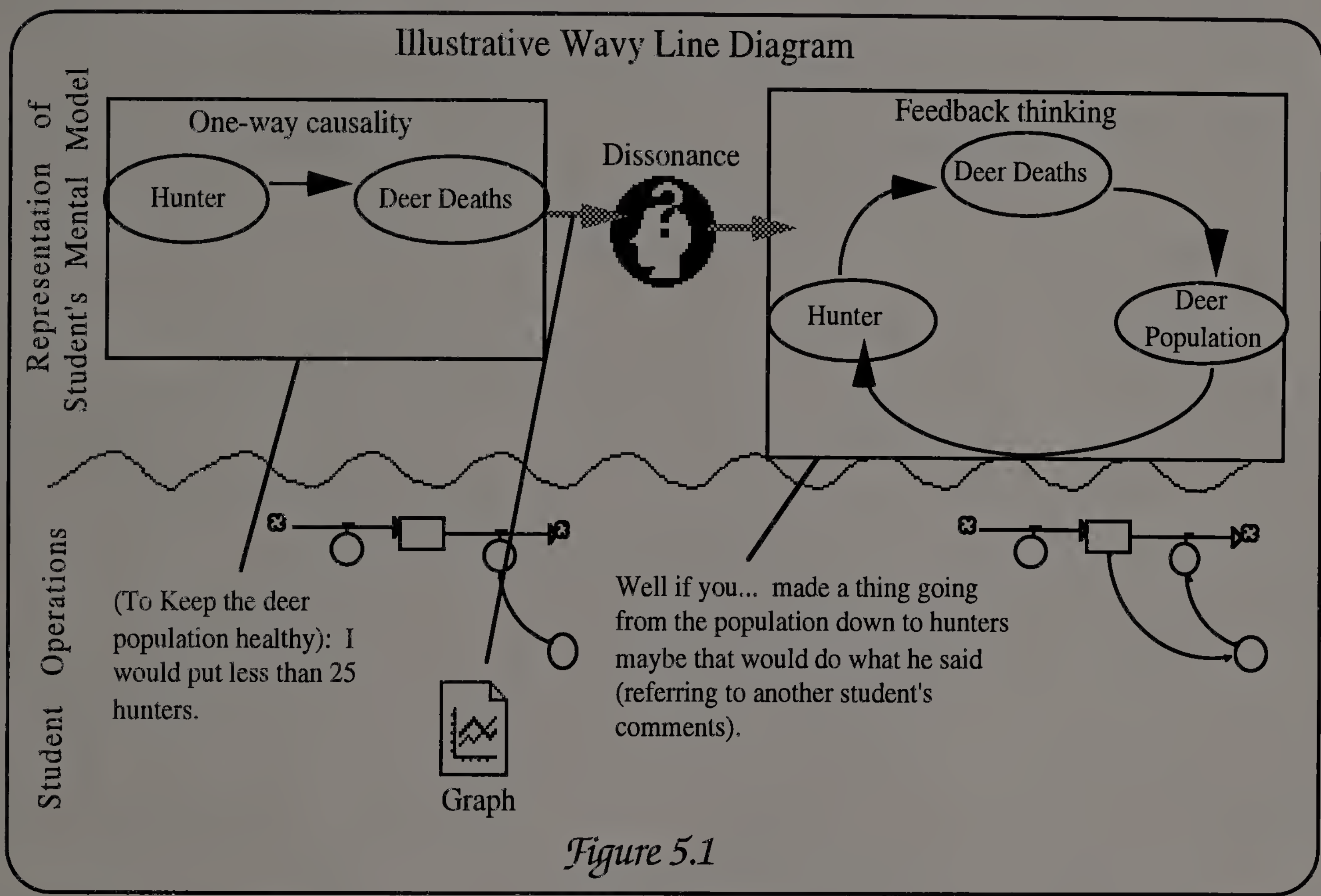


Figure 5.1 Illustrative Wavy Line Diagram

The conventions of the wavy line diagram will be now be explained. The structures above the wavy line are the researcher's model of the student's cognitive structures. The gray arrow extending horizontally represents the passage of time while the cognitive structure of "one-way causality" is active. The wavy line suggests the separation between a student's mental model and observed behavior. Student operations are illustrated with selected verbatim transcripts and miniaturized versions of the students' STELLA diagrams. The portion above the wavy line represents theoretical constructs of the researcher. The information below the wavy line is the recorded behavior of the student. Lines angling down suggest a mapping between the observed behavior and mental constructs. The wavy line diagram is an attempt to make sense out of the observed behavior. The theoretical constructs are the inferences that interpret students' protocols and STELLA diagrams. This close association between observations and theory make theoretical leaps more plausible.

During the course of this research there were numerous instances when a student's mental model was at odds with the STELLA model. This dissonance often was the catalyst either to modify the STELLA model or to modify thinking. To accommodate the depiction of cognitive dissonance an icon depicting a person's head superimposed with a question mark was selected (see Figure 5.2).

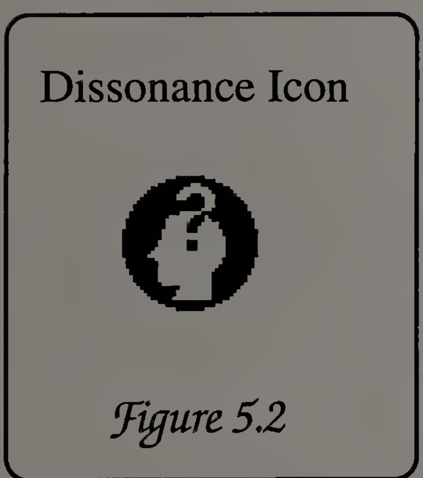


Figure 5.2 Dissonance Icon

Cognitive dissonance will be linked to features of the portrayal through thumbnail icons. Inferences were generated that identified features of the STELLA environment that encourage change in student thinking. Thumbnail icons represent the types of portrayals used (see figure 5.3).

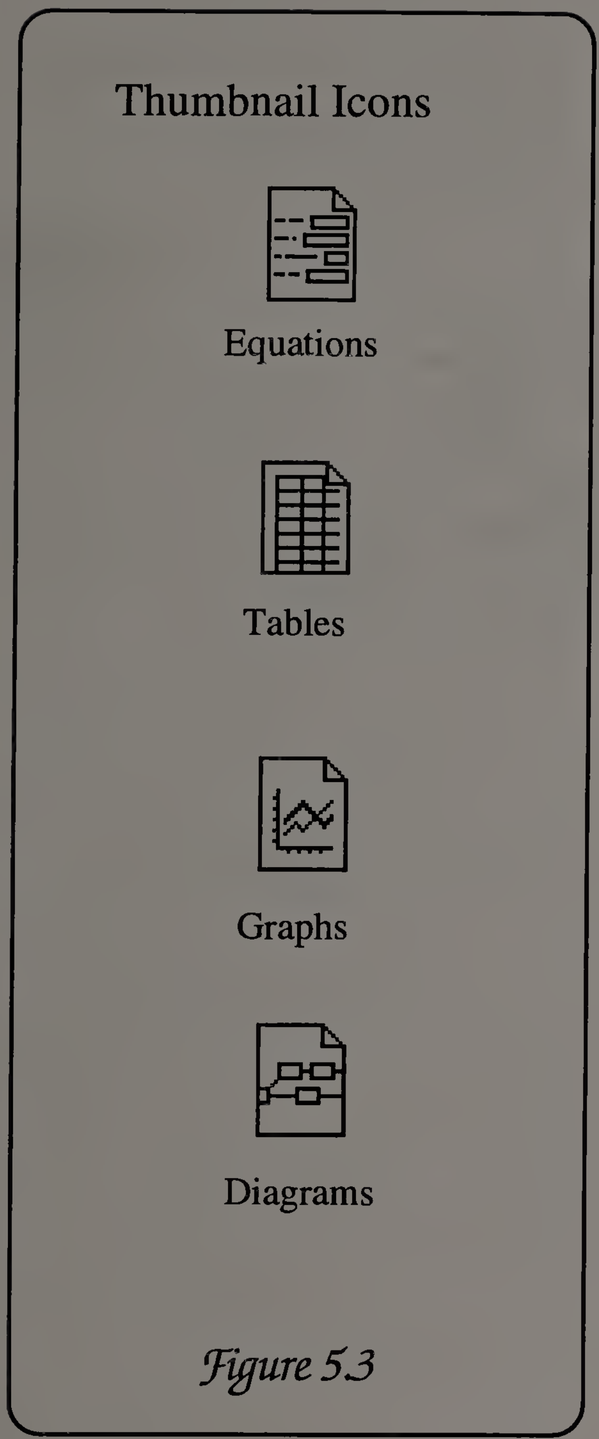


Figure 5.3 Thumbnail Icons

Modification of the STELLA diagram, student gestures, and student protocol will comprise potential evidence for shifts in thinking from alternative assumptions to dynamic assumptions.

Based on identified patterns, the researcher made interpretations of behavior, given a context. Readers can decide for themselves if these interpretations make sense.

5.1 Identification of Assumptions

Due to excessive volume, the dynamic assumptions students exhibited are not included. The following tables represent the progression in student assumptions over time (refer to Figures 5.4, S1's Dynamic Assumptions, 5.5, S2's Dynamic Assumptions, and 5.6, S4's Dynamic Assumptions). The vertical and horizontal dimensions are both ordinal scales. The vertical scale represents change in time with a numbered section of protocol which indicates when change was identified (the number is an arbitrary reference to a location in student protocols). The horizontal scale lists particular assumptions, in order of perceived level of sophistication from left to right. Note that S3's diagram progression chart is not included. Again this was because the session attendance was temporally inconsistent making analysis very difficult (most of the sessions were spent reviewing and getting reacquainted with the model and STELLA).

☐ alternative assumption
☑ dynamic assumption

Chemistry	Idenfication of stocks	Idenfication of flows	Variable Relationship	Partial Feedback	Complex Feedback Thinking	Shifts in Dominance	Delay Thinking	Goal Seeking
S1 S2 Chem 1	☐							
S1 S2 Chem 2	☑							
S1 S2 Chem 3		☐						
S1 S2 Chem 4		☑	☐					
S1 S2 Chem 5			☑					
S1 S2 Chem 7			☑					
S1 S2 Chem 12			☑					
S1 S2 Chem 20				☑				
S1 S2 Chem 22				☑				
S1 S2 Chem 48					☑			
S1 S2 Chem 51					☑			
S1 S2 Chem 63						☐		
S1 S2 Chem 64						☐		
S1 S2 Chem 66					☐			
S1 S2 Chem 67					☐			
S1 S2 Chem 68					☑		☑	☑
S1 S2 Chem 70								☑
S1 S2 Chem 72					☑			☑
S1 S2 Chem 73							☑	
S1 S2 Chem 74					☑			
S1 S2 Chem 78								☑
S1 S2 Chem 79					☑	☑		

Figure 5.4 S1's Dynamic Assumptions

☐ alternative assumption ☑ dynamic assumption		Idenfication of stocks	Idenfication of flows	Variable Relationship	Partial Feedback	Complex Feedback Thinking	Shifts in Dominance	Delay Thinking	Goal Seeking
Chemistry	S1 S2 Chem 1	☐							
	S1 S2 Chem 2	☑							
	S1 S2 Chem 3		☐						
	S1 S2 Chem 4		☑	☐					
	S1 S2 Chem 5			☑					
	S1 S2 Chem 7			☑					
	S1 S2 Chem 12			☑					
	S1 S2 Chem 20				☑				
	S1 S2 Chem 22				☑				
	S1 S2 Chem 41				☑				
	S1 S2 Chem 43			☑					
	S1 S2 Chem 44				☑				
	S1 S2 Chem 46			☑					
	S1 S2 Chem 51					☐			
	S1 S2 Chem 55				☑				

Figure 5.5 S2'2 Dynamic Assumptions

☐ alternative assumption ☑ dynamic assumption	Idenfication of stocks	Idenfication of flows	Variable Relationship	Partial Feedback	Complex Feedback Thinking	Shifts in Dominance	Delay Thinking	Goal Seeking
Cocaine: S4 Cocaine 1	☑	☑						
S4 Cocaine 2		☑						
S4 Cocaine 6			☑					
S4 Cocaine 10		☑						
S4 Cocaine 11		☑						
S4 Cocaine 12			☑					
S4 Cocaine16				☑				
S4 Cocaine 17				☑				
S4 Cocaine 19					☐			
S4 Cocaine 21				☐☑				
S4 Cocaine 22				☑				
S4 Cocaine 23				☑				
S4 Cocaine 26					☐			
S4 Cocaine 28					☑			

Figure 5.6 S4's Dynamic Assumptions

The progression tables illustrated above suggest the development of dynamic assumptions. S2 does not progress beyond the identification of simple feedback loops. This is despite the fact that S1's discourse was laced with references to higher dynamic thinking. This observation reinforces the notion that students build their own mental constructs. S2's discourse made no reference to higher forms of dynamic thinking probably because she lacked the mental structures to value S1's comments. In Vygotskian terminology higher forms of dynamic thinking were outside her zone of proximal development. Scaffolding provided by S1 had little influence on her thinking. It was observed that S1 made most of the adjustments to the spatial model after S2's progression halted.

5.2 Progression in Diagram Construction

It is not surprising, but interesting to note that students' progression through dynamic assumptions is paralleled by a progression through the construction of the model. This is highlighted by the illustration in Figure 5.7 and Figure 5.8 and. These figures show how assumptions paralleled changes in the structure of the diagram.

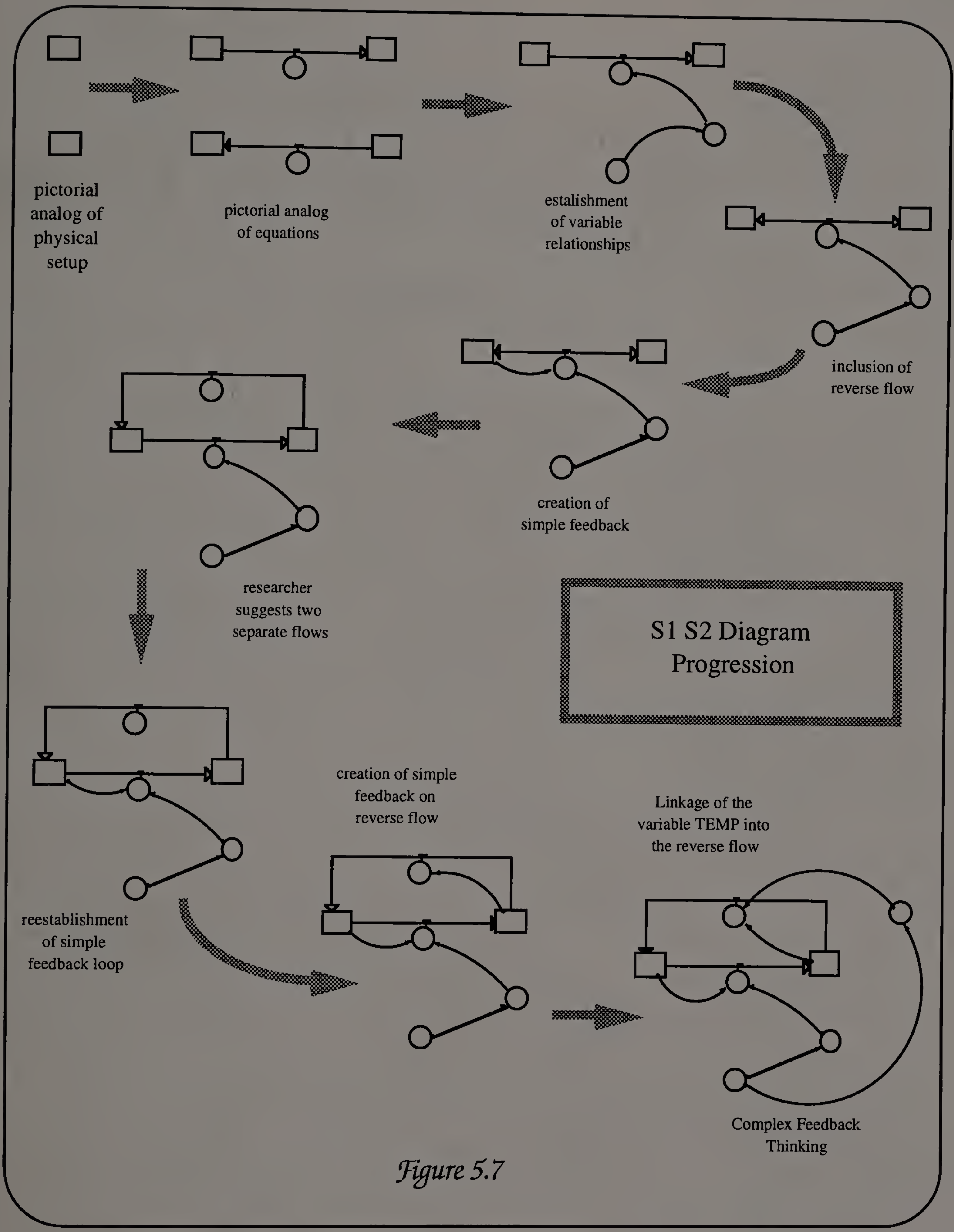


Figure 5.7 S1 S2 Diagram Progression

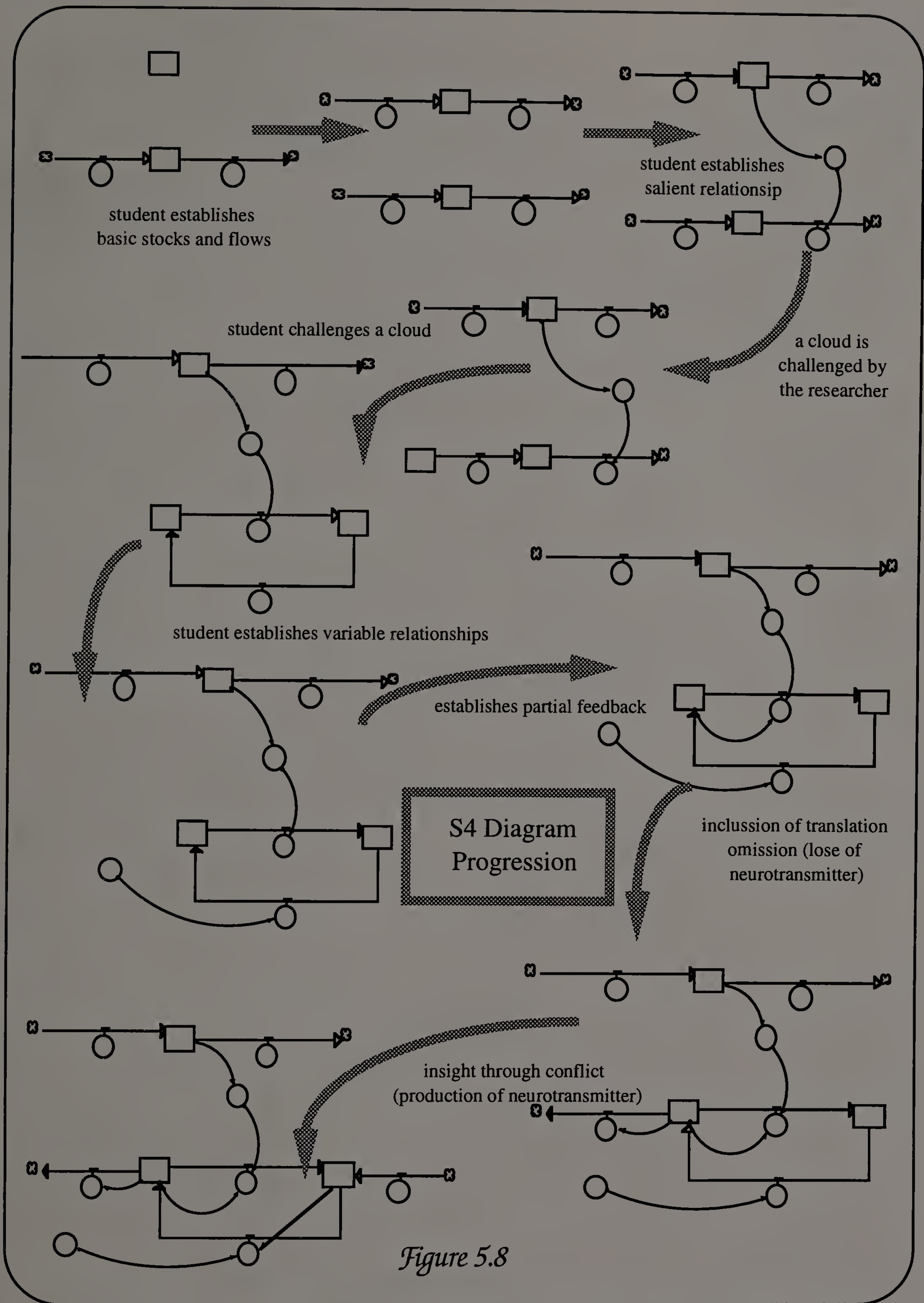


Figure 5.8 S4 Diagram Progression

An interesting note about the sequence of diagram construction is that it roughly corresponds to the progression of dynamic assumptions (refer to Figures 5.4 through 5.6).

At the end of the research sessions, S1 and S2 were asked to compare one of their original models (see Figure 5.9) with the final model and the following discourse was recorded:

S1: These (NO_2 & N_2O_4) have no relation to BREAKDOWN (speaking of the original model).

R: Why is that important?

S1: Well, because it is taking out portions, it is not taking out the same amount each time, it is taking out a portion.

R: Any other differences?

S1: Because this (BREAKDOWN) is going to be different for both sides, so I don't think this (the old model) clearly represents that, how the difference is how this breaks down more when its hot and this (NO_2) breaking down more when it is cold.

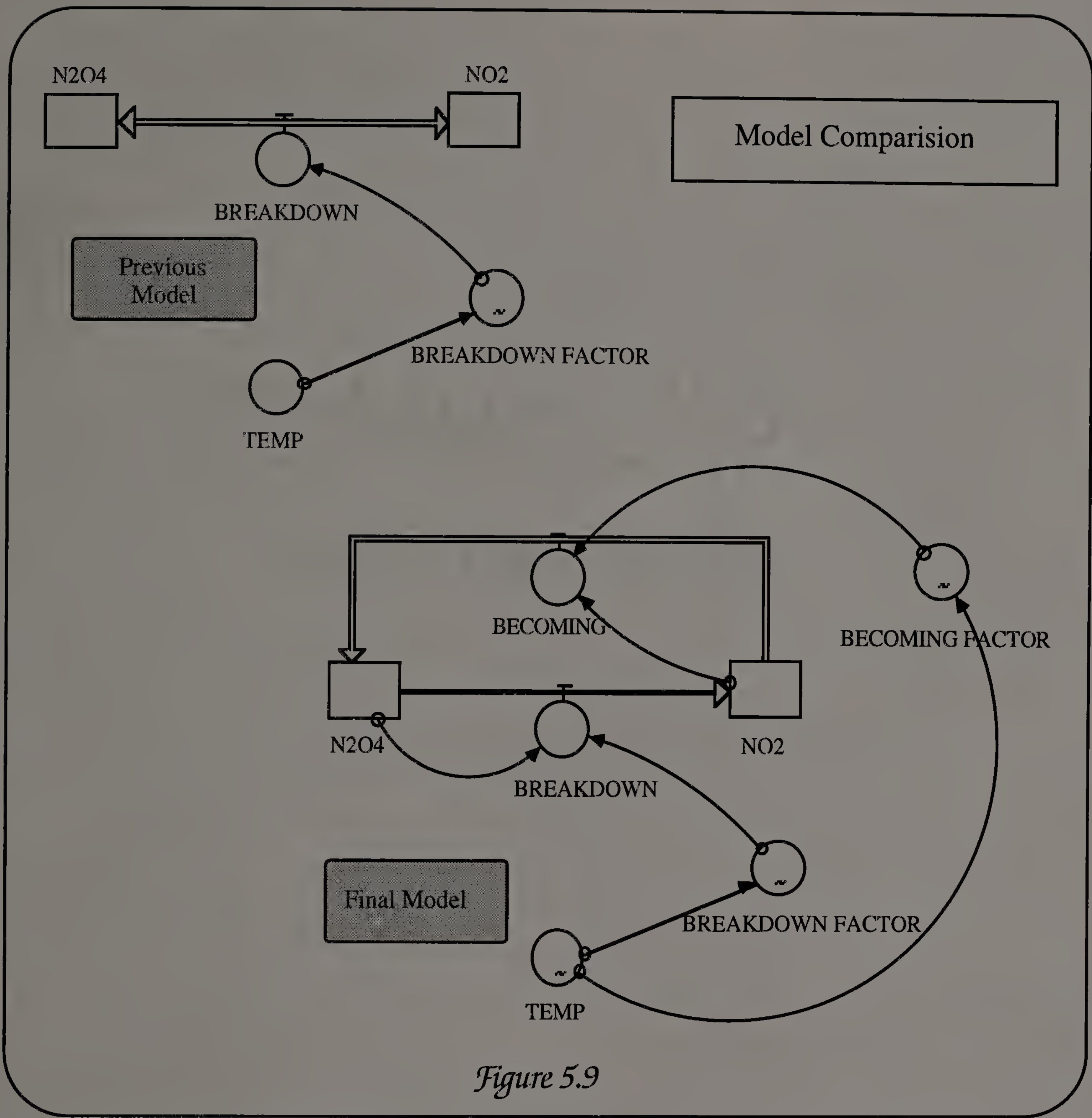


Figure 5.9 Model Comparison

What is significant about the previous dialogue is that the (old) original model, was thought to have been complete. The behavior of the system as depicted in the various stages of model construction encouraged students to change the structure. Structural modifications in a broad sense reflected transformations in assumptions. The previous diagrams depict the incremental changes in students' STELLA models over time (see Figure 5.7 and Figure 5.8).

5.3 Barriers to Understanding STELLA

Before analyzing the benefits of STELLA, barriers to STELLA learning will be itemized. These problems can generally be classified into interpretation and translation problems, logical experimentation, complexity, competing theories, and prediction. Examples of each barrier will be drawn from student protocols. By way of disclaimer it should be noted that although learning barriers have been categorized, it is difficult to disentangle cognitive difficulties from one another.

5.3.1 Translation Problems

Students do not generally have experience translating dynamic relationships into functions. Making a connection, and being able to describe how two variables are related is not sufficient in STELLA. The student has to be able to translate that relationship into either a graphic relationship or into an algebraic expression. S2's protocol suggests that this not an easy task for her:

S2: Maybe.... some kind of equation you would use so that as temperature goes up the BREAKDOWN will increase.

R: How could we do that?
(pause, no response)

In this case the researcher ends up suggesting a solution.

students were sometimes confused by the directionality of connectors. In one instance, S2 was confused about translating causality into connectors. She was able to verbalize the relationship between variables (BREAKDOWN, BREAKDOWN FACTOR and temperature), yet wasn't sure the direction of connector arrows.

Based on later statements S2 understood the direction of the relationship, she just didn't know how to translate that into STELLA notation.

During construction of his cocaine model S4 also stumbled on the semantics of arrow directionality, but then was able to think through the situation.

Another problem area was the creation of intervening variables, like BREAKDOWN FACTOR in S1 and S2's chemical model. Intervening variables are not generated directly from relationships so are not salient.

Another challenge for students was translating their ideas into STELLA notation. It was confusing for students determining which factors should be converters, stocks, and flows. The barrier of selecting an appropriate level of analysis is a nontrivial issue. Different portrayal structures lead to unique insights. As an example, S4 exhibited a problem translating the notion of a circular relationship into appropriate STELLA notation. He confused flows with connectors. S4 suggested that a relationship existed between one stock (FOOD) and a flow (DEATHS) and between another stock (RATS) and a different flow (CONSUMPTION). Even though half of the relationship already existed with connectors he suggested using a biflow (a biflow is a specialized flow structure that allows material to flow in both directions depending on the sign of the value). The dual directionality of the biflow confused the student. He matched the dual directionality of the flow to the dual directionality that he wanted to construct in the relationships. The biflow specifically deals with flows of materials in either direction not relationships per se. He should have used connectors not flows (see Figure 5.10). This was pointed out to him by the researcher and he did not commit this error again.

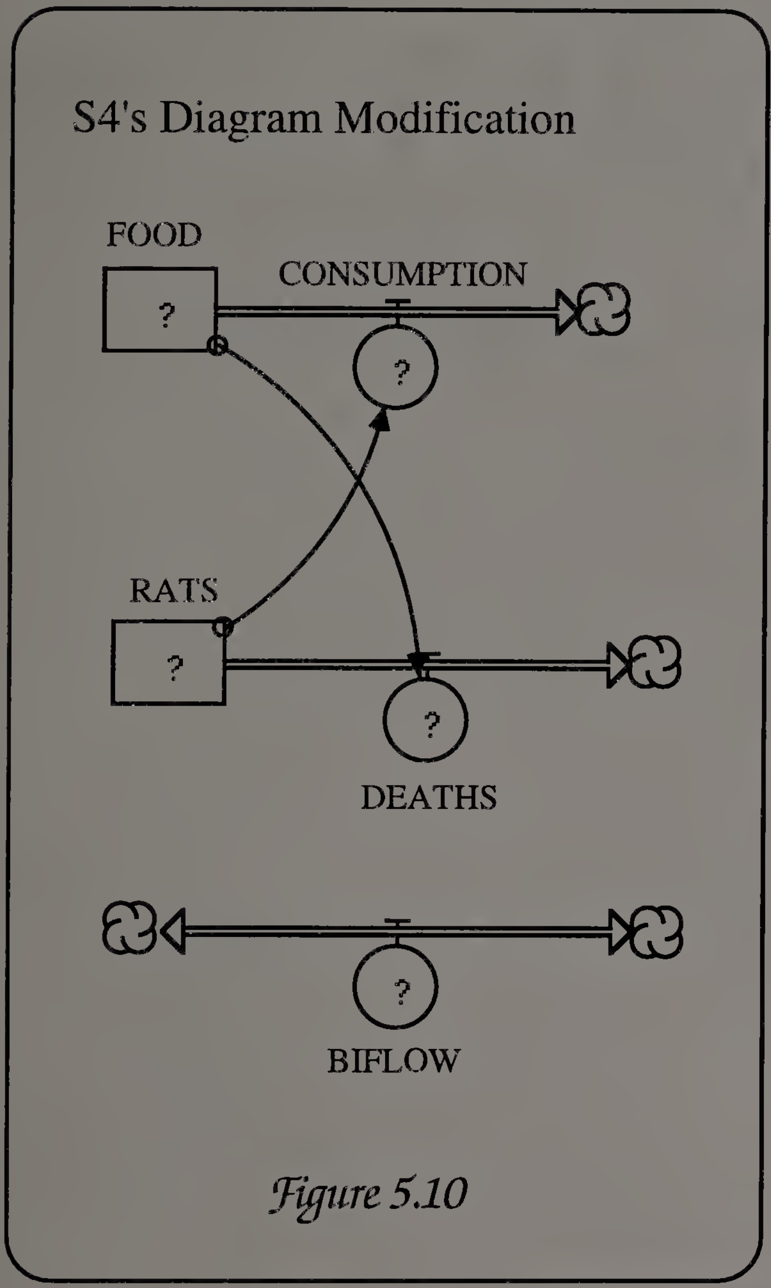


Figure 5.10 S4's Diagram Modification

Another problem of translation was labeling variables. For instance, S2 had a problem that stemmed from an ambiguously labeled flow. In her rat model she had labeled the inflow to FOOD as "FEEDING" (see Figure 5.11).

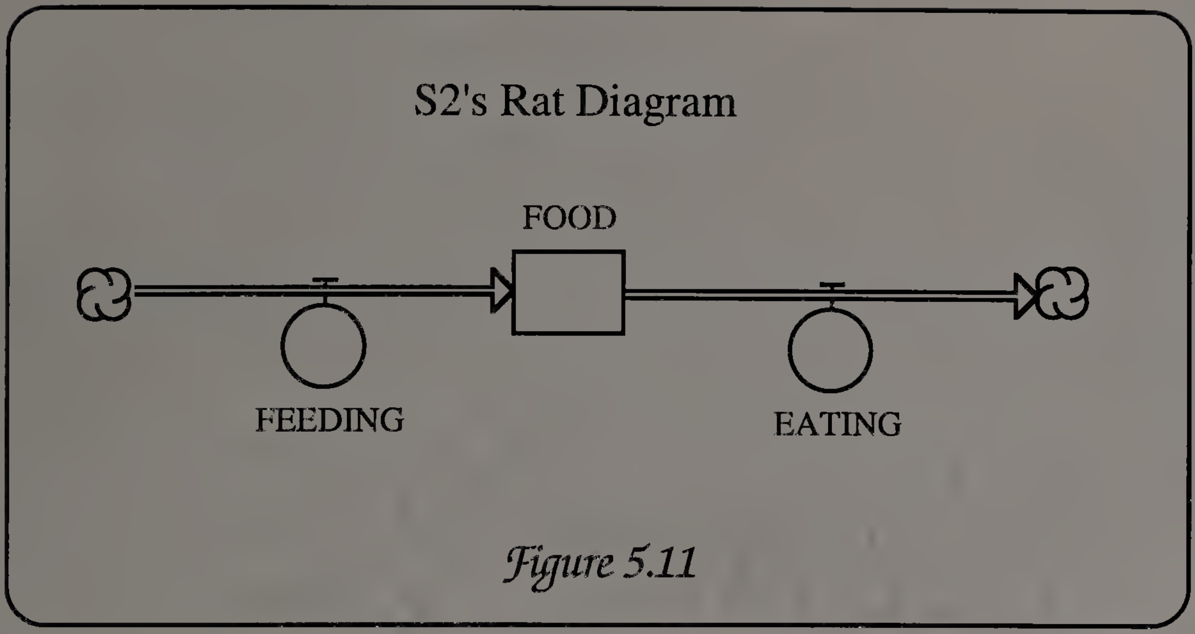


Figure 5.11 S2's Rat Diagram

At the next session she had become confused, thinking that FEEDING was the rats feeding on the food when in fact the STELLA diagram indicated that FEEDING was adding food to the system. She recognized the problem and changed the inflow to "ADDING FOOD" rather than "Feeding" to help clarify the meaning.

In some cases students attempted to translate their mental model into pictorial form. When S1 and S2 began construction of their chemistry problem , they labeled each stock as a glass bulb. In this particular problem the bulb per se is not what is under investigation, the concentration of the chemicals is the main issue. The bulbs were used as a pictorial analog of the referent. The students want to use stocks to depict glass bulbs because they are both containers. The difficulty was an issue of an appropriate level of investigation. This is reminiscent of the work on graphs (McDermott, L., Rosenquist, M., & van Zee, E., 1987; Schultz, K., Clement, J. & Mokros, J., 1986) in which students tended to see the graph as a picture of the event rather than an illustration of abstract dimensions. Reimann (1991) from his research with simulation programs also noted this tendency for students to describe new phenomena in pictorial terms. The focus on the bulbs only lasted briefly, S2 suggested that they needed to portray other dimensions of the information (equation information):

S2: But we have to show somehow.... (gesturing towards the chemical equations in the description)

The students from this point change their focus to portraying the chemical equations rather than portraying a pictorial image of the problem.

However S1 & S2 still wanted their portrayal to have the same physical dimensions as the written equations in the written description. In the description there are two equations so students constructed their model with two flows to make it a visual analog of the description. A useful way of representing this scenario is having the NO_2 and N_2O_4 concentrations each be one stock with either a biflow or two unidirectional flows between. STELLA encourages this by forcing students to use unique labels. Students became frustrated when they attempted to create two N_2O_4 stocks and the system refused, they didn't recognize the value of only having one stock representing one factor in the model.

As students grapple with the problem of portraying the scenario they have to select the appropriate level of investigation. Students analyzed the problem, identified a level of analysis, and then attempted to match it with STELLA's portrayal. When the match failed the students moved on to another level of analysis (from glass bulb to chemical equations and from equations to chemical concentrations). This matching processes is probably similar to analogical problem solving described previously.

S4 provides an example of a pictorial translation error. After reading the description of the cocaine scenario S4's first reaction was to represent the physical dimensions of the information:

S4: Make these little circles (converters) like a neuron, have this as the synapse (stocks), I don't know.

Students first knee jerk reaction was, to activate a strategy that employed searching for the salient similarities between the model's symbols and the referent's physical appearance. Only after further thought and encouragement were students able to shift the focus to the more abstract dimensions of the description.

Understanding rates or flows in STELLA models were also problematic. For instance, S2 had trouble with STELLA's notation of flows. She begins by trying to label the flow as coldness. The researcher then readdresses the concept of flows:

R: Remember this is a rate or a flow.... You have got temperature down here right... What would we call this (pointing to the flow)?

S2: We could...like...the amount of time it takes to go from colorless to reddish brown, I don't know.

Although S2 adds the dimension of time, she doesn't have a stable notion of what a flow is.

S4 also exhibited problems understanding how flows operated in STELLA. He had the idea that an in-flow added material at a given point in time then the out flow took out material at another point in time.

S4: Cocaine will go up and then go down because and then it will go up again.

R: Why?

S4: Because you are going to have it going in (COCAINE ACCUMULATION) and then it is pumped out the INFLOW and OUTFLOW and then there will be 10 going back in.

S4 views flows as being discrete functions as opposed to continuous functions. He sees flows as rates but based on operations that are carried out sequentially rather than simultaneously. Even after instructional intervention by the researcher S4 persists with this view of system functioning as depicted in his predictions of COCAINE ACCUMULATIONS in Figure 5.12.

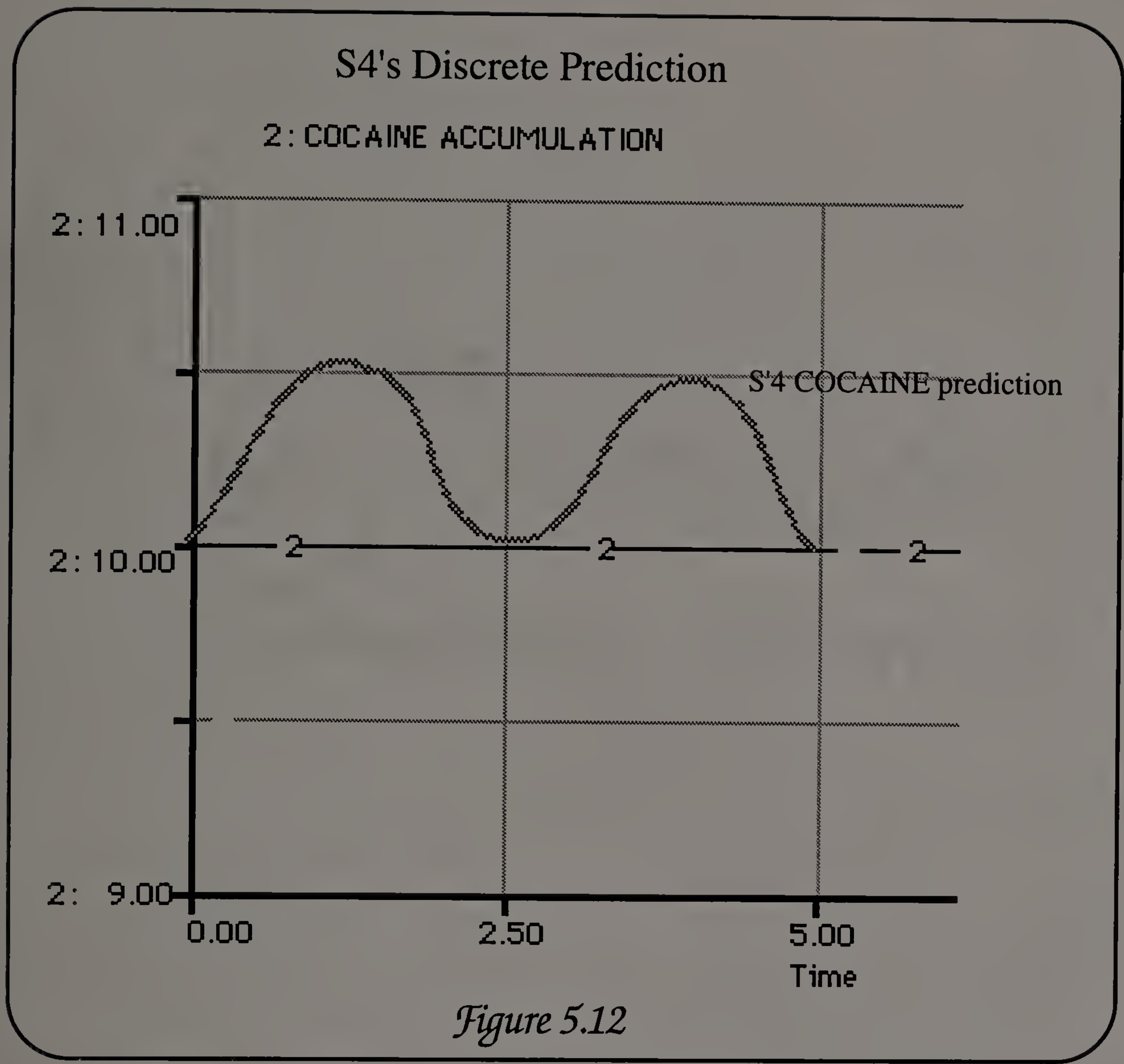


Figure 5.12 S4's Discrete Prediction

The graph helps to provide information that confronts the students thinking. In the following protocol S4 suggests a change in thinking:

S4: It went in a straight line but I see how it did that because there is 10 being put in so it is always at a certain point.

The graph provided S4 with counter evidence that highlighted better how STELLA was operating than the verbal description given by the researcher.

5.3.2 Interpretation Problems

One of the challenges to interpretation was that the STELLA model was not isomorphic with internal representations. This bothered students because they recognized that the model was their own construction and they anticipated it to match expectations.

In one instance, the researcher had suggested putting the model into equilibrium before testing the system. S1 became frustrated when the model was put in equilibrium. She thought rats should increase because more would be born even though the death rate and birth rate were equivalent. Later S2 suggested that the rats were eating each other. Although this was an interesting comment it had no basis in the constructed model. After reflecting on her experience with the model S1 describes a significant discovery:

S1: I think its just this, its just that I think this is reality and I guess this isn't it (referring to the rat model)

Later after making changes to the model the researcher helped put the model into equilibrium. S1 seemed a little distraught that the model was back in equilibrium because she felt that it did not reflect reality:

R: Everything right now is balanced.

S1: Oh no...

R: Because that (death fraction) is .375 and this (birth fraction) is .375.

S1: But weren't we making reality sort of?

R: But isn't it possible that we are adding just enough food to keep the rats alive, and the number of dying is equal to the number being born? Couldn't that be reality?

S1: Not for long.

R: What did you learn from today's session?

S1: "When it isn't reality it drives me crazy."

It seems difficult for this student to understand the value of balancing the model. Starting out in equilibrium allows students to see the effects of single changes to the system. Despite the fact that this rationale was provided to the student S1 insisted that the model should be reality. This probably reflects a lack of experience with the modeling process. This the first indication that she is understanding the difference between a model and its referent.

On occasion students keyed on inappropriate aspects of the symbol system by focusing on surface level features. For example, S2 predicted that the Rat population will decrease. This thinking was an artifact from the last graph. Since the Rat population was declining when the graph ended S2 might have been thinking that it would just continue in that direction. No other explanation was provided. This type of thinking was demonstrated numerous times by S2.

Another example of this thinking was illustrated when S2 made a graph prediction:

S2: Well if we raise the temperature, when we raised the temperature to 35, like when it was 25 it went down more. If we raise to 35 it went up more, if we raise it to 45 it will go up even further.

Instead of thinking through how the variables interrelate, S2 opts to focus on the graph output from past runs as the basis for her prediction.

Looking for patterns in information is typically a good strategy however in those situations described previously S2 was preoccupied with visual output. The visual information was easier to process for her than thinking through the logical structures.

In some circumstances students had difficulty reconciling their predictions with the resulting time series graph. These problems involved interpretation as well as translation processes. On one occasion the graph was close to student's predictions but outwardly appeared different because of STELLA automatically scales the graphs. S1 indicated by her verbal protocol a sense of cognitive dissonance. Initially both S1 and S2 seemed to consider their predictive graphs to be quite different from the actual graph. As was pointed out to them by the researcher, time was a relative factor and can change the shape of the graph. Students using STELLA are stimulated to come to grips with the differences between expected and resulting behavior. This kind of experience may explain the finding that students improved in graphing understanding by interacting with STELLA (Mandinach, 1989; Zuman and Weaver, 1988).

S4 demonstrated a different problem while interpreting graphs:

S4: It looks like it takes a lot of FOOD to bring up the RAT population (as he watches the graph plot) Oh.. I was right (when the RATs started to increase again)

S4: It keeps getting smaller (referring to the oscillations) (see Figure 5.13)

R: What do you think will happen over time?

S4: The RATs will just die out.... It seems that everything is getting smaller.... the same thing happens, it gets less and less.

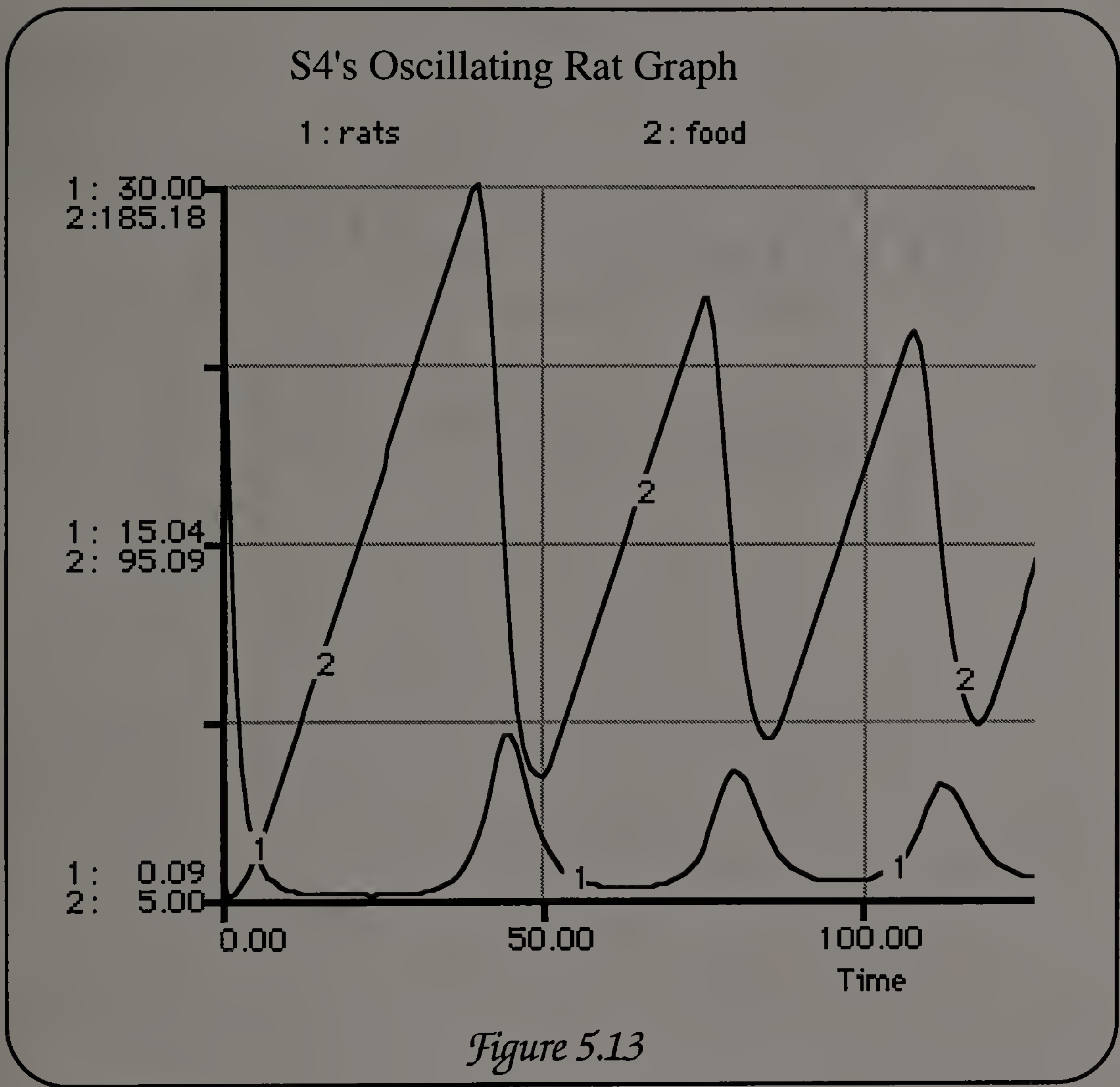


Figure 5.13 S4's Oscillating Rat Graph

S4 was keying on the peak of the graphs to extrapolate interpretations. This misinterpretation erroneously lead him to the conclusion that the rat population would become extinct.

S4 later revealed another possible problem with graph interpretation. The researcher pointed to a segment of the graph (see Figure 5.14) and asked the student to explain the state of the system:

S4: It is that there are no RATs eating the FOOD so....

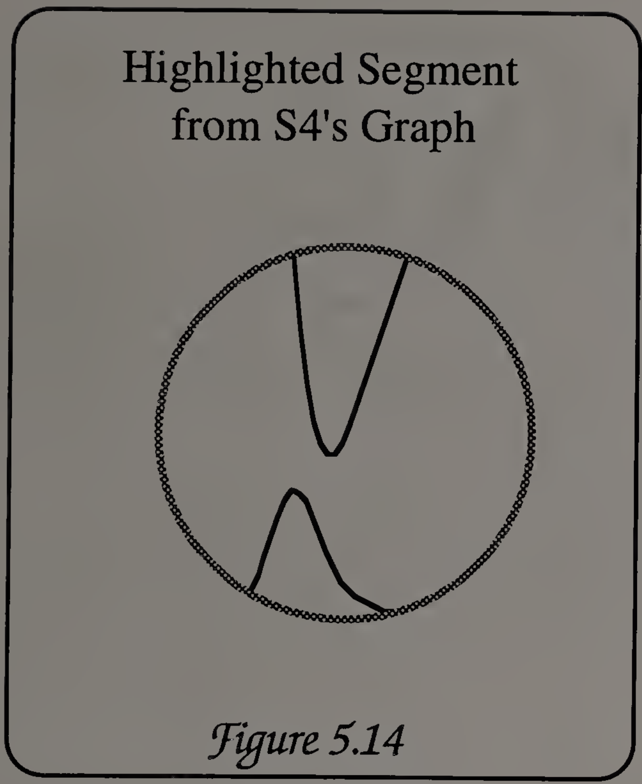


Figure 5.14 Highlighted Segment from S4's Graph

S4 suggested that an increase in FOOD was the result of no rats eating. Such was not the case, this was an error in interpretation. This is an example of students not able to bring together two simultaneous events. Students thought that if part of the loop was increasing the competing part of the loop must be turned right off. It is difficult for students to mentally reconcile two concurrent flows and explain how one dominates over the other.

Another interpretation problem arose as students had difficulty focusing on one relationship in the system. They confounded a variable's functioning by factoring in components that did not directly relate to it. For instance, S2 had trouble isolating one relationship from the rest of the system. This segment is contained in the following segment of protocol :

S2: This section right here (BECOMING) seems a little weird because we aren't doing anything with it right now.

R: Well just forget about that (BECOMING) for the moment

S2: I am trying.... it is hard.

In the previous protocol S2 is having difficulty isolating relationships. In STELLA there seems to be confounding strategies; students are to look at relationships between variables without considering other influences when defining relationships. However, when anticipating the overall behavior of the system the student must consider all the influences that come to bear on the outcome. Problems of selecting an appropriate strategy became another barrier to dynamic thinking.

Later the S1 & S2 were trying to isolate the influences that affect the BECOMING flow (see Figure 5.15):

R: So are you saying the amount of N_2O_4 or the amount of NO_2 that will directly influence BECOMING?

S1: The amount of this (N_2O_4) going into this (NO_2).

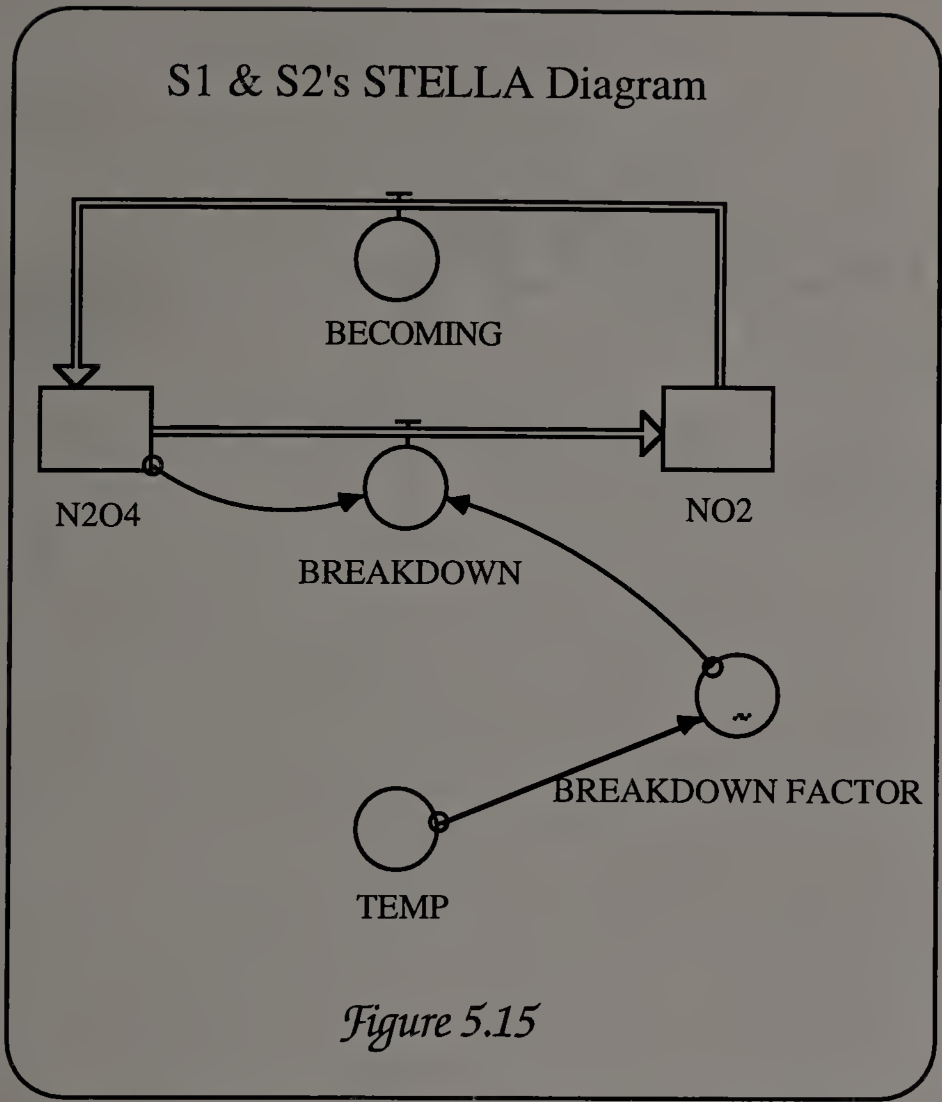


Figure 5.15 S1 & S2's STELLA Diagram

S1 can't seem to isolate those influences that directly affect BECOMING. Although the flow S1 describes does eventually affect the BECOMING flow, it does not directly affect it. Later S2 is able to recognize the confounding influence of a feedback system:

> S2: I think so. Like we have a number in N_2O_4, I am just totally avoiding that (the BECOMING flow) because it gets me all messed up. Number in N_2O_4 and then multiply it (pointing to BREAKDOWN FACTOR) Multiply them together and you get the answer for BREAKDOWN. And then you subtract it from N_2O_4. Ah... I understand it now.

The complexity of the system caused students to create interpretation errors that led to translation errors as in the example that follows.

R: So as temperature increases do we get more NO_2 or more N_2O_4? (An attempt to challenge their current thinking about BECOMING FACTOR)

S1: More NO_2, well actually.... yea more NO_2.

R: So as temperature decreases do you get more NO_2 or more N_2O_4?

S1 &S2: More N_2O_4.

As temperature increases NO_2 increases, but in the model BECOMING is defined as increasing which would result in a loss of NO_2. This is at odds with information in the written description. The confusion may be the result of losing track of relationships just because the complexity of the system is beginning to extend beyond the students' working memory. This may have been averted had STELLA been able to portray the nature of relationships between variables in the diagram view (see modifications to STELLA, section 7.9.7). After the researcher provided a description of the system using the diagram, S1 acknowledged the conflict between the model and the description and resolved it.

When students were asked what they found most difficult about STELLA they mentioned the complexity of the system, everything seems to connect with everything else:

S2: Like the rat one we did, we had so many different arrows.

S1: Yea everything is so connected to each other. You know it is not like we thought before where you could just have this (cutting the system in half with her hand) and a couple of things hanging out and everything is going to be okay, but every thing is related to each other in some way and it is really hard to show that. Its really hard to think how each thing is related to each other.

On reflective abstraction S4 identified similar difficulties using STELLA. He made the following comments:

S4: It was complicated figuring out the arrows what you need to make it work right and the equations, you have got more and more stuff it gets more and more complicated and you have to think of all the things that are happening and figuring that out. I thought that was kind of hard sometimes.

The complexity of the model became a limiting factor for student understanding. However, this complexity is derived from their own cognitive constructions. Coming to an understanding of the complexity of naturally occurring dynamic systems is useful knowledge because it informs perceptions and judgments.

Students came up with different theories to explain the system's behavior. During construction of the chemical model S1 devised a theory based on an analogy of capillary action in the leaf of a plant:

S1: It is just because when something is being taken out of here (gesturing from N_2O_4 and BREAKDOWN) something has to be replaced again (gesturing toward the BECOMING flow) and so that way it can't hit bottom, you know, its just like that cohesion thing with trees, you know what I mean, I remember this from biology, remember like with leaves and stuff remember when like when the moisture is sucked out of a leaf you know, like it is pulled up and another one takes it's place, that's what I was thinking.

After S1 viewed the behavior of the system (graph view) she realized that her capillary theory failed to explain the output of the model.

R: S2, can you explain what is going on?

S2: I don't know.

S1: Well, there goes my theory.
(long pause)

S1: Cause, Wait let me get back (switches to diagram view), it all has to deal with this stuff and the amount that it takes out (pointing to the BECOMING FACTOR & BREAKDOWN FACTOR, then to BREAKDOWN).... Because if this the smaller number (BREAKDOWN) cause this BREAKDOWN is, the BREAKDOWN FACTOR is this (N_2O_4) times this (TEMP), I think.

After some experimentation S1 determined that the capillary theory is not useful for describing system behavior. On the heals of S1's theory's failure, she returns to her feedback theory that elicits a better explanation of system behavior. Not all student analogies competed with dynamic thinking. S1 illuminates a link she has made with other school experiences by explaining her feedback theory to S2. She uses an analogy of business interest rate:

Students reflecting on their experiences suggested that predicting the outcome of system behavior was a difficult undertaking. As an example of prediction difficulty, S4 attempted to predict the interaction between food supply and rat population, see Figure 5.16 below:

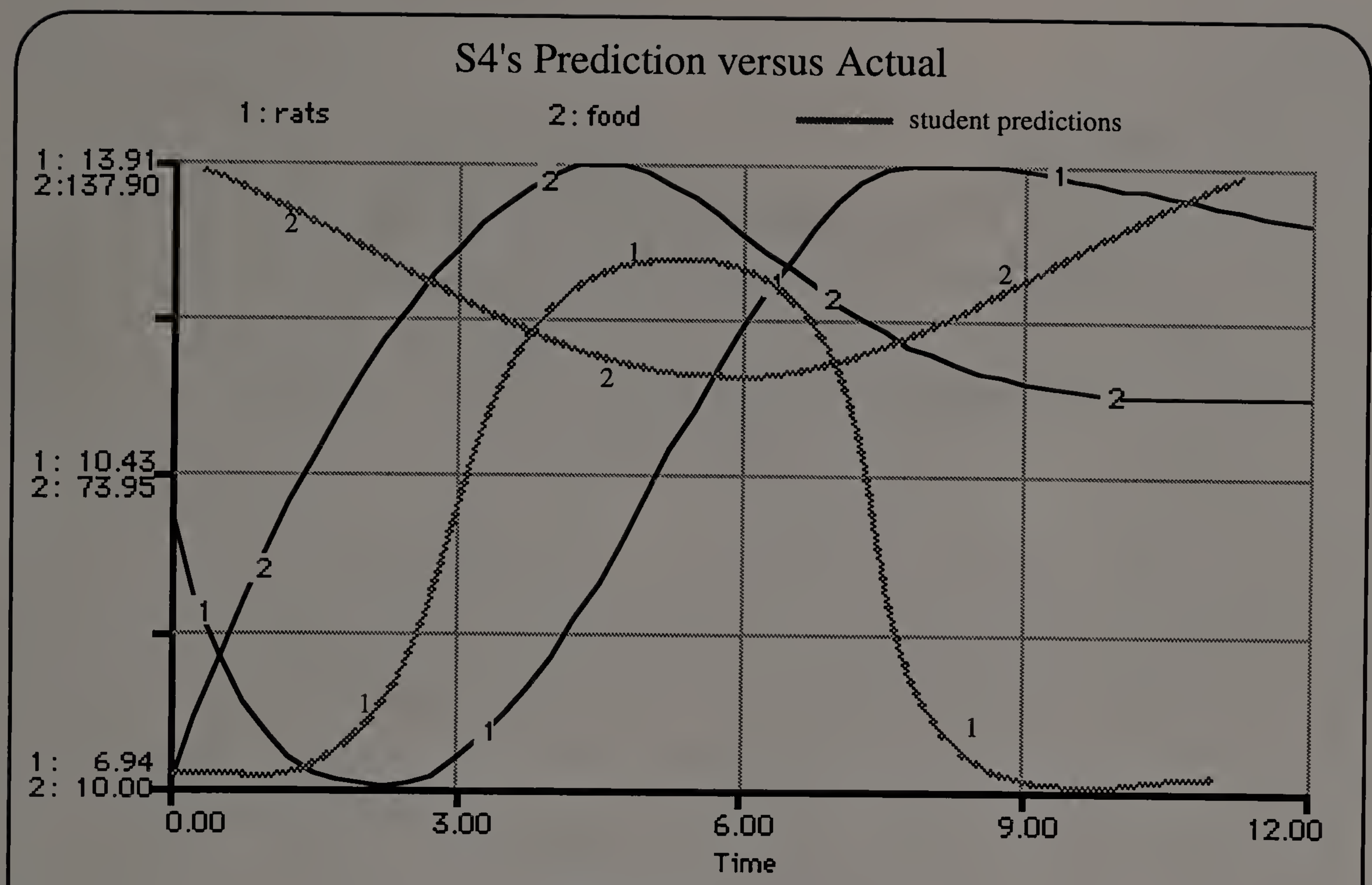


Figure 5.16

Figure 5.16 S4's Prediction versus Actual

Even though his predictions are fairly close to the behavior of the model, he realizes that there are some subtle but significant differences. This incessant incongruity between prediction and system behavior seemed to increase frustration. This frustration is described by S1 in her concluding remarks:

S1: Figuring out those graphs and what they are going to be. I mean after you found out what it was it wasn't as bad because then you could figure out how it got that way, but figuring out in the beginning where it (graph) is going is just pathetic.

Even though prediction was viewed with frustration by students, this process is valued by the researcher.

To summarize this section on learning barriers, there were a variety of difficulties encountered. These challenges were for the most part necessary experiences to come to a richer understanding of STELLA and their own cognition.

5.4 Benefits of a STELLA Environment

The following section itemizes those attributes of the STELLA environment that had inferred cognitive benefits

5.4.1 Multiple Symbol Systems

Different portrayals illuminated distinct dimensions of information. The dimension of data highlighted by a depiction stimulated different learning. The following illustrations provides support for this hypothesis.

In developing a predictive graph S1 referred back to the diagram to help her remember the relationships. This action is significant, it suggests that the STELLA diagram contained information that was not available in the graph view. Note that the dimensions highlighted by the diagram include an iconic portrayal of all the factors and relationships that exist in the model.

In another protocol, S2 observed the animated icons and described the behavior of her Chemistry model as being dynamic. Unfortunately there was no dynamic behavior because the flow was set at a constant rate of zero. However, challenged with the tabular form of the data that suggested static behavior she exhibited mental dissonance (see Figure 5.17) :

S2 Chemistry Table										
Time	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
N2O4	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
NO2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Breakdown	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 5.17

Figure 5.17 S2 Chemistry Table

S2: Well time went by and nothing really happened.

R: Why is that?

S2: I am not sure why....

This expressed doubt is an indication that some mental dissonance was generated. In this case the table presented a better view of the model's behavior because in S2's mind the system was dynamic, but the model's behavior was static. A graph would have produced a straight line. This may have had the same consequences as seeing the table but a straight line may appear to be dynamic because it moves a across the horizontal plane. Seeing the actual values made it difficult if not impossible to rationalize dynamic behavior.

In another instance, S1 and S2 failed to understand the implications of having a negative number in a stock (N_2O_4). In this particular case a negative number as the value for a stock did not make sense since the stock was suppose to represent the concentration of a chemical. The researcher attempted to use the tabular portrayal as a vehicle to stimulate mental dissonance:

R: Lets back up a little (on the table) and find where it makes the transition between positive and negative numbers.

(students scroll the table back to the transition position)

R: So somewhere between those two numbers N_2O_4 reaches 0. How much N_2O_4 is there in the container when it reaches 0? (An attempt to help students relate the output of STELLA to the real world)

S1: None.

R: What happens when you have -.5?

S1: (laughter) You will even have more none.

Students' laughter suggested a realization of a problem nonetheless in a latter protocol they continued to ignore the illegitimacy of negative values. The tabular view confronted their thinking, but they were unable to determine how the system could inhibit the production of negative numbers.

In STELLA graphs provide insight into system behavior through a time series plot of values. This acted as an audit trail of system behavior over time. The animated icons did not allow for this perspective. To illustrate this point, two explanations of behavior will be described, first in graph view then in the animated icon view. In the chemical model, with the graph view S1 described an insight concerning system behavior while temperature changed over time (see Figure 5.18):

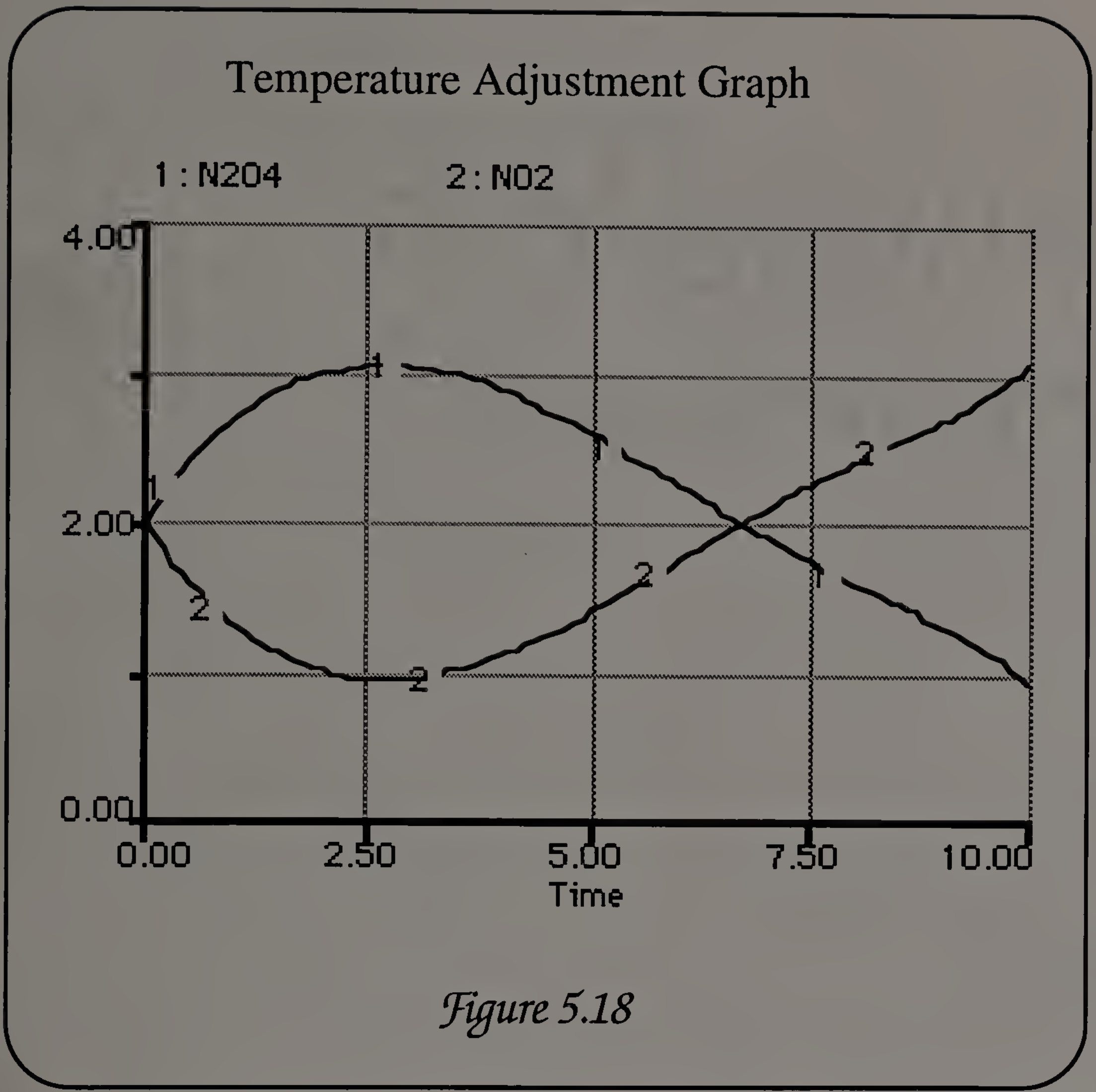


Figure 5.18 Temperature Adjustment Graph

S1: Oh.... because it (TEMP) would be below 25... it is the excitement, it is below 25 so this (N_2O_4) would be breaking down so and this (NO_2) wouldn't be breaking down so much so this (NO_2) would be going into the one (N_2O_4) and then after a while this is where it reaches 25 (where the N_2O_4 and NO_2 cross), right here, and then it starts going higher...

S1: Wait though, and so this is where it reaches 25 and that's when this (N_2O_4) starts breaking down more and this (NO_2) is less, it doesn't go as fast, I think.

Following this protocol she views the animated diagram and makes the following description (see Figure 5.19) :

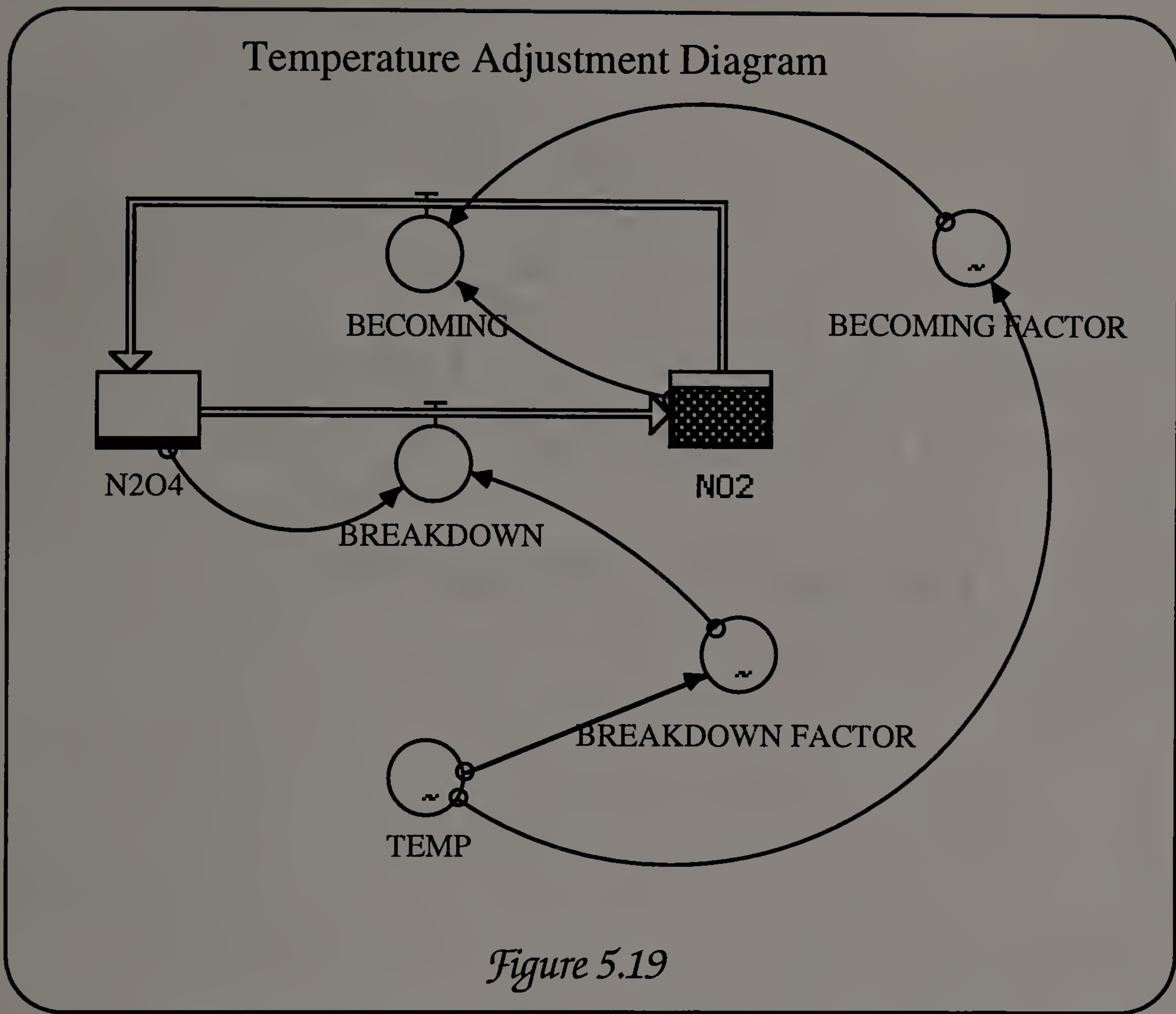


Figure 5.19 Temperature Adjustment Diagram

S1: Cause the temperature , when the temperature is below 25 this (NO_2) breaks down more, and more of this leaves when the temperature is above (25) then this (N_2O_4) breaks down and so therefore since we are starting below and we are starting out at 0 and its working its (temperature) way up, this (NO_2) is the one that will start moving so this (N_2O_4) one fills up first and so then it hits 25 and both are in equilibrium and then as it goes above 25 then then this (N_2O_4) one loses what it has again.

The two descriptions following different portrayals are very similar to each other but the animated icon view stimulated more embellishment and used terminology associated with the plumbing metaphor. One interpretation is that the animated icon view extended think time to formulate an elaborated explanation. Alternatively the animated icon view highlighted the process of accumulation and flow making those aspects of the information available for explanation. For instance note the key phrases “start moving”, “this leaves”, ”fills up” , “loses”. These phrases seem to be derived from the plumbing metaphor. This metaphor funneled student thinking by providing an analogy for analyzing and explaining system behavior.

5.4.3 Translation Bias

Any time a translation occurred between mental models and an external portrayal system the bias of that system had potential influences on which aspects of the mental model were activated.

An illustration of this came from the chemical protocol of S2. S2 had finished reading the description of the chemistry scenario again after attempting to translate it into STELLA.

> S2: I read it over and over again and each time I read it gets harder to understand.

STELLA takes a written description that appears straight forward and fosters a probing of unexplored aspects of the description, namely the dynamic aspects.

Another example of translation bias was illustrated in S4’s cocaine protocols. After reading the cocaine scenario S4 began constructing the STELLA diagram. He determined that cocaine should be a stock called COCAINE ACCUMULATION and he proceeded to discuss the flows. Then there was a moment when he paused and seemed a little disconcerted.

> S4: You would have....I don’t know if you would have cocaine coming in.... it doesn’t really leave, it just clogs up the pumps and then you could have it ....

S4: You could just have an inflow and an outflow.

He then construct an inflow and labeled it INTAKE and an outflow that he labeled it OUTFLOW (see Figure 5.20).

R: So what would the OUTFLOW be equivalent to?

S4: Um... leaving the system.... leaving the body.

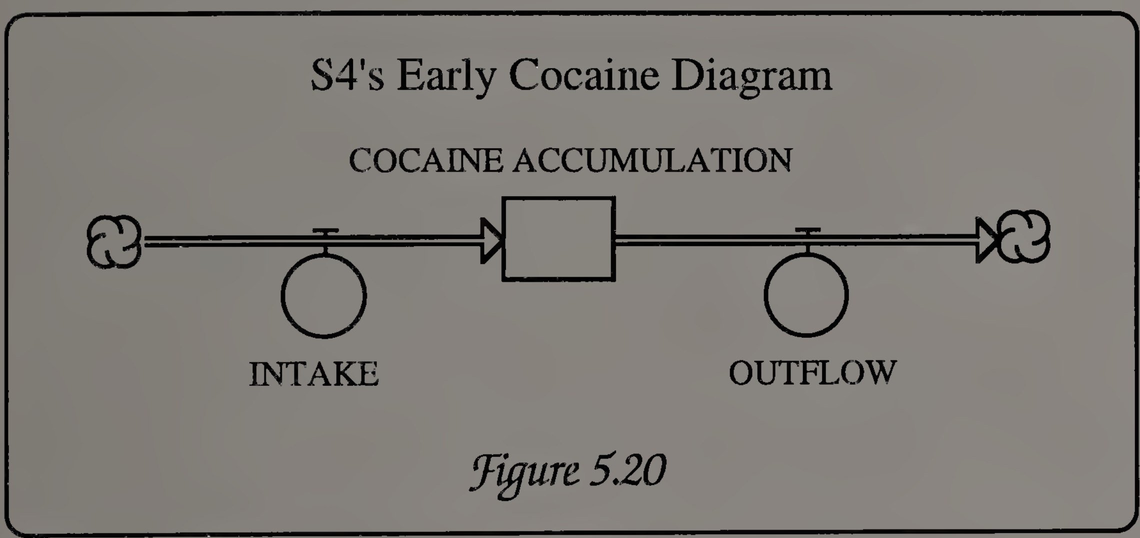


Figure 5.20 S4's Early Cocaine Diagram

S4 was influenced by the translation bias imposed through the plumbing metaphor. Without the plumbing metaphor he may not have keyed on cocaine leaving the body.

STELLA's notational system suggested this change to the mind of the student. Most models that are developed in STELLA are nonconserved in that they have an outflow. The STELLA metaphor caused S4 to scrutinize the written description for something that corresponded to an outflow. When he failed to make a match between the description and the metaphor he naturally queried if there should be one. In this way the student was able to generate an interesting question that resulted in extending the original theory to account for the cessation of cocaine from the system.

5.4.5 Animated Icons

The animated icons view provided students with a dynamic perspective of the workings of the model. This was often used in the session to challenge or clarify student thinking. For instance, S2 had difficulty describing her prediction using graphs, but when asked to think in terms of levels with the animated icons she seemed more adept at describing her thinking:

> S2: First this one would be full (N_2O_4), and then the level would start to get lower and lower, and then at first this one (NO_2) would be empty because nothing gets broken down, this one (NO_2) would start to fill up and that (N_2O_4) would start to go down.... I guess.

The animated diagram depicted the mechanism for dynamic behavior where as the graph portrayed the change in variables over time.

On another occasion, S1 was able to describe the delay in system behavior after viewing the animated icon view. This view provided corroborating information to the graph that also displayed the delay but the student failed to recognize it in the graph portrayal. When confronted with delay in real time with the animated view, S1 conceded its existence. Delay became salient in the animated diagram because the levels were kinetically illustrated by that view showing lags in response. The reason it is salient is because the changing levels of the animated diagrams are closer to student experience (students have concrete experiences with changing levels of materials).

5.4.6 Diagram

The diagram highlights the factors and their relationships. As an example of an affordance of the diagram, S2 uses the diagram view to help explain her thinking:

S2: It is this what we went over last time? Wait can I go back (she returns to the diagram view) Its that (NO_2) times that (BECOMING FACTOR).

The Iconic view provides a quick reference to the variables used in the model and lent itself to communication.

On another instance, S1 and S2 had both made errors in translating the model because of an interpretation error that was generated from the complexity of the system. The researcher uses the diagram as a platform to explain the current model, which then stirs up cognitive dissonance in S1.

R: So as we are heating it up it goes that way (pointing from N_2O_4 to NO_2) and then as we are cooling it down it goes that way (pointing to NO_2 to N_2O_4)?

S1: Yea.

S2: So it just goes in a circle, I guess.

S1: Right.

S1: Wait no, because this (BECOMING FACTOR) says when temperature increases, cause the BECOMING FACTOR is when temperature increases so does BECOMING.

S1 goes on to determine the conflict and resolve it.

In this next protocol S4 indicated that he was using the diagram to select an appropriate causal influence that regulated the flow called PUMP OUT:

S4: Maybe if we make one of those, what do you call it, one of those graph things that regulate what happens, so when you get a lot of cocaine, it depletes... or something like that.

R: How would you do that?

S4: I would have an arrow from here (pointing finger wanders around the diagram, does not seem to focus on one variable) a graph I guess, to this (PUMP OUT).

This kind of a gesture made above indicates a selection was not made yet and the student was using the gesturing motion to check the various solution paths. In this way the diagram visually depicts factors providing the student a spatial method for tracing potential relationships.

5.4.7 Explicit Relationships

STELLA encourages the student to think about how relationships exist. After a student made a connection between two variables the system put a question mark in the factor that required its input to be defined. For instance in the following protocol S2 had made a connection from a converter called TEMP (temperature) to a flow called BREAKDOWN forcing it to be redefined. This is the first time that this had occurred so she was unaware of the implications. However it seemed significant that the question mark did get her attention and she realizes something needed to be altered in BREAKDOWN:

S2: Oh... (she notices that BREAKDOWN now has a question mark on it suggesting that it needs to be redefined, so she opens BREAKDOWN) Oh.... (she doesn't know what to do so she closes it up, but it remains a ?)

Even though S2 didn't identify the errant factor she recognized intuitively that something was a amiss and she even went so far as to open up that factor to take a look. Had she inspected the information provided more carefully she would have realized there was an input not referenced. The question mark is a generic label for something that either answers a question or that needs a question answered. Suggestions for how to improve upon this scheme is discussed in the appendix called "Modifications".

5.4.8 Tables

Tables highlight the dimension of value and make salient discrete value patterns. S2 was thinking that the current structure of her model was going to stop the drainage of material out of N_2O_4. Unfortunately there was nothing in the structure that accounted for that behavior. When she was confronted by a table of values however she was quick to recognize the conflict between her thinking and the system's behavior (see Figure 5.21).

S2 Chemistry Table

Time	14.00	15.00	16.00	17.00	18.00	19.00
N2O4	0.50	0.25	0.00	-0.25	-0.50	-0.75
NO2	5.50	5.75	6.00	6.25	6.50	6.75
Breakdown	0.25	0.25	0.25	0.25	0.25	0.25

Figure 5.21

Figure 5.21 S2 Chemistry Table

R: So what is happening ?

S2: This (N_2O_4) breaks down and there is less N2O4

R: And then what happens?

S2: I am thinking why does it (N_2O_4) keep on going, why didn't it stop?

Tables provide a listing of the values generated at discrete time intervals. This promoted insight because it made salient the discrete value of variables.

5.4.9 Theory Production

5.4.9.1 Conflict with Current Thinking

In summarizing the benefits of STELLA, students identified the shift in thinking that is generated by viewing system behavior.

S1: Yea cause after you see the graph you can figure out...

S2: You can figure out how it turned out that way.

S1: That's when you really see what is happening is after you see how the way the graph goes and then you can actually figure out what is happening there and how each thing , and that's when you realize how everything is related to everything else, but predicting them before they come up is sad, they should have that in like casinos or something, they would make a lot of money.

In the above protocol, S1 questions the value of prediction. However, prediction provided insight into student thinking. Without predictions, viewing progression in student thinking would be difficult. Explanation of the current system behavior was the beginning of making the next prediction. Student predictions resulted in cognitive dissonance because of conflicts between student theory and system behavior, this in turn stimulated shifts in thinking.

5.4.9.2 Generation of Theory

Developing explanations for model behavior was fundamental to developing coherent thinking. S1 suggested in her summary that STELLA had value because it made her think of "reasons why" things happened.

S1: You can make generalizations really easy, you can have some prediction like what to expect you know what I mean, like what you feel will happen and why, like ideas, like why it happens.

R: Can you give me an example?

S1: Like this thing (Chem model) when I was talking (before), Last time I couldn't figure out how it kept on reaching equilibrium when I didn't think it would then I realized that it's because each thing has to be replaced, you just got to think about it.

STELLA encouraged students to build mechanisms and explicit connections that depicted relationships. This explicitness helped students explain the reason why the model behaved in certain ways.

5.5 Portrayal Efficacy

The next section of this document will infer linkages between changes in student assumptions and affordances of the STELLA environment. The following diagrams and accompanying descriptions will identify affordances of STELLA that were instrumental in stimulating shifts in student thinking This is an attempt to capture changes in student thinking as it happened.

The first vignette illustrates how a student moved from thinking in terms of one-way causality to a feedback perspective. Just prior to this next section, S4 was challenged by the researcher to reconsider the portrayal of a cloud in the diagram. The student then replaced a stock for a cloud. The student was then asked what other questions might be posed about the diagram. The student then used the researcher's previous question as a model for questioning the diagram. The student challenges another cloud and the resulting change in thinking produced a conserved flow rather than a nonconserved flow .

The diagram facilitated a reinterpretation by providing an image where spatial thinking experiments were performed. These experimentations resulted in the formation of a new structure.

In Figure 5.22, S1 begins to appreciate the interconnectedness of the factors in the system. The graph introduced a discrepant event by displaying behavior that was not anticipated. This conflict stimulated the student to reflect on the model and consider other relationships that were previously ignored.

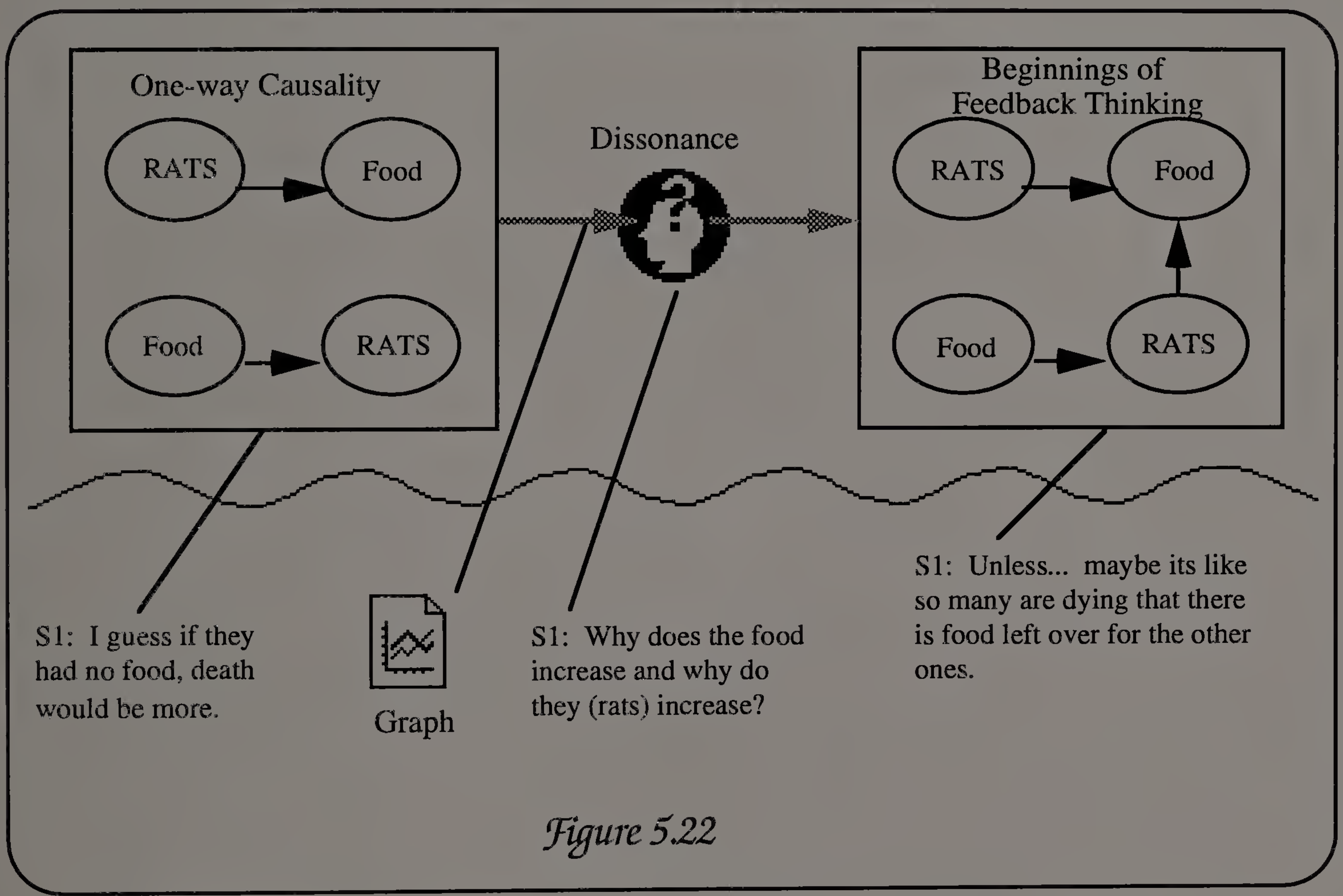


Figure 5.22 Wavy-Line Diagram

The graph encouraged S1 to identify a discrepant event that generated cognitive dissonance. Her questioning resulted in rethinking established relationships and moved her towards feedback thinking.

The following example in Figure 5.23 describes how students moved from viewing the scenario as a picture to a different level of analysis. It appeared that when students saw the diagram as a pictorial image it almost immediately created a conflict because most STELLA diagrams require an outflow or an inflow. In this case the students were working with the chemical model. Representing the Bulbs as stocks negated having any kind of flows.

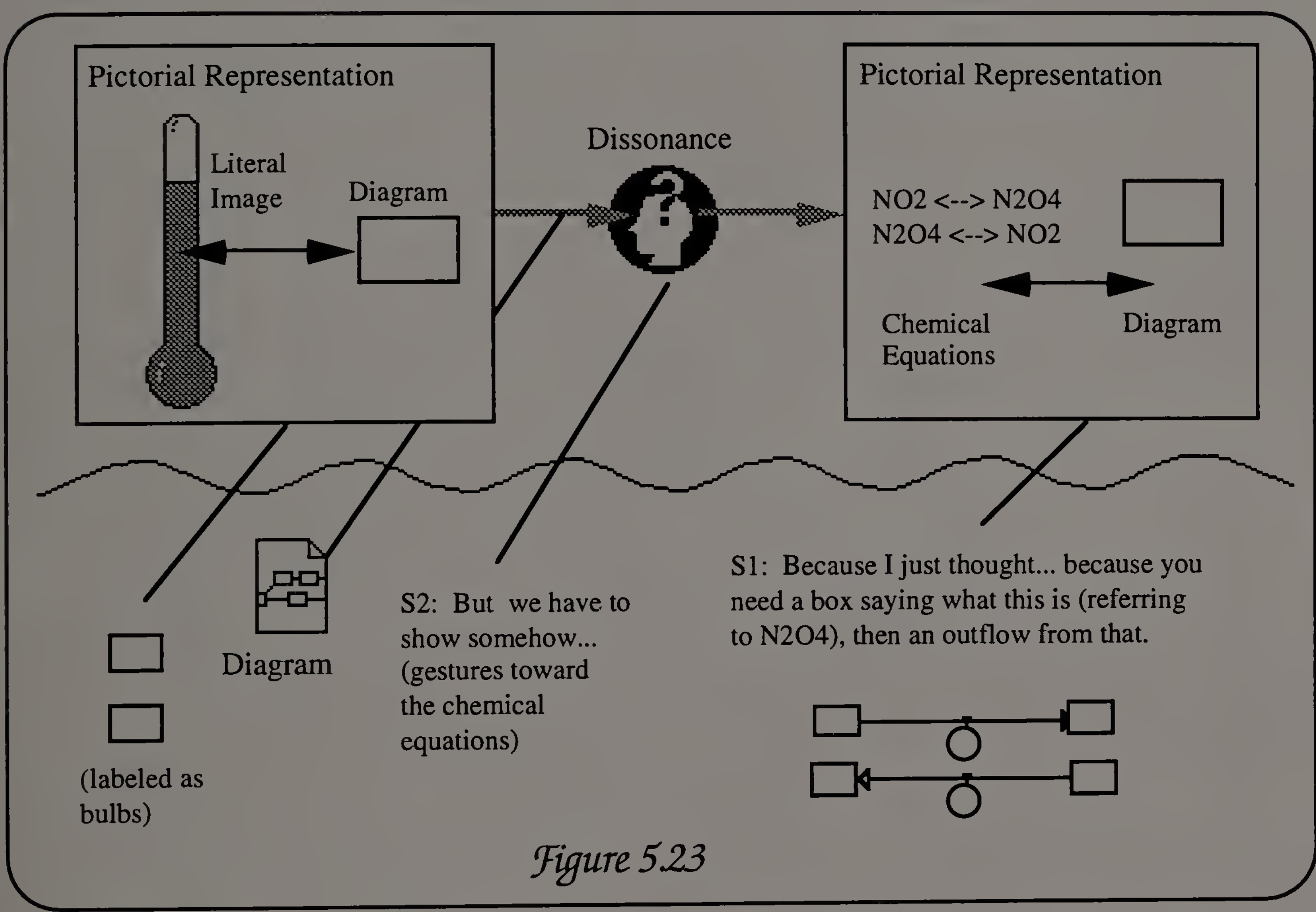


Figure 5.23 Wavy-Line Diagram

The lack of flows in the diagram induced dissonance because without flows there would be no dynamic model, thus the students began a search for an alternative level of analysis and agreed upon chemical equations.

The next diagram (see Figure 5.24) illustrates how the rules of the STELLA diagram assisted students to move from a pictorial portrayal of the equations to a more abstract portrayal that focused on the concentration of chemicals and chemical reactions. At first S1 and S2 were complacent with portraying the problems as a picture of the chemical equations in the description. In the written scenario one chemical equation highlighted the forward reaction and another equation highlighted the reverse reaction. Students focused on this dichotomy and created two separate systems, one representing each equation. However STELLA does not allow two stocks to have the same name. This posed a conflict with the students but both students eventually recognized that a duplicate system was not required, S1 suggested a modification with a reverse flow. These changes indicate a switch from seeing the system as a picture of the equations to focusing on chemical concentration -- a more abstract level of analysis.

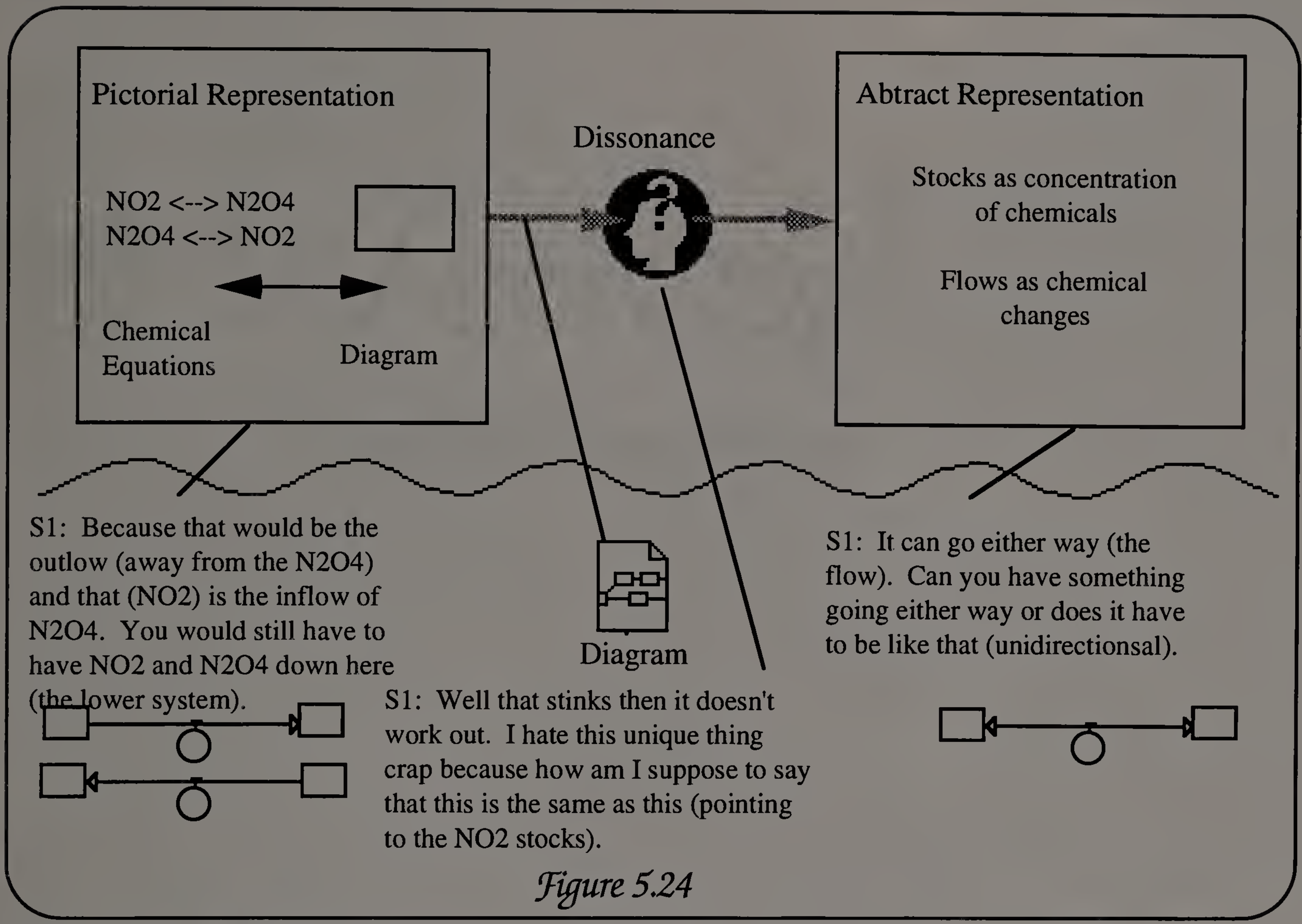


Figure 5.24 Wavy-Line Diagram

This previous illustration was an example of how STELLA revealed a potential difficulty with the textual scenario. The text had illustrated the chemical equilibrium by showing two separate reactions (to highlight the reaction in both directions). The students initially analyzed them as separate reactions (one-way causality). STELLA encouraged a cognitive shift by viewing information at a more abstract level.

In Figure 5.25 the diagram illustrated students transition from one-way causality to simple feedback thinking. S2 began by suggesting that temperature caused the chemical reaction. In this case what is not said is significant. Neither student suggested any influence from the chemical concentration. Students' thinking was challenged with negative values displayed in the table view. S1 and S2 recognized the need for "something to control" for negative values but could not generate the mechanisms for accomplishing this. The researcher revisited a previously constructed model (rats) which exhibited a possible solution. The students saw the analogical similarities (rat population and death rate) demonstrated by making a connection between the concentration of the chemical with the chemical change. After making this change, S1 described system behavior in terms of a simple feedback loop between chemical concentration and the rate of chemical reaction.

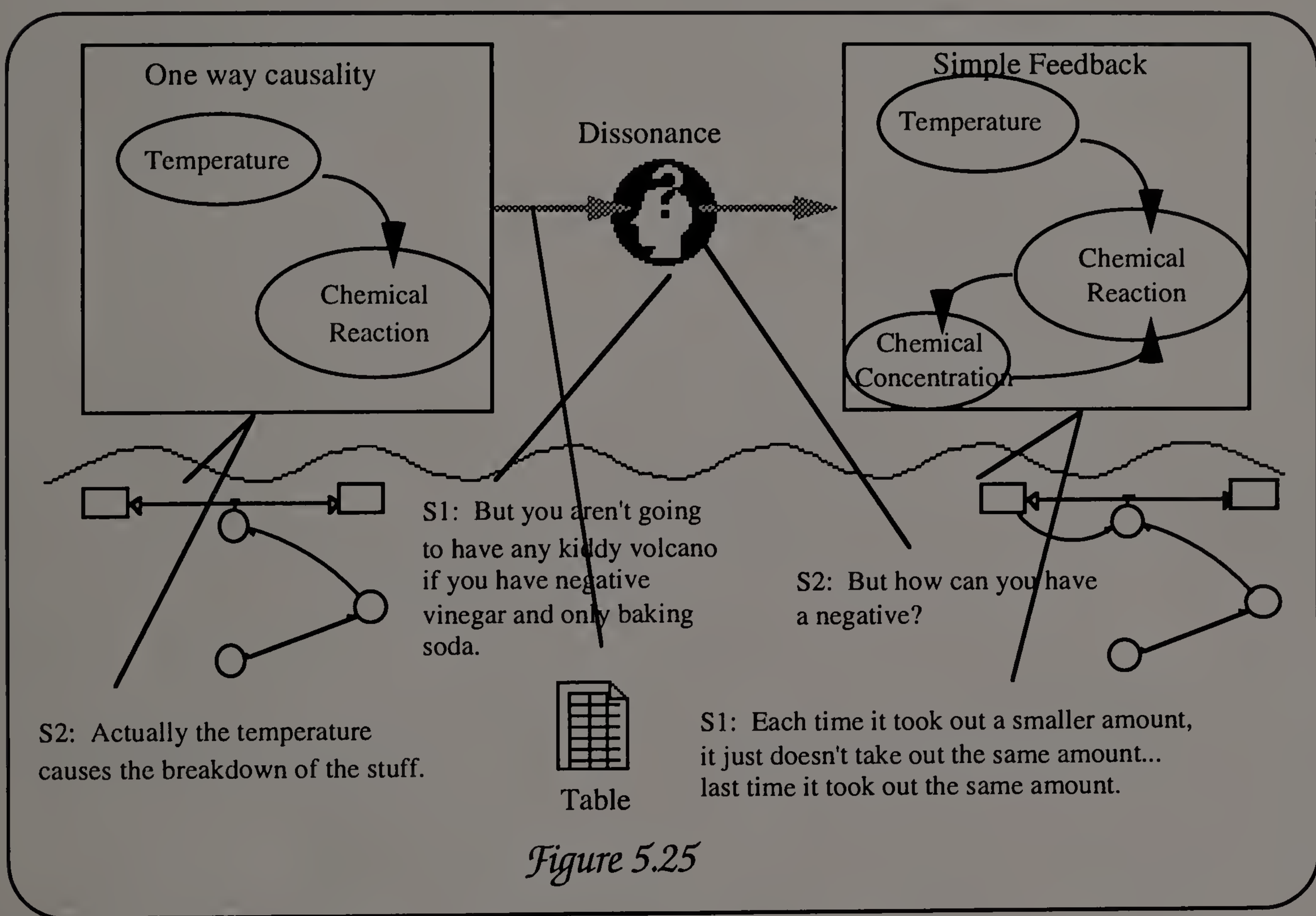


Figure 5.25 Wavy-Line Diagram

In this case the table of values illustrating a negative concentration of chemicals was an impetus to question the system.

Despite the fact that S1 and S2 had constructed a model that exhibited simple feedback, the implications of that structure were not totally comprehended. On viewing the behavior of the system with a graph, S1 noted that she didn't understand an aspect of the graph (refer to Figure 5.26). The cognitive dissonance provided impetus for fine tuning her theory. This supports the conclusion that structural changes preceded a comprehension of system behavior.

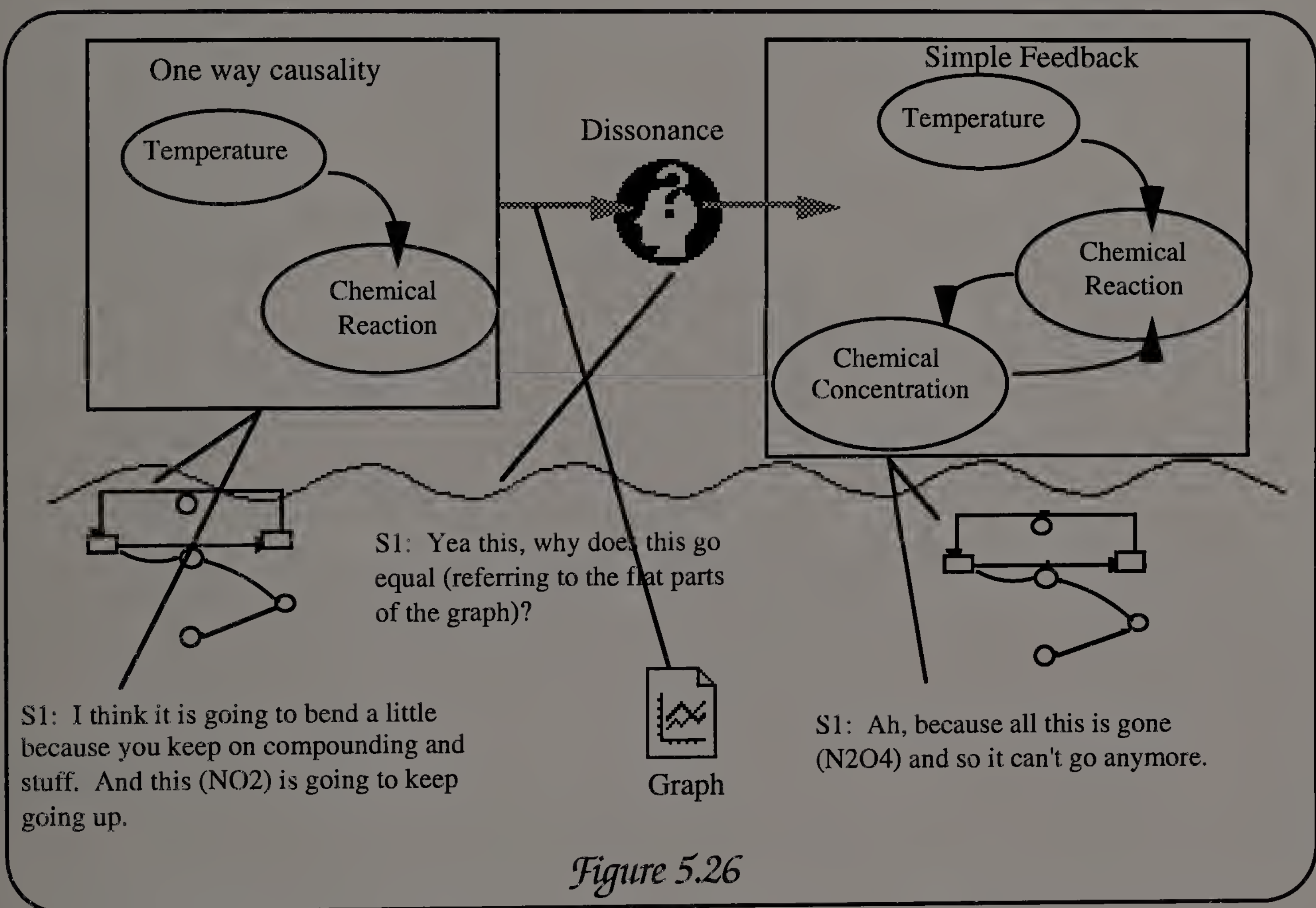


Figure 5.26 Wavy-Line Diagram

Thus the behavior of the system as illustrated with the graph stimulated cognitive dissonance and transformed student thinking.

Figure 5.27 illustrates the shift from simple feedback thinking to complex feedback thinking exemplified with indirect linkages. S1 initially suggested that a reaction will result in a buildup of chemical concentration but later viewed the movement of chemical as a feedback loop. This verbalization comes well after the construction of the feedback structure in the diagram. In fact, earlier she suggested that this same circular movement of chemicals was not desirable.

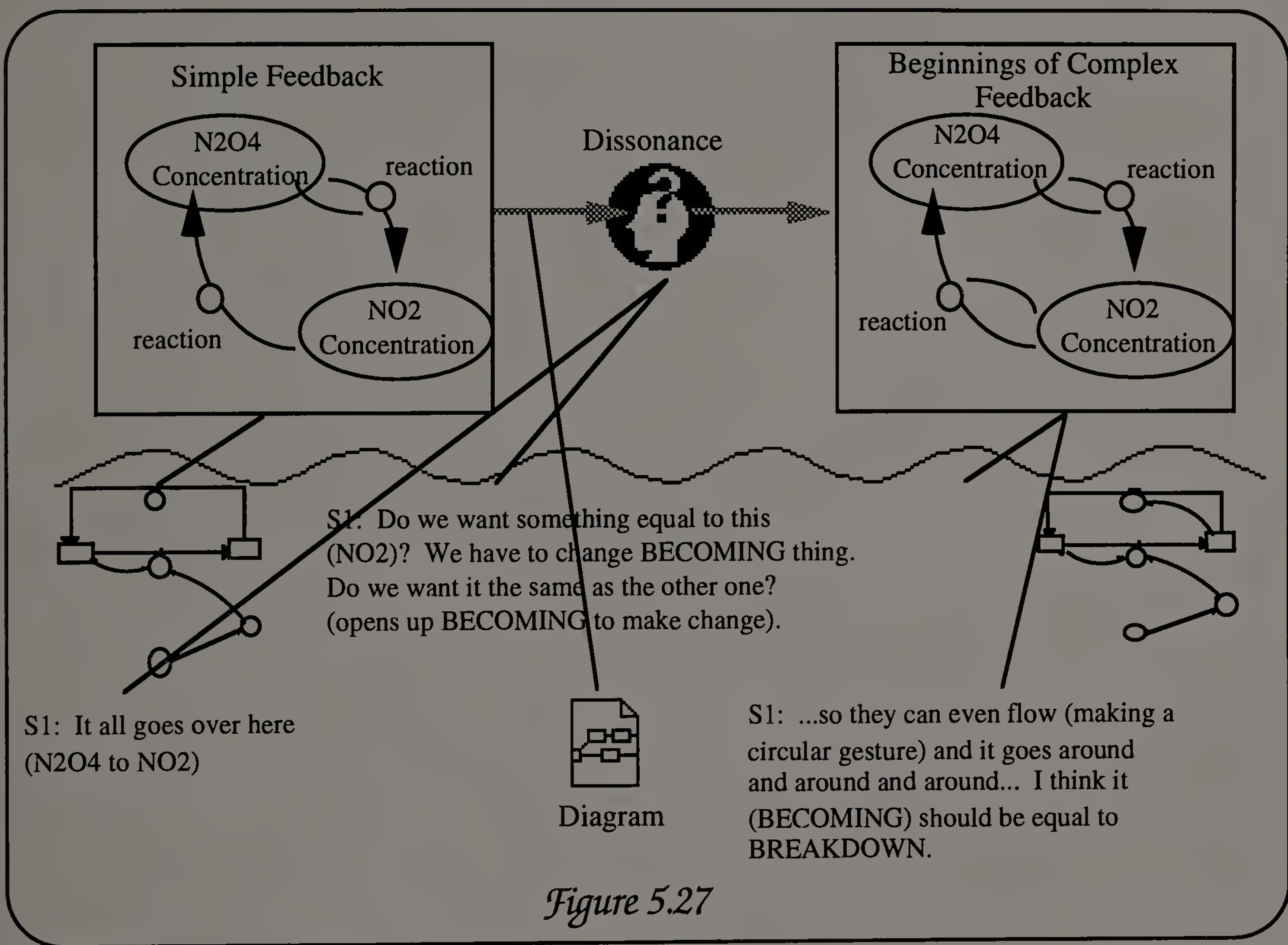


Figure 5.27 Wavy-Line Diagram

The graph provided information that created dissonance in S1's thinking. The progression in S1's thinking from this point forward indicated enhancements to her feedback thinking.

Continuing this scenario, S1's goal was to make a system that would be in equilibrium. However she became confused when confronted with a graph that illustrated an unexpected equilibrium point. Her initial comment in Figure 5.28 illustrates how S1 persisted in viewing the system as two separate flows or subsystem.

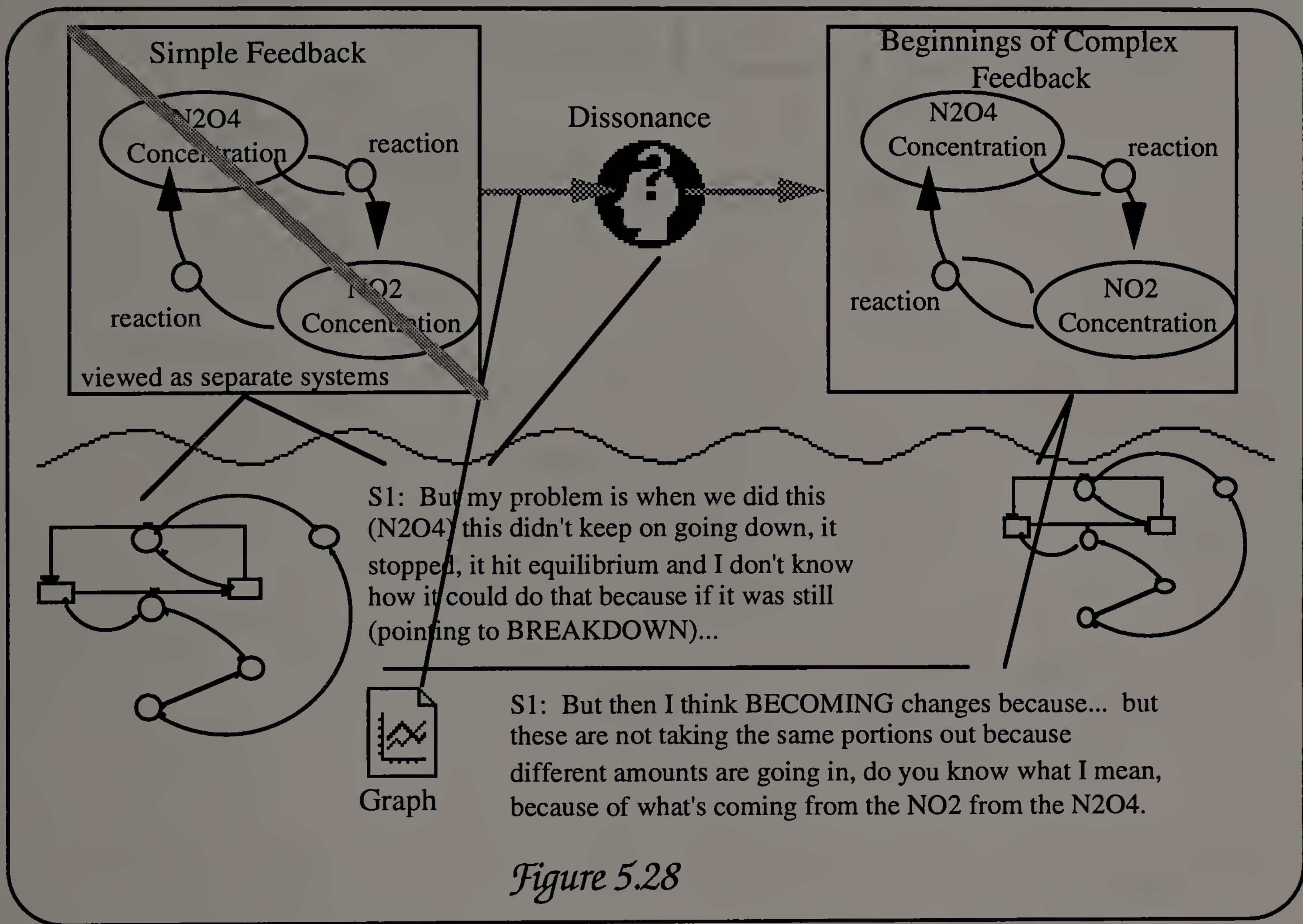


Figure 5.28 Wavy-Line Diagram

After contemplating the graph she began to see how the simple feedback loops are linked to the dynamic behavior of each other. This perspective allowed her to explain the system seeking equilibrium. The graph interjected information that conflicted with her mental model. The resulting dissonance caused her to reflect on the structure of the STELLA model and create an integrated mental model that included a relationship between the two systems.

S4 demonstrated a change in representation after viewing a graph and an animated diagram view (see Figure 5.29). Initially he expressed the opinion that cocaine caused the reduction in neurotransmitters. After S4 was confronted with a graph he seemed to recognize the difference between his prediction and the output but this didn't bring him closer to identifying where the incongruency had originated.

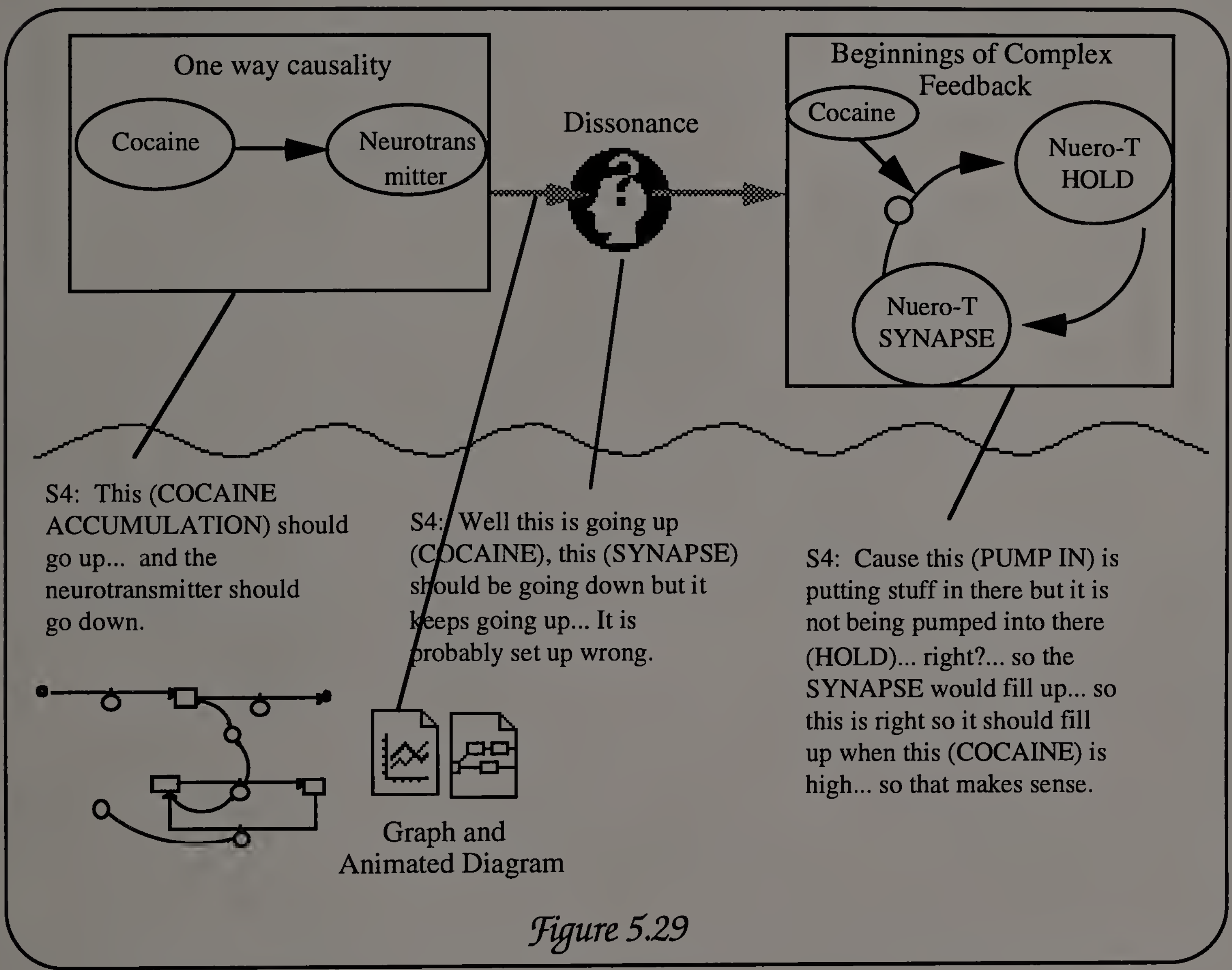


Figure 5.29 Wavy-Line Diagram

After viewing the animated diagram he began talking more about flows and causal relationships. The resulting thinking brought him to a better understanding of the diagram which he had constructed. The animated diagram provided S4 with a link between the values of one stock and another.

The levels in the animated view were visually linked by their kinetic depiction. This moved S4 towards a complex level of feedback thinking.

After viewing the animated diagram, S4 was challenged by the researcher (see Figure 5.30). The researcher's question acted as catalyst for the student to reflect on the animated diagram and realize that there was a conflict between what he saw on the screen and what he thought should happen.

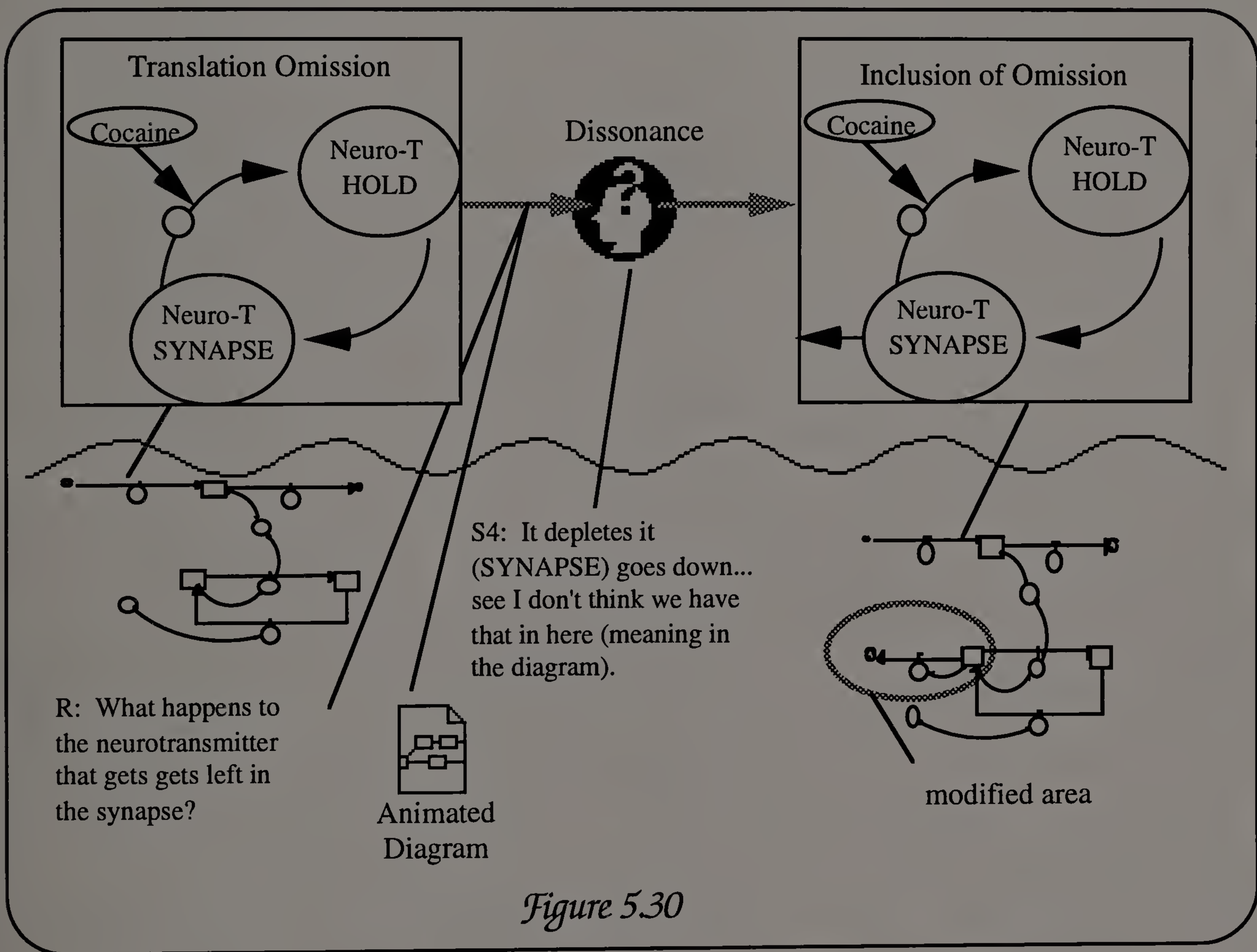


Figure 5.30 Wavy-Line Diagram

The student saw the icon representing the SYNAPSE fill up (animated view) and only had to be asked about it for him to verbalize the contradiction (it should have depleted).

Upon further reflection and researcher probing using the diagram, S4 realized that the system was like a tub with a drain but lacked a faucet. The diagram made this problem explicit as illustrated in the wavy line diagram below (see Figure 5.31):

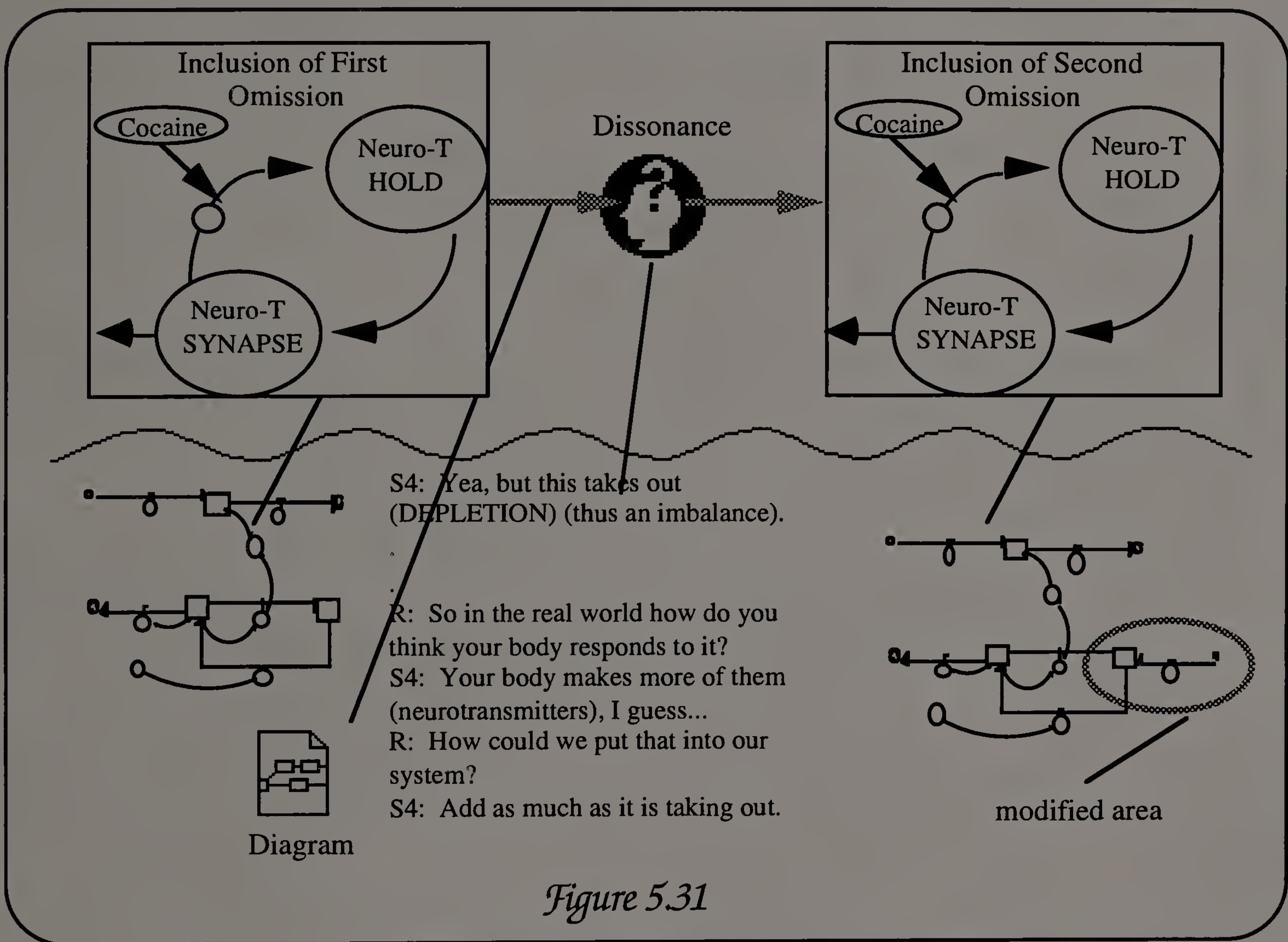


Figure 5.31 Wavy-Line Diagram

S4 had juxtaposed information from running the simulations with the structure of the diagram and created structural changes to the diagram to bring the diagram in line with a modified mental model.

In a later protocol, S4 exhibited thinking in terms of one-way causality. This was evident in his prediction because he only talks about one flow and does not take into account the feedback loop that connects the two stocks (NEURO T HOLD and NEURO T SYNAPSE.) S4 was thinking of the system as two separate flows or systems that were unrelated to each other (see Figure 5.32).

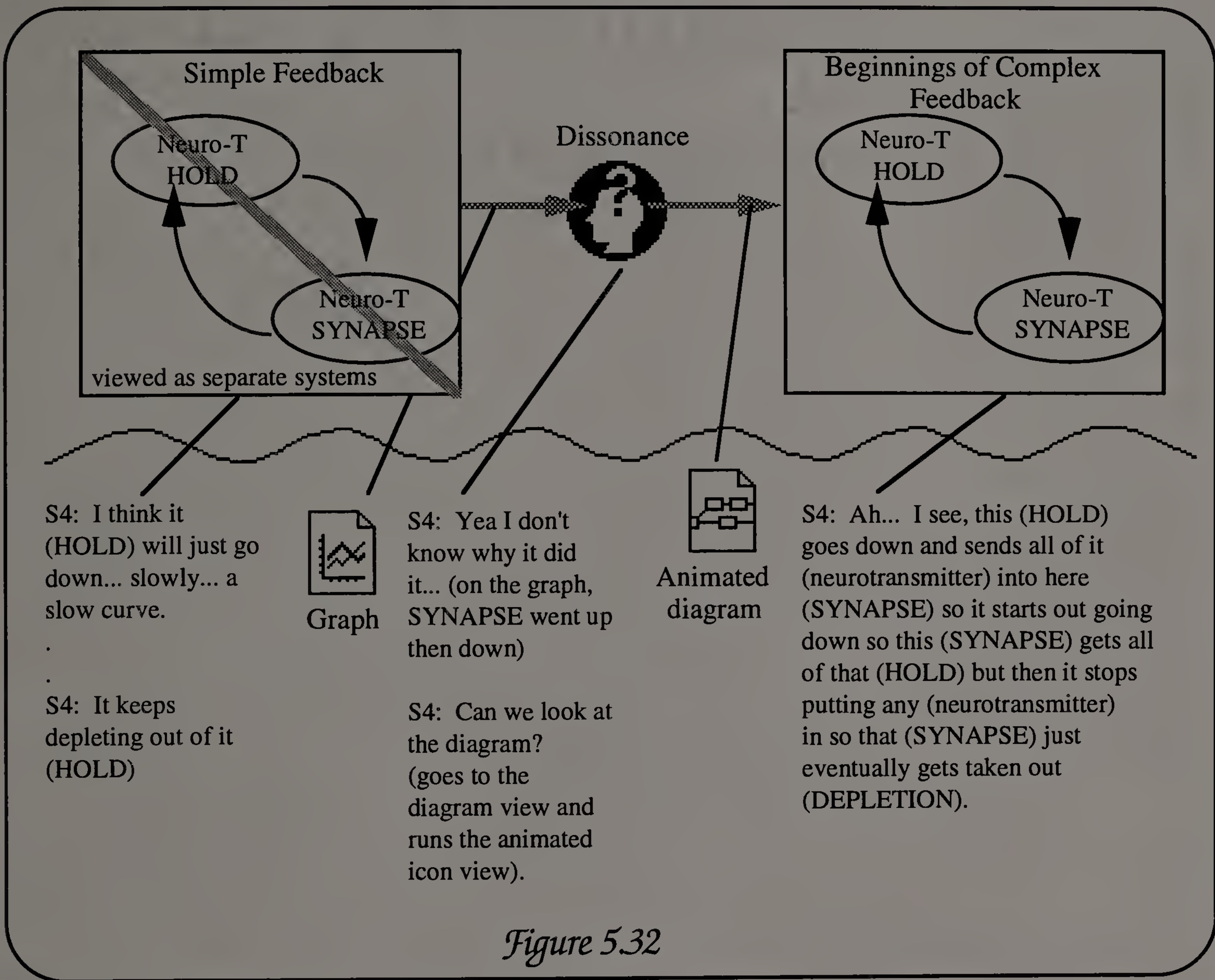


Figure 5.32 Wavy-Line Diagram

It is interesting in to see that S4 was confronted by the system's behavior displayed in the graph view but then he used the animated diagram to resolve the conflict. Juxtapositioning the dynamic behavior of the two stocks in a form that is closer to the student's experience facilitated recognition of the interrelationships between them.

Later S4 was asked to relate his ideas back to the real world, he was observed utilizing his diagram to generate explanations:

R: What are the negative consequences that we might want to get rid off? The way you have got it set up (diagram).

S4: The depletion and this right here (NEURO FLOW) because this is what connects COCAINE.

R: Can you think of any creative ways... Let us say you are a medical researcher tackling this problem....

S4: You could cut off the cocaine from going there...

R: In what kind of a way.... what are you thinking?

S4: If you made something that would go in with the cocaine that would stop it from blocking up the pumps.

R: Where would that come in our diagram?

S4: It would probably be right here (PUMP OUT) wouldn't it? Or you could have it so that the more cocaine it wouldn't affect the flow.

In the previous protocol S4 was able to identify structural solutions that he inferred from the structure of the STELLA model.

S4 was asked to think about other ways to test the system. The following was a question that he came up with that seemed to come from looking at the diagram:

S4: What if it didn't outflow, but accumulated over time?

R: That's nice.

S4: I don't know if it does that....

R: Why don't we do that.... does it tell us in the description?

S4: No. (changes value of OUTFLOW to 10)

S4: Maybe the high would just go up and stay up because it is always there or maybe it would go up and then go down because it is always there, I don't know.

In the above protocol S4 suggested experimentation that involved structural changes to the model. By making visual amendments to the diagram an interesting line of thinking resulted. Unfortunately he does not follow-up on this by testing out the structural change.

Shortly after seeing the influence of indirect causal loops, S1 was able to articulate a coherent set of ideas for the goal seeking behavior she had seen in the graphs (see Figure 5.33).

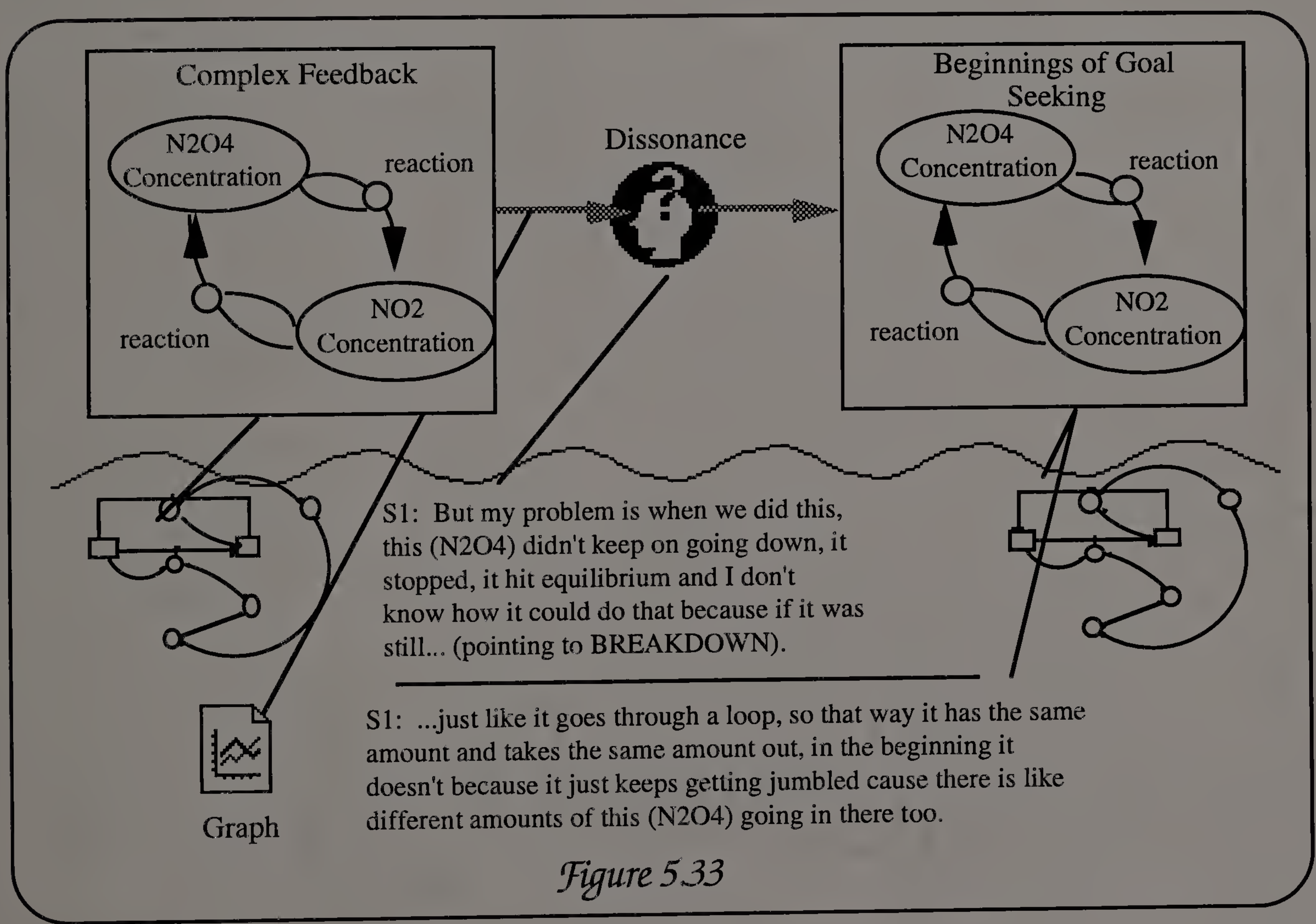


Figure 5.33 Wavy-Line Diagram

This theory was a result of viewing complex feedback loops in the system through STELLA's depictions (graphs, diagrams).

Figure 5.34 depicts a further embellishment of S1's thinking based on the discrepant event provided in the graph. The researcher had modified the temperature so that it increased over time. In all the other situations the temperature had been a constant. At first the students didn't even recognize what had changed in the model. This emphasizes the need for students to maintain ownership in model construction and experimentation. After S1 recognized that temperature was changing over time the resulting graph invoked conflict for her.

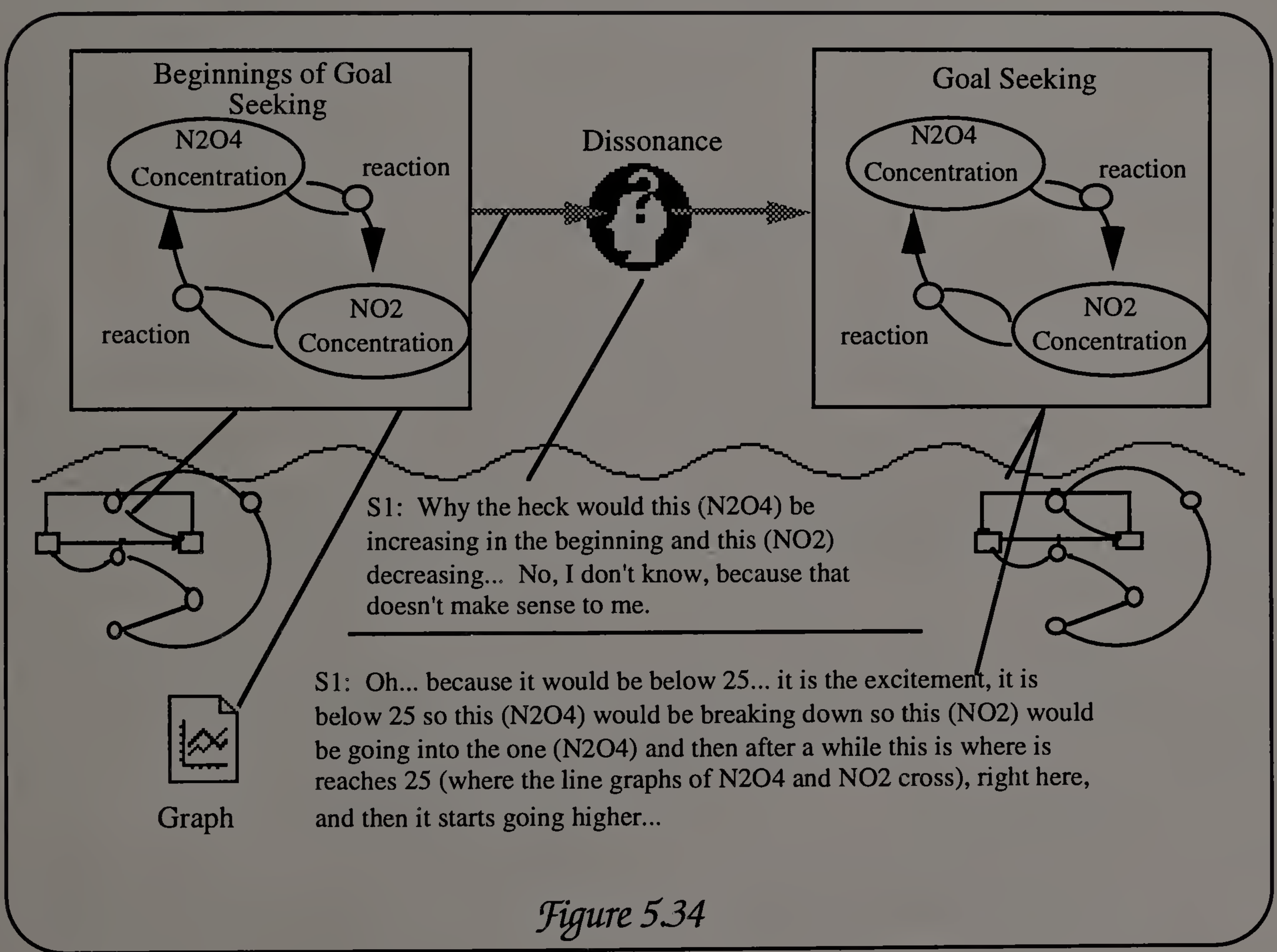


Figure 5.34 Wavy-Line Diagram

S1 was thinking that since the temperature was increasing the values of one stock would go up and the other would go down. However she reflected on the structure of the diagram and the graph, recognized that the two flows exhibited a shift in dominance which resulted in identifying goal seeking behavior.

While S1 was advancing towards the comprehension of complex feedback loops, S2 was still struggling with simple feedback loops. Figure 5.35 shows that S2 had difficulty explaining the structural changes S1 had made to the system. The researcher provided a remedial session with a simpler model and confronted her with a table displaying negative numbers.

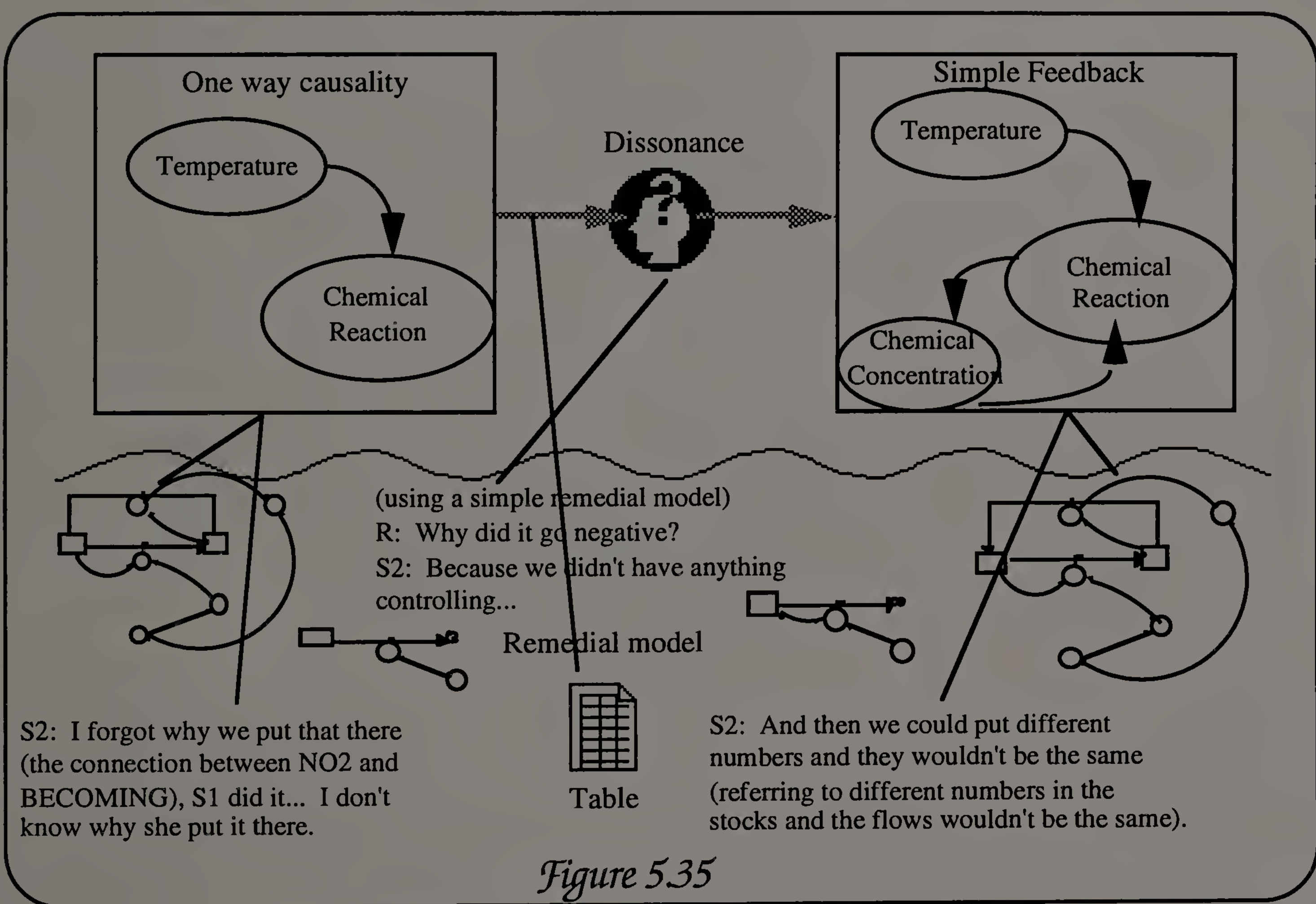


Figure 5.35 Wavy-Line Diagram

The tabular display highlighted the existence of negative values that stimulated S2's self-questioning about the values going negative. This was expressed in the need for some "controlling" factor. She was then able to take the concepts from the simple model and apply it back to the chemical model. Her reference to different numbers in stocks affecting different numbers in the flows suggests a notion of a simple feedback system.

Different portrayals stimulated cognitive change, to flesh out the attributes of these portrayals an analysis of S1's descriptive protocols were assessed. The first description comes while S1 was looking at the graph view. The second description came immediately after but in the diagram view:

S1: (graph view) As the temperature decreases the N_2O_4 increases and when the temperature increases the N_2O_4 decreases so I just did the opposite so when this (N_2O_4) increases, this (NO_2) decreases and when this (NO_2) decreases this (N_2O_4) increases, so it just sort of does the opposite. (explanation with graph)

R: Can you explain it using the diagram, how that works?

S1: (switches to diagram view) Well when the temperature increases the amount of NO_2 increases because the BREAKDOWN increases I don't know how to say that so the amount of NO_2 increases because there is more N_2O_4 going into NO_2 and then when the temperature decreases this goes the other way (pointing towards N_2O_4) then this (N_2O_4) increases and this decreases (NO_2)... Oh because the BECOMING increases (explanation with diagram).

In the graph view the description emphasizes an increase or decrease in the variables. The focus of the diagram explanation also describes an increase and decrease in the variables but mentions the "amount" and alludes to the movement of materials ("going into NO_2", "goes the other way"). The gestures also provide some information. In the graph description the students were pointing to the lines on the graph, while in the diagram view the gestures included pointing to the iconic symbols representing stocks (amounts increases or decreasing). When talking about movement, their gesturing switched to a stroking motion that animated the idea of movement. This brief encounter may not provide much insight when taken in isolation, but the researcher noted that this was typical of the kind of discourse that occurred in response to these portrayal. The implications are that different portrayals provide a unique bias that encourages students to think in different ways. For instance a diagram may help students to think about the actual amount and the movement of those materials in the system, and the controlling mechanisms, while a graph provides an abstract depiction of change in the variables over time.

S1's summary of STELLA incorporated thoughts about the value of graphs:

S1: Yea cause after you see the graph you can figure out...

S2: You can figure out how it turned out that way.

S1: That's when you really see what is happening is after you see how the way the graph goes and then you can actually figure out what is happening there and how each thing , and that's when you realize how everything is related to everything else....

The graph often presented the discrepant behavior and stimulated student questioning. The diagram furnished a framework for understanding and mapping relationships. The following discourse represents a classic case where the diagram view encouraged a perspective that the graph didn't. S1 had just finished viewing a graph that had caused her some confusion. She then moved to the diagram view to help her explanation.

S1: (starts out viewing the graph) Oh... Oh... You know why, I know why, I think I know why. Each time a smaller amount is being broken down of (she moves back to diagram view) each time a smaller amount is being broken down because this (pointing to

BECOMING and BECOMING FACTOR) is takes different amounts out, different portions (pointing to NO_2) out, so each time the portion is getting smaller and smaller and then it gets regular. Do you know what I mean?

In the above protocol S1 felt the necessity to go back to diagram view to mediate her explanation. The graph did not lend itself to talking about portions of materials being moved around the system.

The next protocol illustrates the use of equations to assist student thinking. The equation view inspired students to think in terms of quantitative terms. This thinking in turn assisted students in coming to a qualitative understanding of the behavior.

S1: (opens up BECOMING)

S1: Since this (BECOMING) is times these two (BECOMING FACTOR & NO_2) well if this (NO_2) is larger, this (BECOMING) is going to be taking out larger percentages and this (BREAKDOWN) is going to be taking out smaller percentages, so this (NO_2) will go down and this (N_2O_4) will go up because this (NO_2) is going back in here (N_2O_4), is that right?

S1 was able to come to a better qualitative understanding by determining the quantitative mechanisms that STELLA utilized to achieve its results.

In summary, the previous section included selected protocols that exhibited noticeably strong effects of shifts in thinking. These sections of protocols highlighted salient aspects of students' dynamic thinking and captured attributes of the environment that contributed to cognitive change. The next section will discuss the implications of this analysis.

CHAPTER 6

DISCUSSION

This section will juxtapose information gleaned from the analysis with the background information. In addition unexpected results will be discussed along with suggested modifications to STELLA and future research directions.

6.1 Order of Assumptions

The distinction between levels of dynamic assumptions was somewhat arbitrary and these were merely a means to an end. The end was identifying cognitive change. The categorization of student operations into dynamic assumptions provided indicators of shifts in cognition. Typically speaking STELLA students progressed through dynamic assumptions in the order listed below:

1. Identification of stocks
2. Identification of flows
3. Interdependence of variables
4. Partial feedback thinking
5. Complex feedback thinking
6. Seeing shifts in dominance in flows
7. Delay thinking
8. Goal-seeking behavior

This order suggests a micro-level developmental sequence for dynamic thinking. The first four assumptions were sequential in nature. In other words students progressed from one to five in that order. However the hierarchical nature of five through eight was less clear. S1 was the only student that dealt with those upper levels. Thus it was difficult to draw any conclusions.

The previous sequence holds if a curve-fitting approach is taken. However, closer inspection identifies interesting anomalies with the onset of a new level of dynamic thinking. One such anomaly is that once students exhibited progression to a new level of assumption, it was not uncommon to observe a reversion back to a previous level of thinking (see assumption progression diagrams, Chapter 5). It was as if students doubted their own insights and were returning to something that was more secure. Perhaps students were thinking that they might be "hill-climbing"; this often takes place during problem solving, where the problem-solver moves toward the solution but ultimately comes to a dead-end and then returns to the previous level of thinking and moves on from there. In this particular study, student thinking often regressed before moving on again.

Identifying the sequence in dynamic thinking was useful because it provided a means of identifying cognitive change.

6.2 <u>The Value of Construction</u>

In this study the act of construction was valued for learning. The constructivist paradigm suggests that optimal learning takes place as learners are engaged in doing, constructing, and critically analyzing. In this study students created models of dynamic systems that they manipulated and analyzed. This iterative process of constructing, investigating, and manipulating is not emphasized by many classroom teachers. Instead, the goal of many teachers is to prepare students for standardized tests. The regurgitation of facts however does not usually fuel discovery or conceptual change. Students need many opportunities to build knowledge, discover new ideas, and accommodate current conceptions. However, if education fails to provide students with constructivist learning opportunities, then students will see rote learning as the goal of education. In our rapidly changing society individuals need to apply knowledge, generate novel ideas, and alter less useful conceptions. It is unlikely that minds schooled in memorization and regurgitation of facts can abruptly transform their cognitive processes to facilitate the construction of new ideas or application of knowledge to new situations. Society's challenges suggest that students will be expected to call upon creative, analytical, and problem-solving strategies often developed through constructivist activities. The time commitment for this kind of approach is considerable, and not all knowledge can be discovered through working with construction tools like STELLA. However, the activation of prior knowledge, constructing models, and the successive refinement cycle (Clement, 1989) represent important means of coming to knowledge that should be a component of well-rounded learning experience. Findings from this research confirm the importance of having students view the consequences of their conceived ideas. It is just as important for students to see the results of flawed thinking as to see the consequences of "correct" thinking. STELLA provided a platform for identifying inconsistencies in students' representations with a variety of portrayals.

Figure 6.1 illustrates an iterative process where students' conscious focus moves from mental representations to externalized STELLA models and then back to representations. In this diagram, the symbols are arbitrary but the change in shape reflects a change in representations. Internal representations are illustrated with symbols on the left hand side of the diagram. The symbols on the right hand side of the diagram represent the externalized STELLA model. The line moving back and forth illustrates the conscious flow of focus, and the changing shape of the icons represents where changes are being made. This oversimplifies the process but highlights the linkage between changes made to the external depiction and changes to internal representations. Once available to conscious control, thoughts are available for reflection.

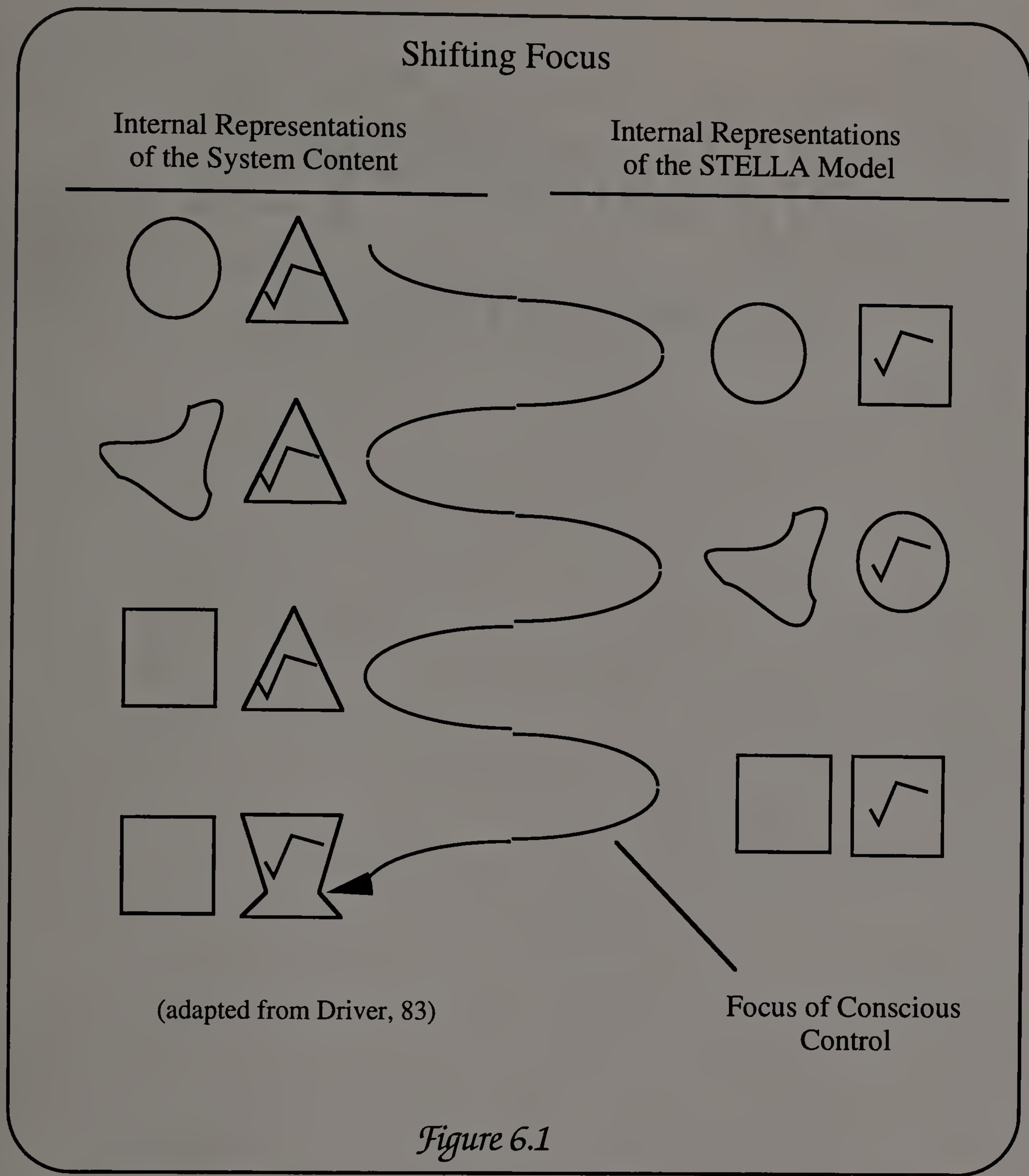


Figure 6.1 Shifting Focus

In the previous diagram the end results are not identical. In fact the final results of translating mental models into STELLA will never result in a perfect match. In this study the students' entire mental models were not translated into a STELLA model, however translation and model manipulation transformed their internal models. This transformation was evident in their changing cognitive attributes as exemplified in diagram progression and cognitive change tables. The translation process stimulated cognitive change by activating knowledge structures that might not otherwise been brought to bear on a problem.

There are no well-defined rules for deciding how to translate ideas into a STELLA diagram; there is no one right way. An example is the differing approach S3 and S4 used to represent cocaine in their STELLA models. S4 chose to represent cocaine as a stock while S3 chose to represent it as a converter. Both approaches to the problem were justifiable. Their differing approaches to portrayal reflects a difference in the focus of the investigation. One view perceived the accumulation of cocaine as being primary to the problem, the other perspective viewed cocaine as an external factor that influenced the internal structure. An interesting educational experiment would be to bring these individuals together to discuss their differing approaches.

Translation into STELLA is a two-edged sword. On the one hand, translation introduced a bias that encouraged students to view the dynamic dimensions of the information. On the other hand, translation into STELLA was fraught with complexities. For novice students the process of selecting appropriate information to portray and matching that with appropriate symbols was a difficult task. Constructing STELLA models challenged the integrity between the students' mental model and their externalized models. In a mine field a mine sweeper detects possible mines that are hidden from view; with STELLA a skilled instructor acts in an analogous way by alerting students to possible dead-ends or helping students detect weaknesses and inconsistencies in their models. One of the techniques that proved useful during this detection process was having students check the reasonableness of information with the help of multiple portrayals (graphs, diagrams, etc.).

The operations of STELLA students indicated that they were building their own theories of the system rather than relying solely on theories provided in the description of scenarios. This was evident from the differences between the description of the scenarios and the diagram. In translating their perception of the system description into a diagram there were often incongruencies. Some of those differences were due to translation problems. Other differences were the result of trying to mesh perceptions of the theory presented with ideas reconstructed from experience. For example S4 suggested that the cocaine stock should have an outflow, but outflow was not accounted for in the description. Another example: S1 suggested that the system acted like the capillary action in plants. She attempted to apply her biology knowledge to her STELLA experience. This is significant for education because it provides credence to the notion that students' bring their own ideas to learning environments and can't be expected to act as empty receptacles. Furthermore, system behavior and the reasons for that behavior were not explicit in the descriptions; the students constructed that through the modeling process.

Another value of the construction process was the flexibility that is encouraged with STELLA. Flexibility in thinking is an attribute normally associated with expert thinking, however this may come from being able to recast problems in a new form. The abstract notational system of graphical portrayals may yield expert-like thinking about the problem through uncovering the underlying structures of the problem. For instance S4 was able to identify the need for an outflow from the cocaine accumulation because the problem was recast into a STELLA model. The STELLA model activated the flow analogy within the student's knowledge structures. It is the activation of this kind of alternative knowledge that assisted novices to think more like experts. This facility gave them flexible ways of approaching problems that might only come with a more extensive knowledge base.

Despite the value of model construction there were barriers that challenged student thinking. These problems included: interpretation errors of symbolic depictions, viewing the model as a picture, perceiving the model as isomorphic with reality, translating errors in diagram construction, failing to comprehend the complexity of the system, being torn between competing theories, and lacking systematic experimentation. Most of these barriers weakened with experience in the STELLA environment and as the students struggled, greater understanding of STELLA developed which lead to insights and understanding. Despite the difficulties there was considerable value in the construction process.

6.3 Primary Spatial Ability

As noted in the analysis chapter, students often began translating conceptions into pictorial portrayals. This suggests that they were using a concrete frame of reference that is tightly linked to their immediate spatial surroundings. Perhaps such a primary spatial orientation (Presson, 1987) is used because STELLA students tried to portray their ideas through the spatial world on which they have direct action. Presson (1978) noted that young children draw a map like they would a picture. They focus on the shape and detail of objects rather than those aspects of the portrayal that highlight the abstract concept of directionality. Presson stated: "Spatial symbols are typically first interpreted directly with respect to the world as defined by a person's primary spatial orientation." (p. 96) The pictorial depiction is closer to a child's perceptual experience. Students in this study initially display a similar tendency when first translating their conceptions into a STELLA diagram. S1 and S2 initially depicted their chemical equilibrium model with icons for glass bulbs rather than chemical concentrations. STELLA students began to shift towards a secondary orientation when it became apparent that their concrete depictions were inadequate. The knowledge required to treat spatial information in an abstract way is tied to cognitive development and experience in the environment. Thus in a STELLA environment students had to overcome their primary spatial orientation before being able to move to secondary orientation.

6.4 Shifts in Thinking

STELLA instilled a dynamic perspective for learners by acting as a scaffold (Bruner, 1976; Ratner and Stettner, 1991). A scaffold is a term that suggests being able to reach higher cognitive actions than with one's own resources. A portrayal's scaffolding comes from its bias for organizing and displaying information. This bias skewed the perspective taken by students and thus encouraged analyzing ideas from a different slant. This enabled students to grasp ideas that were previously out of reach or deeply embedded in knowledge. Within the STELLA learning environment a fresh perspective was depicted by the plumbing metaphor and was reinforced by simulation output. This dynamic perspective stimulated the asking of self-probing questions that encouraged seeking new relationships between chunks of knowledge. In addition, the STELLA learning environment acted as a tool that made transformations between symbol systems. This acted as a scaffold by off-loading burdening calculations, facilitating higher order processing.

Learning from the bias of the tool is evidenced in a previous section (5.5 - Portrayal Efficacy). In the cases presented in section 5.5, students were either influenced by the translation bias of the plumbing metaphor or the cognitive conflict induced by interpreting simulation output. For instance, students have been observed to exhibit difficulty relating rate with chemical equilibrium (Banerjee, 1991):

> "Practical courses in school and undergraduate classes normally do not have experiments which aim at measuring the rates of both forward and reverse reactions simultaneously. Thus, students are not exposed to kinetic studies near or at equilibrium. This results in the development of conceptual difficulties in relating rate and equilibrium." (p.490)

The chemical equilibrium model constructed by S1 and S2 addressed the integration of rate and equilibrium by demonstrating the simultaneous influence of both the forward and reverse rates on chemical equilibrium. This information proved useful in challenging student's' one-way causality model of equilibrium.

The scenarios that students modeled did not have explicit problems stated in the descriptions. However, inevitably problems were generated by translation or interpretation processes. The stated or unstated problem was, what is the dynamic behavior of the system and can it be explained? STELLA was a problem-solving environment where students generated their own questions. If an assumption was missing, was not made explicit, or was logically inaccurate, then it usually became apparent in feedback to the user. In STELLA this came in the form of error messages, graphs, tables, or animated diagrams. Cognitive dissonance was the result of viewing these portrayals and often resulted in student generated problems.

The generation of questions was an indication of learning. STELLA provided numerous opportunities that stimulated question production. This was shown by the wavy line diagrams illustrating changes to student thinking (Analysis, section 5.5). In almost every case students were questioning model behavior or their own thinking. Here is another example: S1 viewed a graph that acted as a discrepant event generating cognitive dissonance.

S1: (referring to the graph) I don't think it would go straight, I don't understand that... wait wait, that is something I don't understand. Let's change this again because I forgot what it looked like.

The discrepant graph resulted in the generation of a question.

S1: Yeah this, why does this go equal (referring to the horizontal parts of the graph)?....

This cognitive dissonance stimulated a search of the problem space that resulted in the identification of a possible solution.

S1: Ah, because all this is gone (pointing to N_2O_4) and so it can't go anymore.

Cognitive dissonance was the source of self questioning that led to a manipulation of the model and modification of mental representations.

The goodness of fit between STELLA's portrayals and internal mental representations is an interest to this dissertation. There are four possible outcomes resulting from experimentation with STELLA (see Figure 6.2). The first possibility is that students find the results of experimentation in alignment with expectations. The second possibility is that the experimentation output suggests modification to the STELLA diagram, but does not jeopardize the integrity of the mental model. A third possibility is that the results of the experimentation challenges the current mental model yet the student views the STELLA model as a valid portrayal of the scenario. The fourth possibility is that interpretation challenges both the structure of the STELLA diagram and the student's mental model.

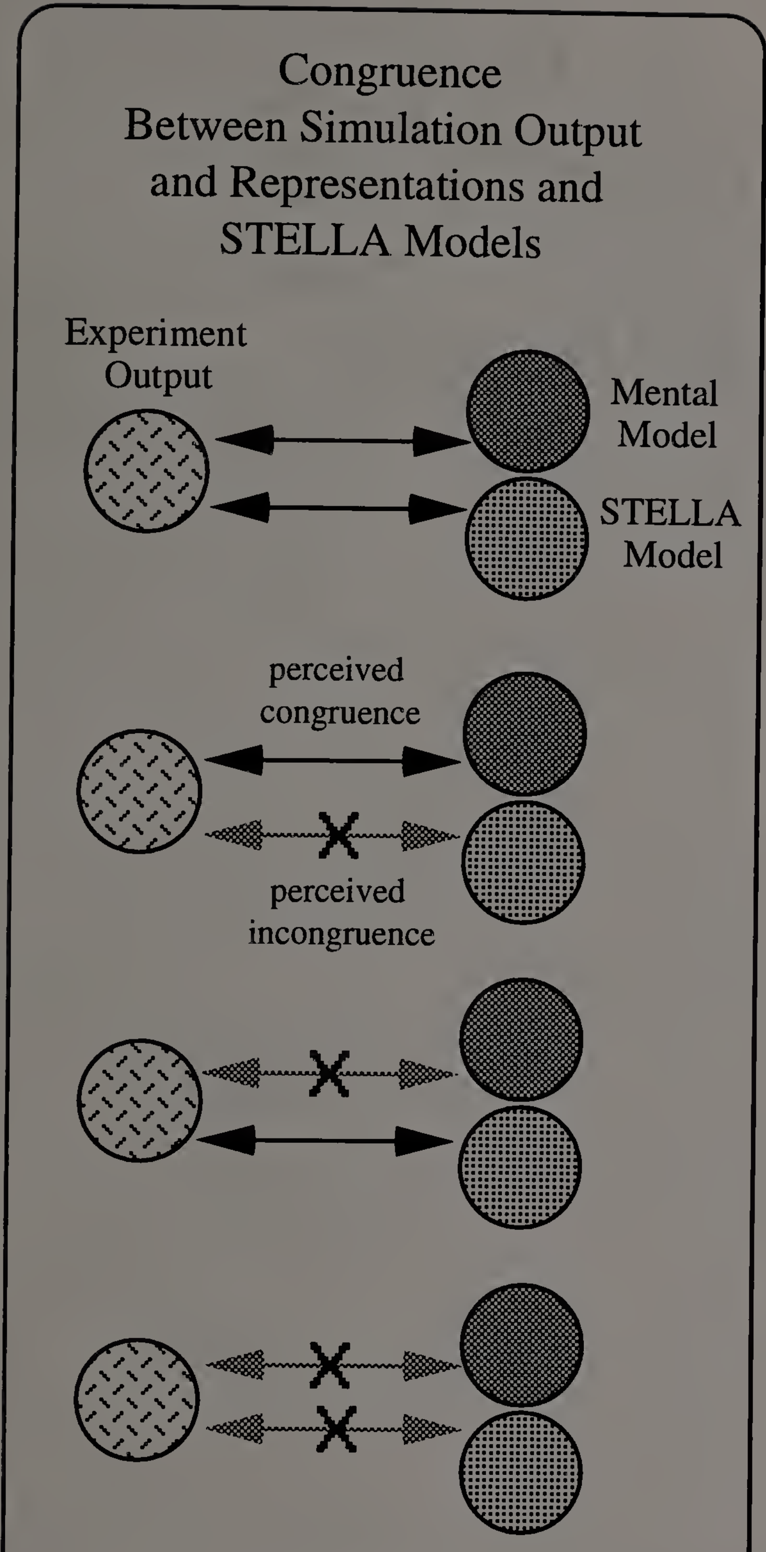


Figure 6.2

Figure 6.2 Congruence Between Simulation Output

Although there seems to be a change in perspective by some of the students, this shift in thinking did not happen rapidly. The process resembled the incremental process of assimilation and accommodation rather than a sudden shift in gestalt. Clement observed a similar incremental approach when studying scientific breakthroughs ("aha! experiences") with physics students (Clements, 1989).

On occasion, students fluctuated between a dynamic perspective at one point in time and a static perspective at another (e.g. S1 identifying the feedback loops in the model). The existence of competing assumptions is consistent with diSessa's theory of knowledge in pieces (1988). Interacting with STELLA also assisted students in resolving conflicts produced by competing or disparate ideas. For instance, running the simulation highlighted the relationships between variables for S1. STELLA was a favorable environment for integrating pieces that might otherwise have remained detached. Viewing different portrayals of simulation output encouraged a switch from a local view to a global perspective (feedback thinking). This was evidenced in the progression of student diagrams, assumption tables, and wavy line diagrams (chapter 5).

6.5 Multiple Portrayals

This research studied the role of multiple portrayals on learning. On the one hand, multiple portrayals highlighted and reinforced common aspects of information; on the other hand multiple portrayals highlighted different aspects of the information. The reinforcement of concepts was achieved through links between shared information. This is illustrated in Figure 6.3 (Links Between Multiple Portrayals with linking arrows. In this case the interconnectedness of stock NO_2 is portrayed. Note that linking the different portrayals not only identifies that which is common, but the distinctions as well. Although different symbol systems portray the same information (e.g. NO_2 stock), different dimensions of that information are depicted. It is as if a set of painters sat down to illustrate a common object, and each one approached it from a different perspective, highlighting different attributes of the object. The pictures produced by the artists comprise a depiction of the object, yet each picture is biased by the artist's perspective. One artist may emphasize hue, another contour, another perspective, etc. Likewise, different forms of portrayal highlight different aspects of data and thus activate differing epistemological structures. For instance, a table highlighted the discrete values produced by a model at a given time interval; individual values are highlighted from the two dimensional relationship between rows and cells. A graph provided an audit trail of changes to a variable(s) against another variable. The general shape of a line graph represented the relationship between two variables (time and NO_2 stock) without having to know the exact value of any one particular point on the graph. Equations provided a mathematical definition for relationships. A diagram highlighted the directionality of relationships such as the direction of flow. An animated diagram provides a visual image of the relative values of variables at any point in time giving a real-time qualitative feel for the relative values of accumulators and flows in the system. An animated presentation provided many of the same dimensions as a graph does, but a graph retains a historical picture of the information while the animated icon view depicts the level of the variables relative to each other in real time. The animated icons were closer to students' personal experiences. For instance students have had experiences with fluctuating levels of fluids in glasses or bathtubs. The animated icons are closer to a student's encounters with perception than the more abstract line graph. Thus each form of portrayal in the STELLA environment had linkages with other forms of depictions, yet highlighted unique information about the system. In this study students benefited from multiple representations in the STELLA environment. (see the wavy line diagrams - section 5.5). Student's conceptions that were strongly embedded such that counter evidence was seen as unrelated or unbelievable were challenged by the use of multiple portrayals.

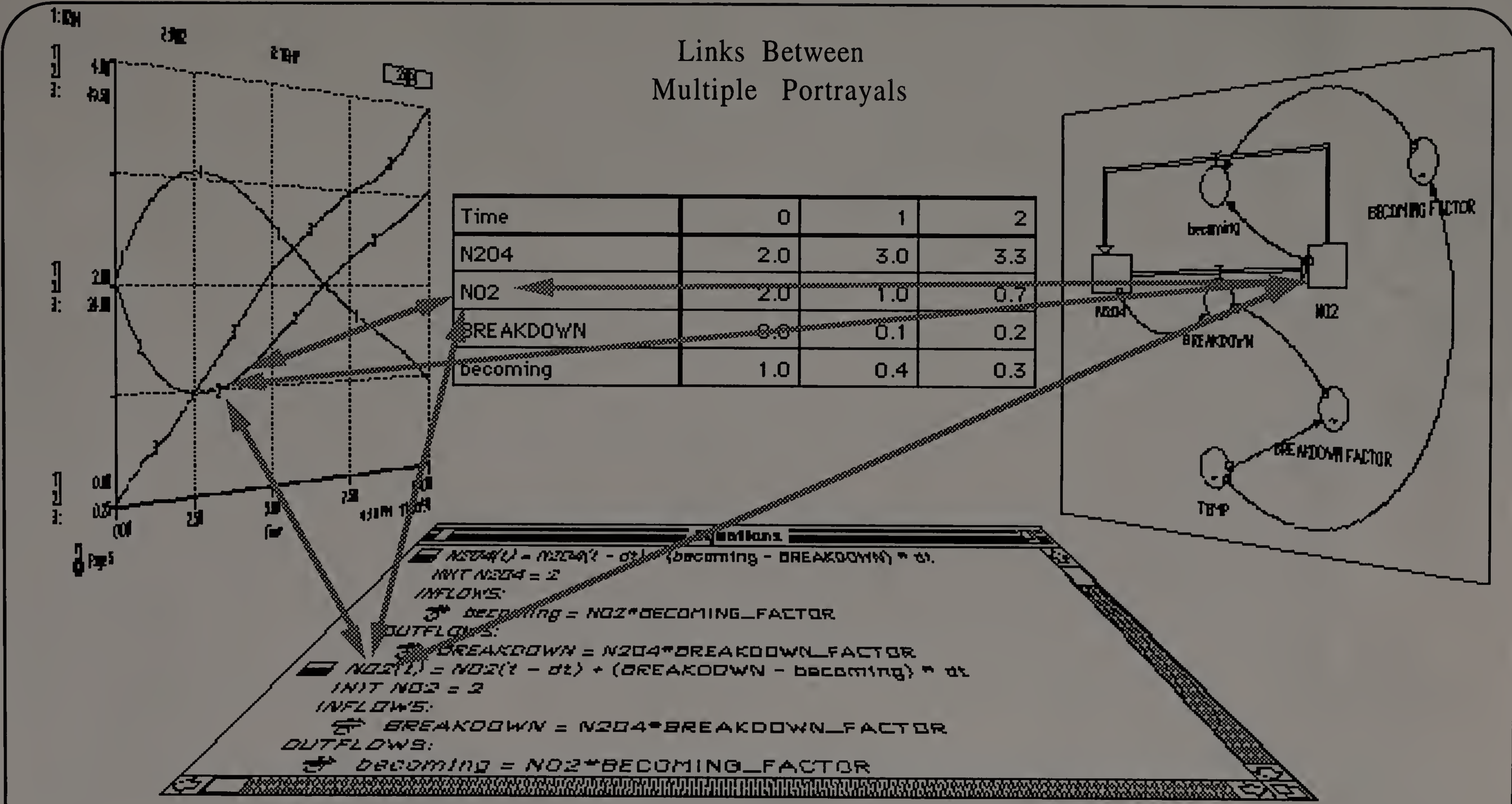


Figure 6.3

Figure 6.3 Links Between Multiple Portrayals

6.6 Delay Between Construction and Coherent Thought

A décalage was observed between the construction of relationships in the diagram and the rationalization of the consequences of changes. For example, in the Portrayal Efficacy section (5.5) there are several instances of students who make significant changes to the diagram but did not understand the implications of those changes until after viewing system behavior through portrayals. The diagram was in place before student thinking changed to reflect the change (as demonstrated by transformations in student protocols). This supports the notion of students having knowledge in pieces. The students were able to justify modifications to the diagram but the significance of those changes were localized and not seen as influencing disparate parts of the system. Only after significant interaction with the STELLA environment did students begin to view their models in terms of causal loops.

STELLA students frequently analyzed various components in isolation. Students were often unable to link the various components together, to synthesize the overall effect of the individual relationships, and recognize feedback loops. The portrayal of simulation output had significant impact on student thinking because it was after considerable thought and experimenting with the system that students began to talk about causal loops. For instance, the researcher worked through each relationship in S4's model with S4. Despite this S4 was not able to visualize the overall system behavior (S4 Cocaine 20). In most cases students withheld comments about feedback loops until well after the model had been constructed and executed. Apparently students need time to think and experiment with the system before they are able to synthesize the parts and explain the system's overall behavior.

Another kind of décalage was also observed. Students exhibited delays between making a prediction and being able to rationalize it in a coherent manner. For instance, S1 recognized that the rat population should go to equilibrium , but it wasn't until later that she provided an adequate rationale. This kind of conscious level verbal décalage has been reported by others (Karmiloff-Smith and Inhelder, 1975). It is difficult to infer why this behavior is occurring. Perhaps this delay is the result of tentative ideas and students are unwilling to commit to these budding ideas verbally. Alternatively students may have a tacit understanding of the system but lack the verbal formulation to express their ideas. In Vygotskian terms their inner speech and social speech are out of synch.

6.7 Portrayal Selection

For the most part (with some exceptions) students in this study failed to demonstrate an awareness of the affordances of different portrayals. Students were not able to select appropriate forms of representations to test their ideas. In other words when faced with a decision about what to do next, students generally were unable to suggest a portrayal that would challenge or confirm their thinking. One possible explanation is that students lacked sufficient experience with the environment to make appropriate projections. Another possibility suggests that by the very nature of a discrepant event students would not know what form of portrayal would elicit a challenge. By definition discrepant events involve unexpected outcomes. This argument suggests that since the outcome is unanticipated, students should not be expected to select portrayals that will generate discrepant events on their own. Despite this rationale, scientific thinking contends that unexpected results are often encountered through systematic selection of portrayals. The literature on using diagrams corroborates the idea that visual images can assist in a more systematic approach to solving problems (Hayes, 1988; Rubinstein, 1986). In a STELLA environment students may require more experience before they are to a point of making systematic selection of portrayals.

6.8 Plumbing Metaphor

The researcher provided students with the plumbing metaphor to help them understand the workings of the model. However, students occasionally generated their own analogies to explain behavior. Clement (1989) also observed students generating spontaneous analogies. A prudent instructor might allow students to build their own analogies since they seem inclined to do so regardless. This exercise might comprise an introductory exploration of the STELLA environment followed by some time for generating a useful metaphor. It is interesting that S1 made an analogical connection to a domain with a similar structural identity (interest rates with the chemical equilibrium model). To accomplish these linkages students were presumably searching their knowledge for similar structures.

6.9 Negotiating Meaning

For students in this study the interpretation process was an additional source of stimulus for cognitive change. When information was displayed that contravened prediction, cognitive dissonance was sometimes the outcome as manifest in the wavy line diagrams (section 5.5). Cognitive dissonance naturally provoked self-probing questions. Interpretation and translation processes also have interactive effects. For instance, when students encountered cognitive conflict, their search for possible solutions was influenced by knowledge activated by the translation process. Thus the interpretation process was a way of reflecting on their knowledge structures.

The researcher found that STELLA was a useful tool for inferring a model of student thinking. For example, probing into graph understanding suggested that students construct alternative dynamic assumptions. STELLA's portrayals often highlighted information that conflicted with students' theories. Hence STELLA was a useful tool for revealing student theories. STELLA provided a symbol system for discussing abstract ideas. This was not beneficial just for the researcher but valuable for student thinking as well. STELLA's portrayals were used with spoken word and gestural symbols to clarify personal ideas and to communicate with others. In this way STELLA was a useful tool for clarifying meaning.

Students' expressions were not always accurate mirrors of student thinking. Through extended observation of students the researcher gained a new appreciation for the importance of negotiating a model of student thinking. The term negotiate may not be the best because it suggests that others are facilitating and contributing to the development of the student model. However students did contribute considerably. Students were often asked what they were thinking or why they performed a particular operation. In this way meaning was negotiated between the researcher and the students. Traditional forms of evaluation are thrown into question for the purposes of diagnosing students' problem because initial externalized expressions were often not be a good characterization of internal representations. It often took exposure to different portrayals and or probing questions to clarify meaning. Skilled intervention is a function of developing a useful representation of students' mental models. A tool like STELLA provides a compelling environment for negotiating a model of students' mental representations.

6.10 Explanations for Students' Cognitive Change

Alternative explanations for the shifts in thinking observed during this study can be identified. Could the shifts in thinking be explained by the researcher's participant-observer role? Certainly the researcher took an active role that influenced student thinking. However, the researcher's interventions were part and parcel of the learning environment. Could the changes in thinking have been mainly the result of time-on-task? It is possible that similar shifts in student thinking could have been observed had the students been pursuing other avenues of exploration. Nevertheless, this study suggests that learning was distinct because the avenue of exploration was distinct. Different learning environments activate different knowledge structures and in turn stimulate different kinds of thinking and learning. Granted there may be disparate environments that stimulate similar thinking but those environments probably have features that highlight similar dimensions of the information. Other influences than the STELLA environment could have accounted for changes in student thinking. However the changes seen in this study are consistent with the affordances of STELLA.

Changes in assumptions indicate that a paradigm shift had taken place. The external portrayals produced by STELLA activated different frames of reference about the topic. These different frames of reference brought to bear new knowledge structures on the topic and facilitated cognitive dissonance resulting in cognitive accommodation. The portrayals and their activated knowledge structures are illustrated in Figure 6.4.

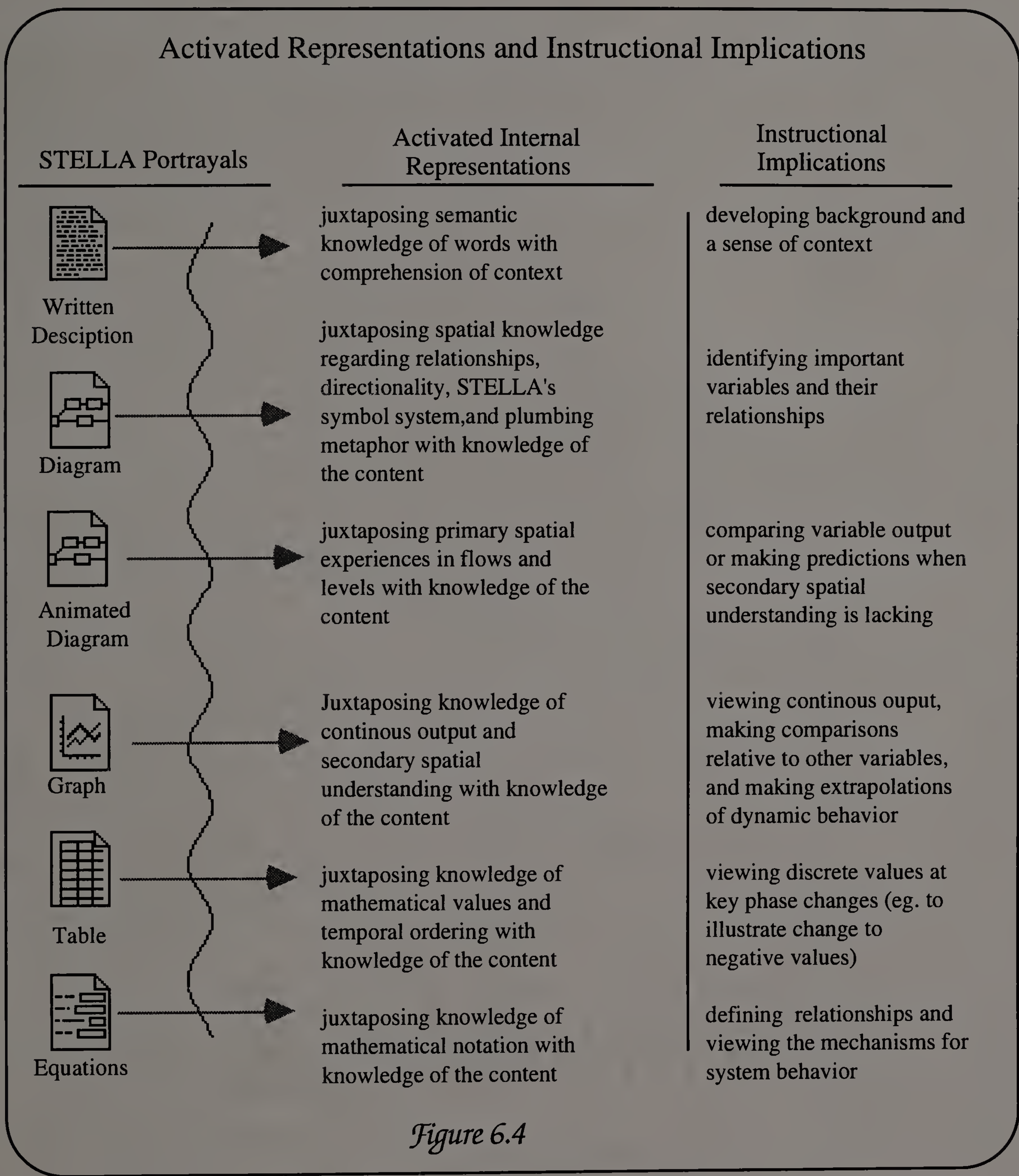


Figure 6.4 Activated Representations

Figure 6.4 does not suggests that there is no overlap between activated knowledge structures. There is often overlap of knowledge activation independent of the portrayal. However, distinct knowledge structures were depicted to highlight the possibility that alternate forms of representation activated distinct knowledge structures. Each form of portrayal illuminates different dimensions of the information and in turn activates different knowledge structures potentially encouraging knowledge restructuring.

STELLA provided a platform for thinking about the abstract dimensions of a system. Presson (1987) identified a primary or concrete framework or a secondary or abstract framework. The results from this dissertation suggest that certain displays tend to activate certain kinds of abstract frameworks. The use of different portrayals, such as STELLA diagram or graph, activated knowledge structures that activated secondary frameworks. The students were then in a position to come to question their view of the content knowledge. Cognitive dissonance was often evidenced by students asking questions. Good education is good questions. Through creating simulations students generated questions and as the simulation evolved interesting inquires were pursued. The portrayal influenced the students' perspective and in some situations resulted in cognitive change. This is evidenced in section 5.5 that illustrates students' shifts in thinking.

One counter argument is that many of the insights the students experienced were evident in the description of the scenario. However, students' accounts would suggest otherwise, as in S4's summary of his STELLA experience:

R: What value does this have [STELLA], or does it have any value?

S4: Well you can figure out long term things that happen, you can build a model of the real world and something like you want to do and you can try and build it close so you can see what happens maybe in the future, maybe predict the future maybe of something... the model. With this you could see that according to that, you lose your neurotransmitters and die or something from that.

R: Any other comments?

S4: I learned how to... about the cocaine and I didn't know any of that. It was interesting.

R: For instance what would be the difference just reading this [cocaine description] description out of a text book and building a model like this [cocaine model] in terms of your understanding?

S4: It sort of puts it into pictures, not pictures but it explains what happens. You can experiment with... you can't really experiment when you read. If I do something else what would happen?

R: Why couldn't you do that with the written word, why couldn't you say if I changed this....

S4: Well it is there in what you have. It [written description] doesn't give you any more information... for what would happen if you kept cocaine in your body or if you didn't get rid of it and stuff like that. You can experiment. You can pretty well do what you want in the model.

S4's statements suggest that he was able to identify the unique nature of STELLA and appreciated that this gave him unique insights.

6.13 Implications for Cognitive Study

There are many ineffable cognitive processes that comprise learning. These tacit processes can only be inferred from learner behavior. However, despite the challenge of generating useful inferences this informs instructional intervention. Seeking an understanding of student thinking is the mandate of any educational researcher or skillful instructor. STELLA is a tool that facilitates the negotiation of meaning.

One line of reasoning explains that development of a computer model mirrors students' mental development and becomes a scratch pad for making assumptions explicit. In essence, model development parallels student construction of understanding, allowing the luxury of monitoring and refining the process. This is true but only to an extent. The idea that STELLA is a perfect analog of students' mental models is questionable. The research done by this study suggests that the STELLA model is often at odds with students' mental models. It was the incongruencies between internal representations and the externalized STELLA model that encouraged cognitive change. STELLA was a tool that clarified thinking by identifying contradictions in thinking. Students made transformations of a computer model and reflected on changes to the content and back to the model in an iterative fashion. Multiple portrayals provided a means for seeing the differences between their thinking about the content and the STELLA model. STELLA juxtaposed student theories with counter evidence because of the existence of multiple symbol systems. The implications for cognitive studies are that portrayals activate alternate knowledge structures. The juxtaposition of diverse knowledge stimulated metacognitive strategies that in turn fostered cognitive change.

6.14 Implications for Education

STELLA represents one of the tools effective teachers might choose that will diversify student experiences and move them away from a preconceived view of how the world works. It is an excellent tool for moving from the known into the unknown. It can act as a platform for the development of coherent theories through social cognitive processes with peers and an informed instructor. The analysis indicated that STELLA is a system that works best with informed intervention. STELLA is an involved program and novice students could have easily spent considerable time floundering. Prudent intervention by way of probing questions, modeling, and guidance was an important element for the success of this environment.

One concern is that STELLA takes a long period of time to become adept with. Is that educational? The answer to that question is difficult, there are at least two ways to look at it. For educators interested in getting students through the curriculum and having students retain declarative kinds of information, STELLA will appear as a waste of time. Many educators look for plug-and-play kind of solutions (refer to Sidebar 6.1). STELLA is not such a program. For educators who are interested in students' cognitive process, in discovery learning, and in developing a scientific approach then STELLA has much to offer-- but at a price. The STELLA manual brings out the point that "disciplined thinking always will be “hard work". Developing a good simulation is not an easy chore and will require time. New techniques require time, not only to learn the conventions and how to apply them, but also time to invoke the higher order thinking skills. Instructors will need to be challenged to rethink what education should accomplish. Teachers need to be convinced that the time and effort required to work with tools such as STELLA is worthwhile.

Integration Note

"technology does not have a life of its own, nor does it stand on its own". (Sheingold, 1987).

Sidebar 6.1

Sidebar 6.1 Integration Note

Simulation construction is not an efficient way to learn factual knowledge. However simulation construction is a means of coming to an understanding of complex dynamic relationships. Thus complex systems that exhibit multivariate relations are prime candidates for use with tools such as STELLA. Other kinds of knowledge may best be targeted using different instructional strategies.

One of the primary arguments against computers specifically, and media in general, is that differences in student thinking result from differences in method rather than differences in technological aspects of the medium. To a considerable extent the argument is a valid one. The effective use of a medium is based on how it is used and integrated into learning environments. However, the tool often dictates the methods used. For instance, in the STELLA environment it is fairly easy to ask the student to modify a variable, predict the result, and view the consequences of that change. Given a different medium (say paper and pencil) this request might produce a prediction but would lack the viewing of the consequence. It was the juxtapositioning of students' predictions with the models' consequences that provided a powerful way to elaborate or differentiate mental models.

Learning is surely influenced by method, but the medium constrains and enables method. The methods used in this study would have been difficult if not impossible in other media.

Furthermore, the idea that novices require less sophisticated tools than experts requires scrutiny. Experts can often predict the output of portrayal tools, but the novice requires the computation power and display characteristics of the computer to be able to utilize higher order thinking. For instance professional modelers can predict the system dynamics of some models without the computational power of the computer whereas the students in this study had initial difficulty with basic relationships.

It is difficult for educators to know how and when to use computers in education. Through research and experience educators are coming to an understanding of how learners interact with these powerful transformational tools. However, with the advent of different tools, new methods and new uses will become apparent. This will not be an issue that will be resolved once and for all. There is a need for an ongoing process of refinement into research and development between the interaction of computer tools and student cognition.

Portrayal tools could be just one of a repertoire of strategies that stimulate mindfulness and reflection. Instructors need to model alternative forms of portrayal and students need to experience the tool in diverse learning situations so that strategy selection processes can be honed. Bringing theories to the level of conscious control may call for metacognitive strategies that some students lack. The implications are for teachers to modify their role, to teach and model monitoring and questioning strategies.

Assessment with portrayal tools is a constructive process more than a summative kind of comparison against the performance of others. Portrayal tools are for self illumination so the normal forms of testing don't make sense. Perhaps the best form of evaluation is for students to share their constructions with their peers, allowing questioning, and an opportunity to elaborate and justify their rationale. This is evaluation because the purpose of evaluation is to determine the significance or worth of something. Worth or significance is a societal decision. Through feedback from others, the value of ideas can be ascertained.

Another possible conclusion to come from this research is an attitude - an outlook towards science/education. Students building STELLA models see themselves as apprentice scientists because they are building and testing their theories. Although data on this conclusion was not collected directly one can infer this from the comments of the students. This kind of activity simulates the authentic work scientists engage in. In a sense this gives the students an apprenticeship experience, an opportunity to engage in scientific theory construction. Finally STELLA inspires an alternative approach suggesting to students that there is more than one way of thinking.

Using a program like STELLA requires a change in the static way that processes are considered. Students think in terms of dynamic processes, positive and negative causal loops, flows, accumulations, and converters. Students look for patterns in the dynamics by identifying shifts in dominance between positive and negative causal loops and view the structure of the system as the basis for behavior.

6.15 Integrating STELLA into Classrooms

Because STELLA is a general purpose system that can be utilized for a broad spectrum of applications. It is also adaptable to diverse pedagogical strategies. There are a number of ways which this program can engage the learner (Steed, 92). Although most of these approaches were not the focus of this study, listing the possibilities is useful for practitioners:

1. Simulation templates could provide students a set of predefined elements and connections. The students could then begin by testing out the model as part of the scientific process. Another level is to have the diagram created but leave unspecified the relationships between the variables. The student would then be able to go into the structure and deduce their own relationships.

2. At still another level the student would be given the problem and asked to create a simulation from scratch. There is additional value in having the students create their own models. This requires analysis and evaluation of systems to know how to create the causal loops and determine what elements are important and where to draw the boundaries.

3. Using the system as a class demonstration, an instructor can construct a model that is built through input from the students. Students could engage in group problem solving as individuals

contribute ideas for the creation of the model and justify their ideas.

4. Students can use this model building program to translate concepts or processes from textbooks into dynamic models. Often the meaning of a concept can be ambiguous and abstract. This program can stimulate students to translate words into an "operational map" of how the process works. Abstractions become concrete structures, ambiguities become clarified, and inconsistencies can be scrutinized. As one analyzes the concepts through rigorous thinking, differences that arise could be a topic for class discussion or the topic of further research.

5. Narode (1987) noted that using graphical portrayals may be useful in science laboratory settings before doing an actual experiment. He noted that with graphical portrayals students had representational structure to interpret their findings. A simulation's data could be compared with data collected from the real world. The STELLA model would provide a rigorous environment to develop student theories. First, they could specify assumptions, test those assumptions, and redefine or modify their theory. Basically, let the student play the role of the scientist.

6. An idea presented by Kahn (1985) is to use a classroom as a scientific community with small groups working on different models of the same phenomena, occasionally sharing insights,

analogous to the sharing that goes on in scientific journals, conferences, electronic mail, and on-line conferencing. This idea can be used in classrooms by having groups of students develop STELLA models and then share their theories by sharing STELLA models.

6.17.18 Portrayal of Learning through STELLA

Whenever the ideas from this dissertation have been presented to educators one of the issues that inevitably arises is, the value of using such a tool to represent learning. If this tool is useful in one domain, such as science, why not use it to model learning? To address this issue it must be made clear that this task would result in a structure that does not represent cognitive structures. Rather it would represent an abstraction of the perceptions of cognitive structures. The purpose would be to gain insight and understanding. On the other hand, hard core information processing theorists believe that their constructions are attempts to make a computational model that is isomorphic with human learning mechanisms. The value of using a portrayal tool is in the dimensions of the information made salient through its use. STELLA models focus on the dynamics of systems that are typically generated by causal loops. Learning is not like a plumbing system, yet by translating learning theories into a system like STELLA, dimensions of those theories become salient which might prompt the asking of interesting questions.

6.18 Potential Research Topics

There are numerous questions that arise from this research that warrant further investigation. For instance:

1. How can portrayal tools be integrated into traditional education?
2. What kind of problems lend themselves to portrayal tools and when would portrayal tools best be utilized?
3. How would assessment be made of student-constructed portrayal tools?
4. What activates student selection of portrayals and how does this change with experience in a particular symbol system?
5. When do students focus on surface level features rather than on the underlying structure and how can pedagogical intervention with portrayal tools assist?
6. How will different pedagogical approaches influence learning with portrayal tools?
7. How does learning with portrayals that are imbedded in a context differ from learning with those that are disembedded?

Information concerning these research questions would contribute toward a unified theory of portrayal tools. This would assist in making meaningful pedagogical interventions or designing portrayals that invoke desired cognitive processes.

CHAPTER 7

CONCLUSIONS

This study provides an account of student cognitive processes involved in modeling dynamic systems and how a computer portrayal tool (STELLA) effects cognitive change. With this information educators can draw inferences regarding the value of portrayal tools and their appropriate implementation.

Students in this study evidenced progression through increasingly sophisticated assumptions about dynamic systems. The order of assumptions provided an indicator of cognitive change. Although there seemed to be a general learning sequence, it was not always a smooth transition from one assumption to the next. This suggests that thinking was not always stable, as new ideas were being established, they seemed tentative and required nurturing. Progress through dynamic assumptions also suggested a shift from primary representations to secondary or abstract representations. This reflects an important advance for student thinking from a focus on visual reference to abstract references. The nature of differences in individual student progression requires further exploration. For instance, identifying students who use intuitive methods (surface level features) and who ignore a coherent rationale might help instructors or peers provide useful interventions.

STELLA is a portrayal tool that by its design encourages a constructivist approach to learning where students develop concepts for dynamic systems by viewing the consequences of their own thinking. This was a challenging environment for students. The first hurdle was learning how to interact with STELLA and understand its conventions. The second challenge was generating explanations for dynamic systems and recognizing conflicts in their own thinking.

As students in this study interacted with STELLA's portrayals they experienced cognitive change because they questioned their own representations. Students reflected on activated knowledge structures associated with the tool's frame of reference which stimulated the asking of questions. This in turn acted as a springboard for cognitive change. STELLA's frame of reference was achieved through the built-in plumbing metaphor and multiple portrayals. The plumbing metaphor stimulated students to think about the dynamics of system behavior by focusing on rates and accumulations. Multiple portrayals were useful because they linked common information but also illustrated distinct attributes of that information. One way STELLA altered thinking is that it changed students' perspectives. Consequently STELLA stimulated S1, S2, and S4 to ask questions about their own epistemology as they linked dynamic perspective with knowledge of the content. These questions arose from inconsistencies in students' epistemology that STELLA made salient. The result was that students came to a more informed view of dynamic systems demonstrated by the change in dynamic assumptions. The knowledge activated by STELLA's portrayals led students to cognitive dissonance by juxtaposing conflicting ideas.

Portrayal tools can provide an alternative approaches that encourage connectivity of ideas, stimulate reflection, and introduce new frameworks that changes conceptions. These tools will activate a new framework from which to explore and visualize information as well as act as a platform for instructional intervention. This new framework may or may not be persistent or available in other contexts.

One conclusion that can be drawn from this study is that construction kits like STELLA require considerable time. Not only a significant period of exposure but consistent exposure. This was demonstrated by S3's lack of progression. However, cognitive change takes time. Students developing their own ways of thinking require time -- time to ponder, construct, question, experiment, and alter thinking. For instance, students exhibited a delay between constructing their models and understanding the significance of their constructed models. In other words metacognitive time was required to reflect on how the various subcomponents worked together to create overall dynamic behavior. If the objective is to develop a sense for dynamic systems then STELLA or similar portrayal tools may well be worth the time and effort.

Another conclusion is that portrayals can be complex. In STELLA even small, seemingly simple models, can generate complex behavior that is difficult to think through. The complexity of models is thought to have value in that it reflects the complexity of real systems. Model building is an iterative process, moving from identification of causal loops to computer simulation and returning to hypothesizing important causal loops. Through this process comes deep involvement in the topic and, consequently, deep understanding. With STELLA's complexity comes options for experimentation.

For novice users there were so many avenues of exploration that students spent time on unproductive ones. While some unproductive explorations are educational, a skilled instructor or informed peers seem to be required to economize cognitive effort by guiding explorations with suggestions and probing questions.

Portrayal tools may be useful for negotiating meaning. For instance, the spatial views within the STELLA environment acted as a means for inferring student thinking. The depictions acted as reference points for discussion and clarification. The same amount of inferences about student thinking would have been difficult without the mediating function of STELLA's spatial portrayals. The design of alternative portrayal tools may be a useful means of exploring different kinds of thinking. Educational research should consider the thinking that is to be investigated and identify portrayals that might foster the negotiation of meaning with students. Educators should attend to the nature of portrayals because the forms of depiction activate student representations which provide a platform for instructional interventions.

There are numerous ways computer portrayal tools might be used successfully in educational environments. They could be used as construction devices for illustrating student theories, or as teacher presentation tools for stimulating group problem solving. They might be useful for presenting and discussing student ideas. A simulation construction kit (STELLA) could be used to compare empirical data with theoretical constructs. Additionally, certain portrayal tools are generic in nature so that they can be used across the curriculum.

Previous studies involving STELLA have focused on statistical outcomes that showed improvement of graph understanding but no significant improvement in math understanding and demonstrated that dynamic thinking increased with STELLA use. This research confirmed that dynamic thinking increases with STELLA use but did not investigate the other issues. This research attempted to look specifically at how this portrayal tool influenced shifts in thinking. It contributes to current research by adding to a growing body of knowledge on how learning takes place with portrayal tools. Specifically, it suggests an interaction between multiple portrayals and representations. This study also dealt with dynamic thinking which is an often-overlooked aspect of knowledge. There are numerous theoretical perspectives that tie into the findings of this study. For instance, Vygotsky's theory of social tools is pertinent because portrayal tools are social tools and according to this theory we learn by interacting and internalizing social tools. Piaget's theory of structural development is relevant because it involves a conflict that arouses a state of disequilibrium and multiple of portrayals can stimulate the juxtapositioning of conflicting knowledge structures. Piaget's notion of reversibility could be used to describe moving back and forth between multiple portrayals. Constructivism suggests that learners are builders of their own knowledge, so providing students with a portrayal tool that parallels this construction process would be viewed as educationally useful. See Chapter 2 for a more thorough review of theoretical perspectives.

In summary, multiple portrayals can be useful for disembedding dimensions of the information. They can also stimulate reflection on representations by activating alternative frames of reference and by juxtaposing conflicting representations. Knowledge of system dynamics is difficult to broach with traditional pedagogy so it tends to be glossed over. Portrayal tools like STELLA address the construction of dynamic thinking. Students in this study were observed to use portrayal tools for thinking rather than a program to be taught from. Computer portrayal tools can be considered partners in the learning process. Educators considering construction tools should consider the time and cognitive benefits involved. Further research into portrayal tools will advance knowledge of their effect on student cognition and provide further ideas for integration into educational settings. Education needs tools to think with, not just tools to teach with.

APPENDIX A

QUESTIONNAIRE

Strictly Confidential Information

Name_________________ Age____________

Interests/Hobbies:____

High School courses taken: ________________________________

____

Overall GPA: _____

GPA in

Chemistry: ____

Biology: _____

Physics: _____

Social Studies: _____

English: _______

Math: ______

Other courses (please specify): ______________________

Career goals_____________________________________

Computer experience : Have you had previous computer experience:____

If yes, specify type of experience: (Word processing, programming, etc.)

___________________ length of time in months or years ______

___________________ length of time in months or years ______

___________________ length of time in months or years ______

Have you ever used a computer simulation before? ___________.

If yes, specify the names of the programs and how long you worked with each of them _________________________________

____

____

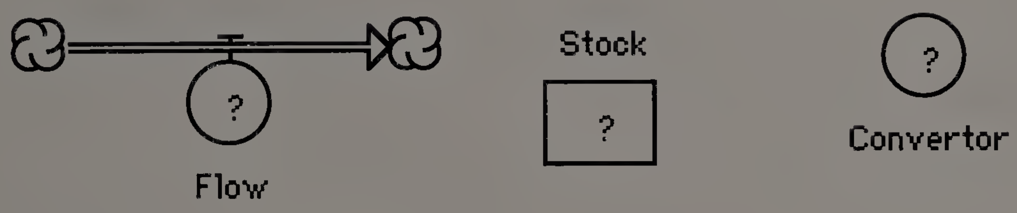
Do you think that computers might help you think about science topics?___

How?

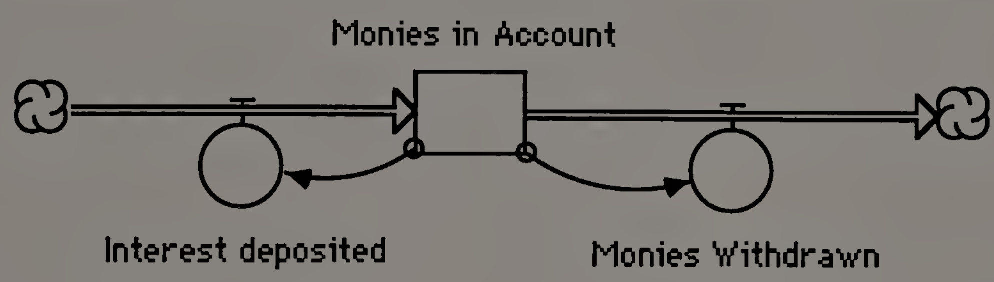
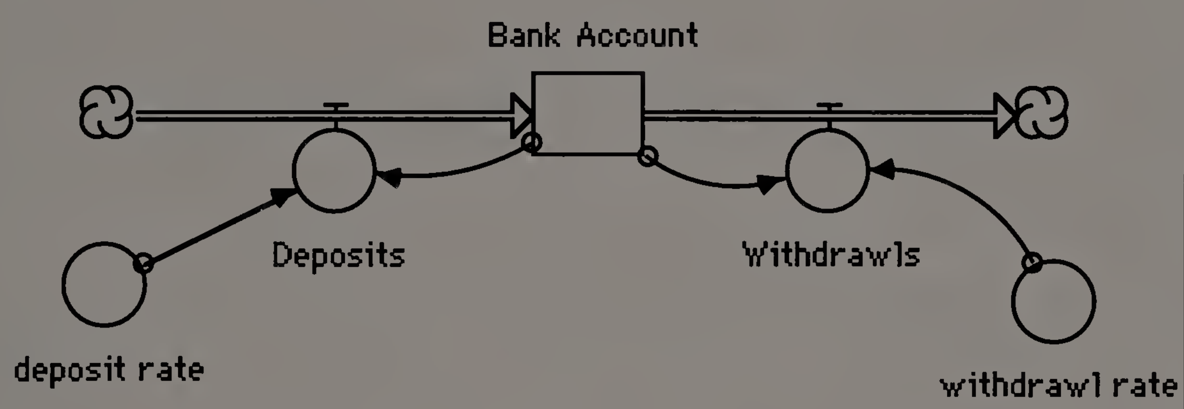
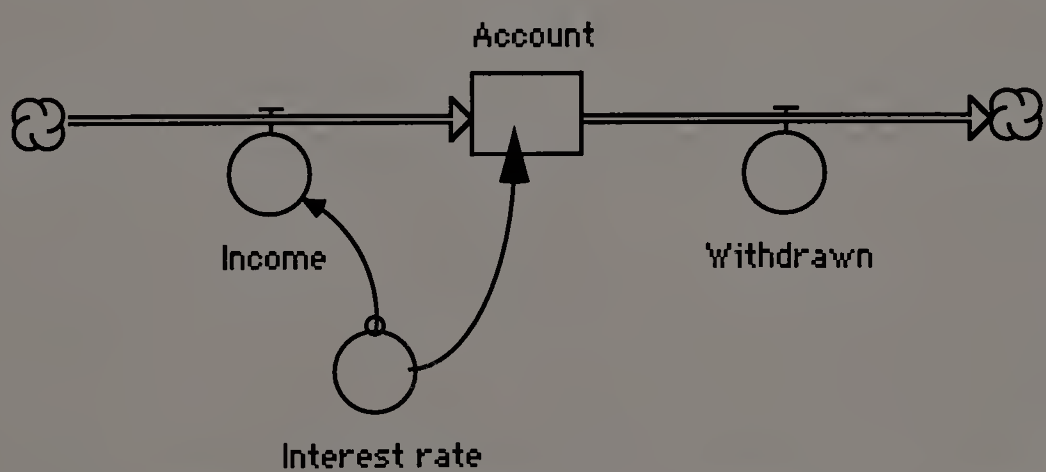
APPENDIX B

TEST CASES

Determine the flows, stocks and converters in the following scenarios: create a simple STELLA diagram.

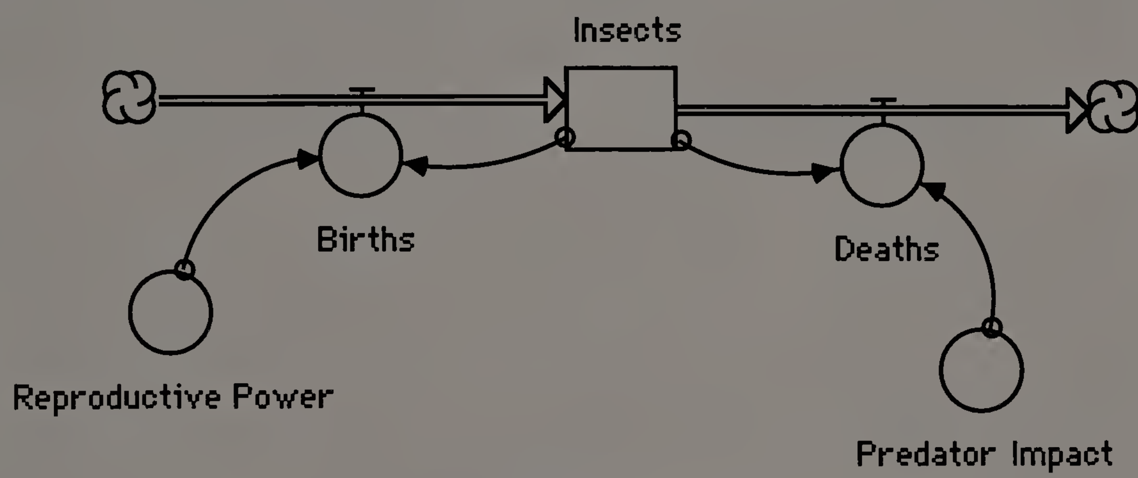


1. Your bank account increases as interest income is added. The interest rate will determine how fast the balance (total money in account) grows. The bank account will be depleted based on how fast moneys are withdrawn.

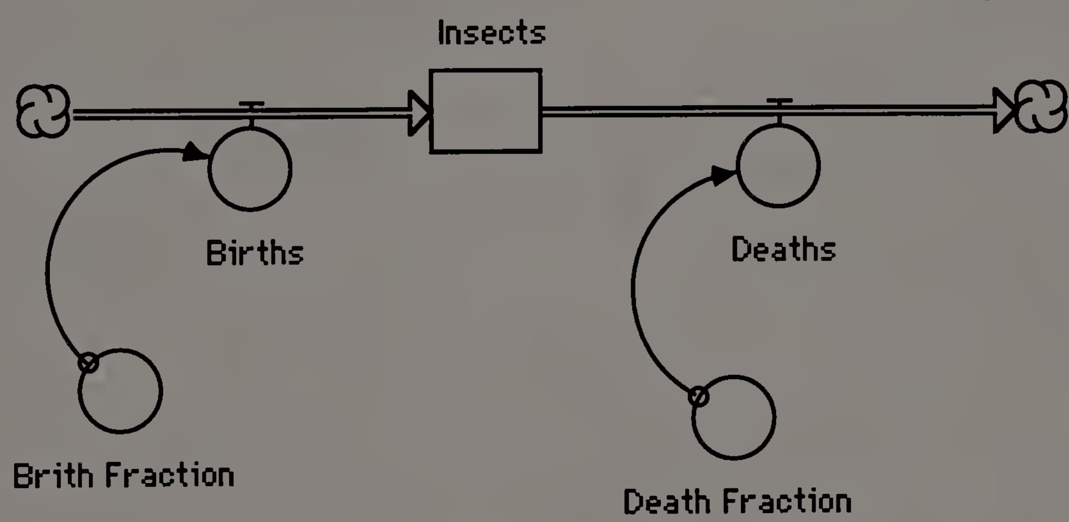
Researcher's Model	
S1's Model	
S4's Model	

2. The total number of insects increases exponentially because the birth rate sky rockets. This dramatic increase is due to insects incredible reproductive power. Soon the world would be overrun if predators did not influence the deaths of insects.

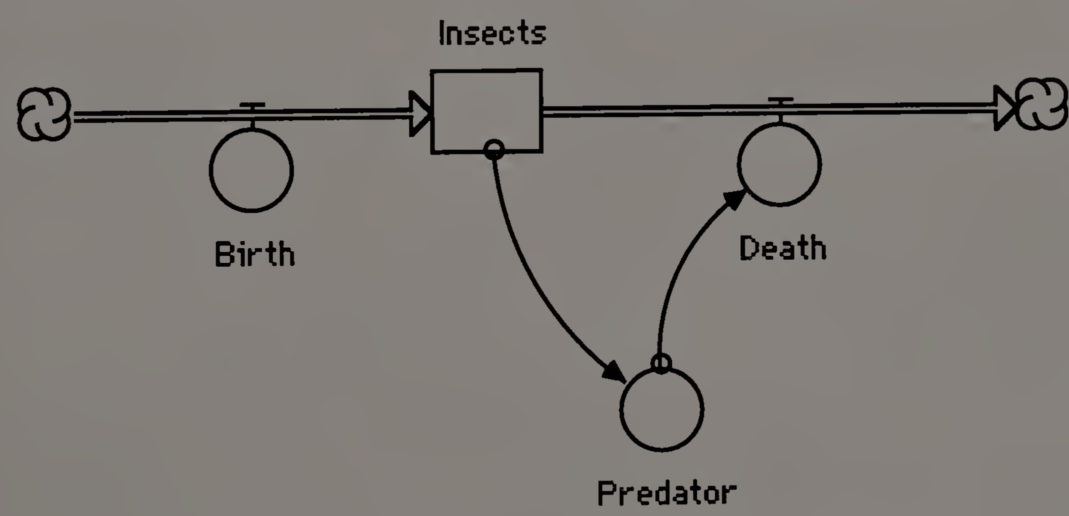
Researcher's Model



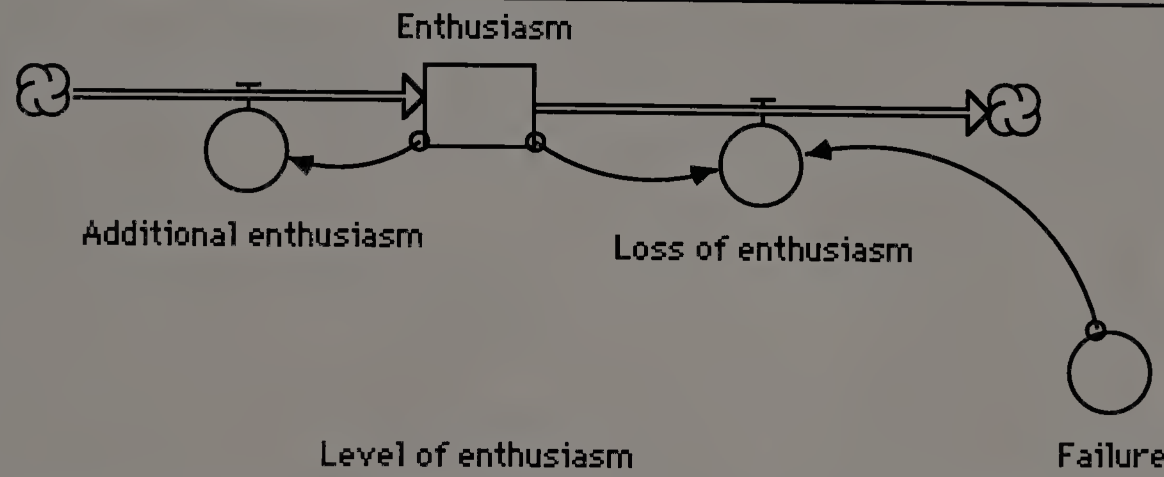
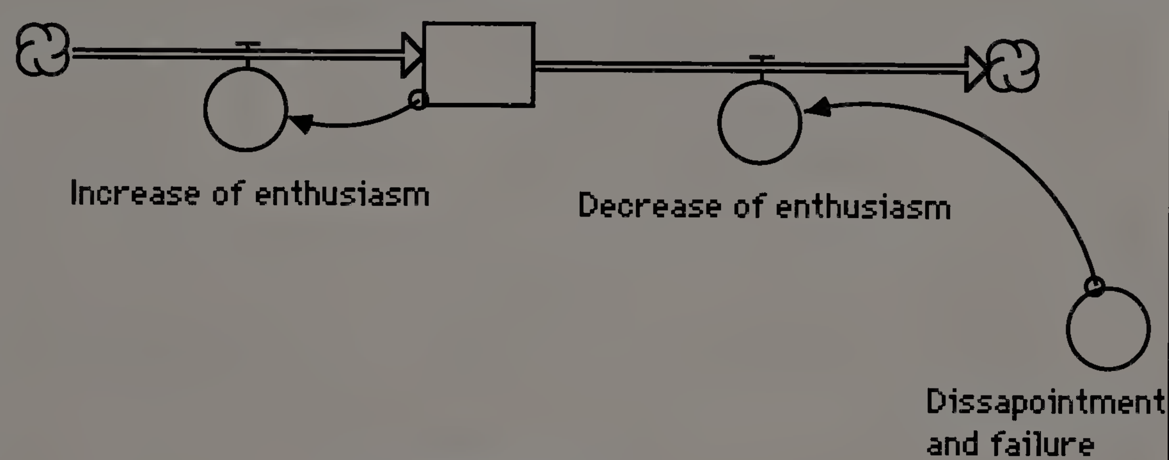
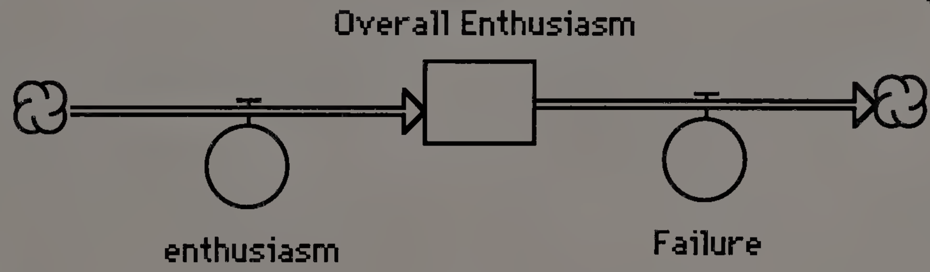
S1's Model



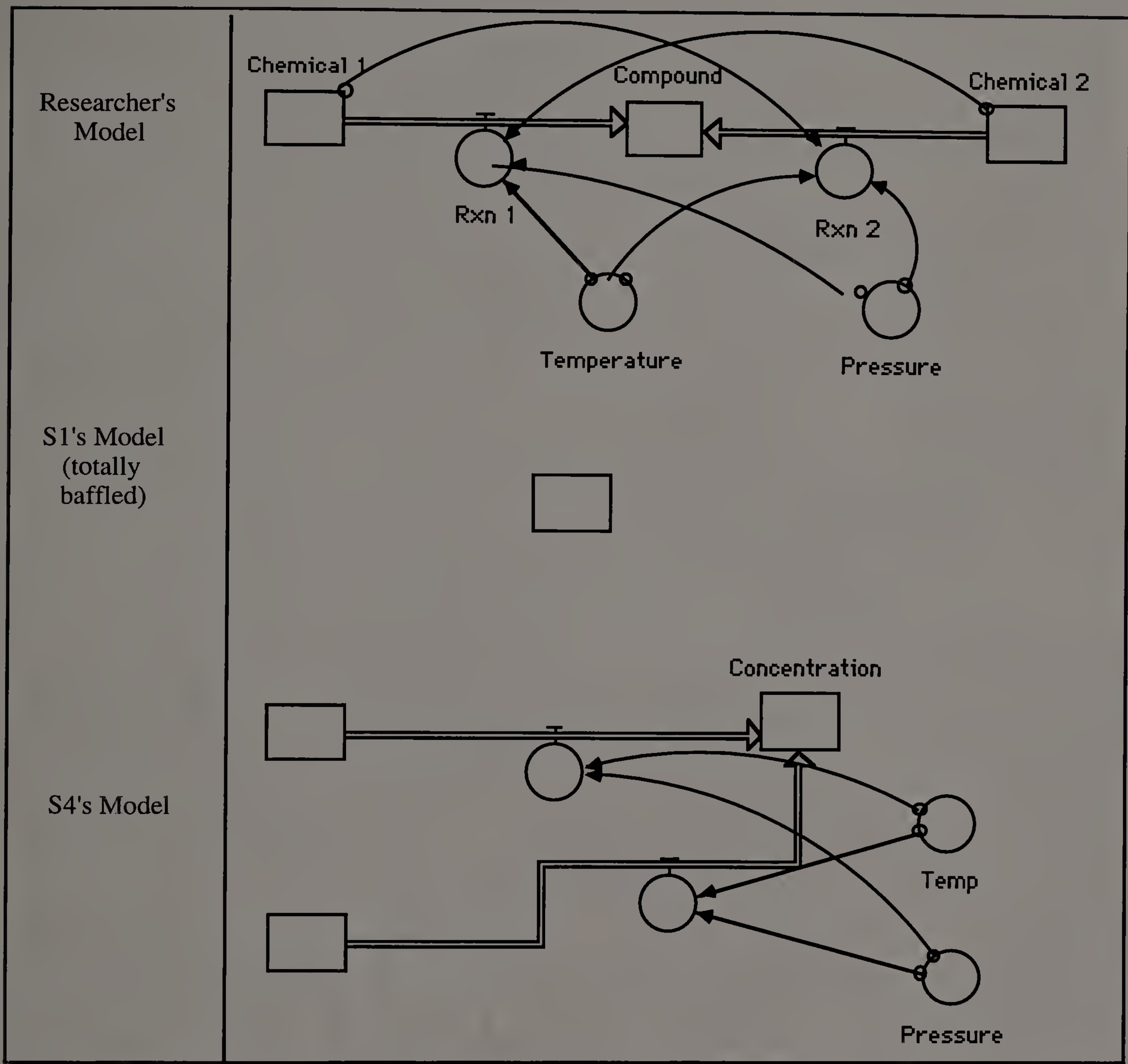
S4's Model



3. As people increase their enthusiasm each day their overall level of enthusiasm increases. However at the same time, disappointment and failure work to reduce people's enthusiasm.

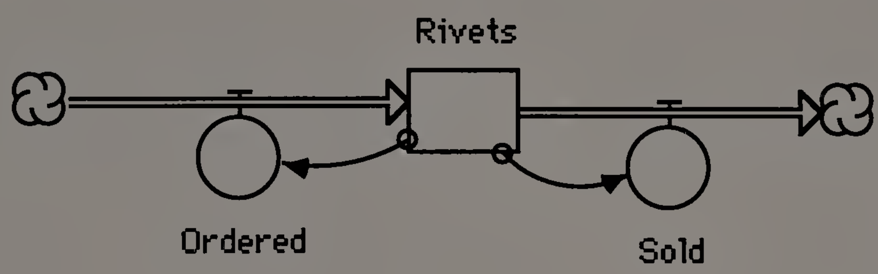
Researcher's Model	
S1's Model	
S4's Model	

4. The concentration of a chemical is the result of two elements combining together to form a compound. How fast the chemical reaction takes place is dependent on temperature and pressure.

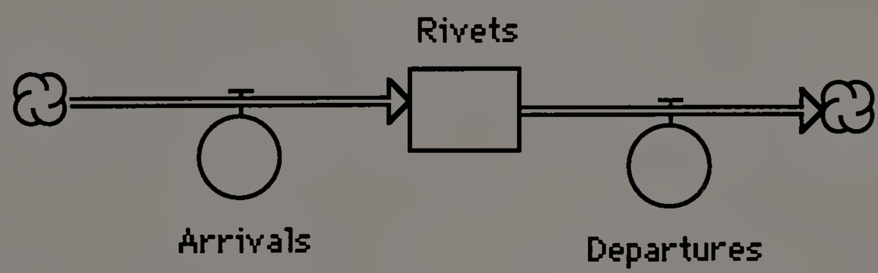


5. A company is attempting to maintain an adequate inventory of rivets. Monitoring the use of rivets helps in ordering rivets to maintain a constant supply.

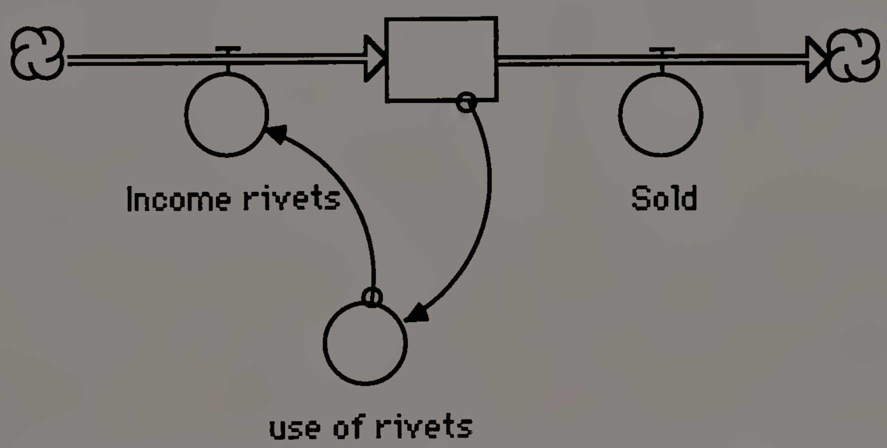
Researcher's Model



S1's Model



S4's Model



APPENDIX C

STELLA TOOL PALETTE AND MENUS

The tools identified by "*" were used extensively by students, tools identified with a "~" were used occasionally, and those not labeled were not used at all (See Figure A.1 and Figure A.2).

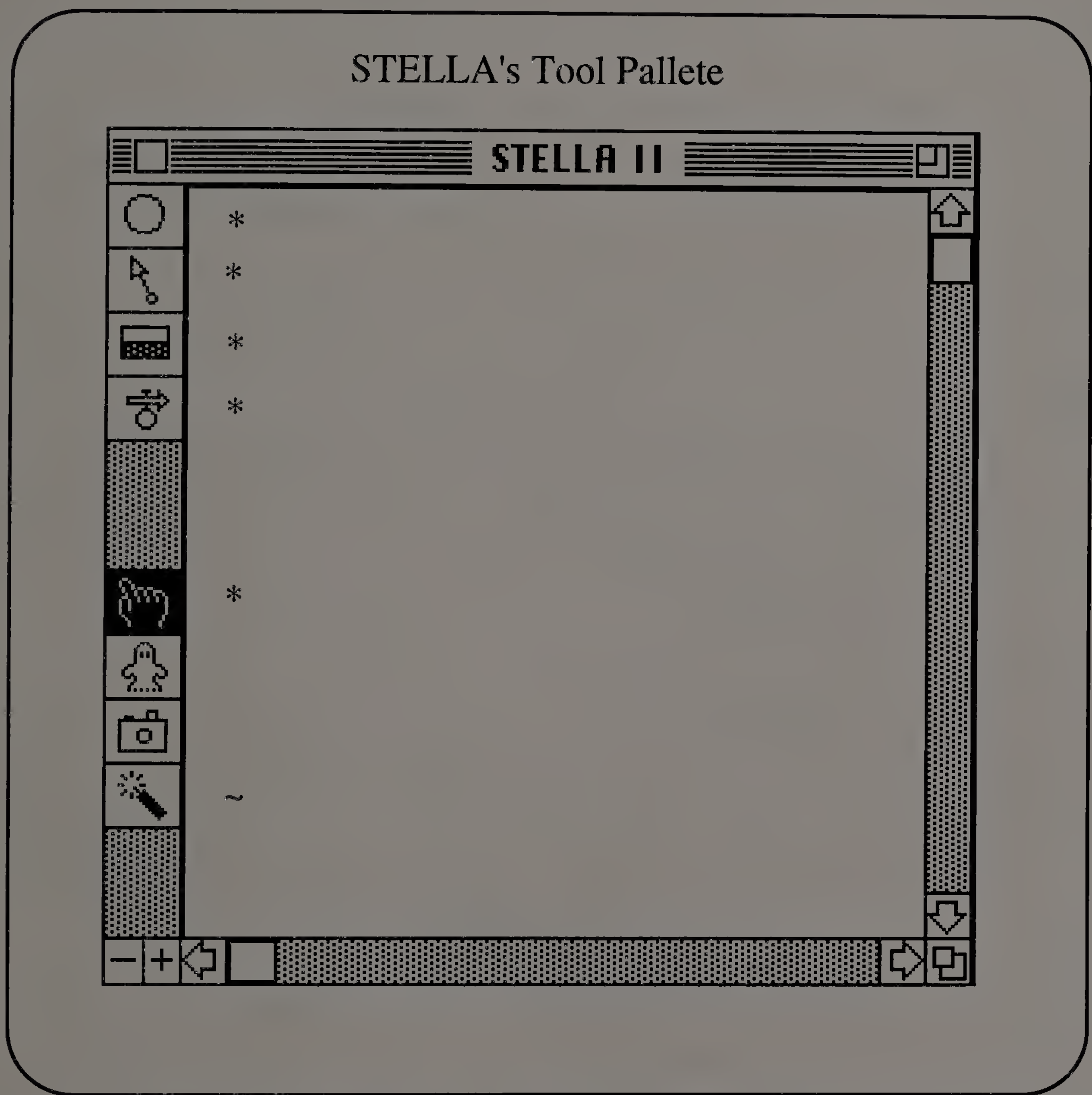


Figure A.1 STELLA's Tool Palette

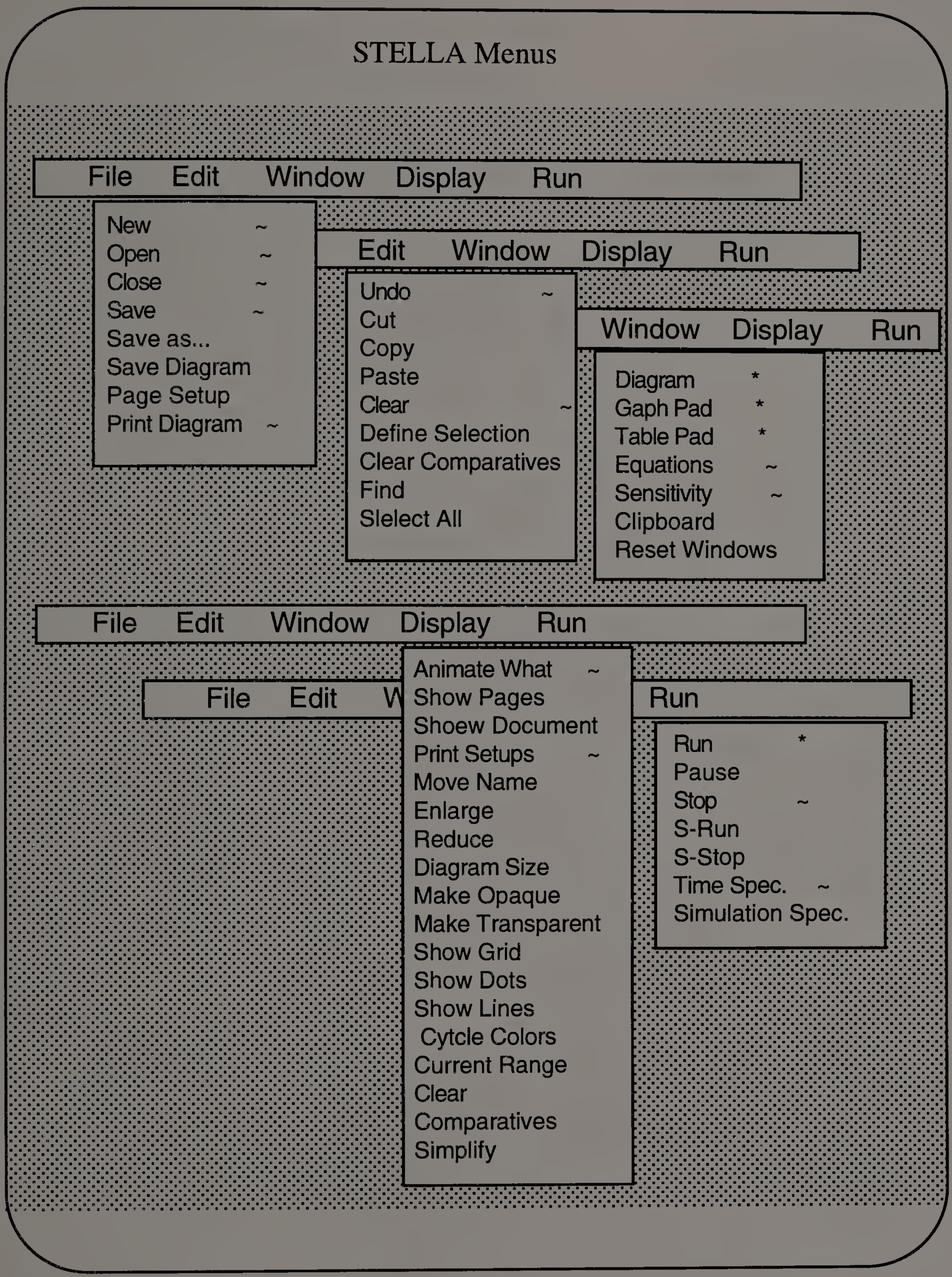


Figure A.1 STELLA Menus

APPENDIX D

MODELING SCENARIOS

Cocaine Scenario

To cross the synaptic gulf, an electrical signal triggers the release of neurotransmitters, substances that float toward receptors on the postsynaptic neuron. By binding to the receptors, neurotransmitters restimulate the electrical signal, which takes off along the second neuron. The presynaptic neuron terminates this chemical stimulation with specialized pumps that retrieve neurotransmitter substances from the synaptic gap.

Cocaine, however, jams these reuptake pumps, so that neurotransmitters remain in the synapse longer, initially enhancing stimulation. According to theory, chronic cocaine use, by blocking neurotransmitters retrieval, depletes the brain's overall supply of some these valuable chemicals.

In blocking the retrieval pumps, cocaine initially boosts the effect of neurotransmitters by keeping them in the synapse longer, thus prolonging their action on postsynaptic cells. This enhanced neurotransmitter stimulation, in fact, may produce the short-lived euphoria. With repeated cocaine use, neurotransmitters are used up, in effect "wasted" instead of retrieved, which diminishes the brain's overall supply of these chemicals. Many researchers now think that this depletion causes the "crash" that occurs when the high wears off: users feel depressed anxious, sleepy, and extremely hungry.

What are the dynamics of this theory, can you build a model to help you understand this phenomena better?

Chemical Equilibrium

Imagine two glass bulbs, at the same pressure, containing nitrogen dioxide gas. Place the first bulb in an ice bath and the second in boiling water. The gas in the bulb at 0 degrees C is almost colorless. The gas in the second bulb, at 100 degrees C, is reddish brown. Other experiments show that most of the molecules in the colder bulb have the formula N_2O_4. Since the gas is colorless, N_2O_4 must not absorb visible light. On the other hand, experiments show that most of the molecules in the warmer bulb have the formula $2NO_2$. Since the gas is reddish-brown in color, $2NO_2$ must absorb some visible light. When these bulbs are moved to a water bath at 25 degrees, the color in bulb 1 deepens. A chemical change is occurring.

bulb 1 $N_2O_4 \rightarrow 2NO_2$

colorless reddish brown

During the same time interval the color in bulb 2 fades. A chemical change is taking place in this bulb also.

bulb 2 $N_2O_4 \leftarrow 2NO_2$

colorless reddish brown

The gas color in the two bulbs becomes identical when they reach the same temperature.

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