System Blocks: Learning about Systems Concepts through Hands-on Modeling and Simulation

by
Oren Zuckerman

Bachelor of Arts in Computer Science
The Academic College of Tel-Aviv-Yaffo, Tel Aviv, Israel, 1998

Submitted to the
Program in Media Arts & Sciences,
School of Architecture & Planning
in partial fulfillment of the requirements of the degree of
Master of Science
at the Massachusetts Institute of Technology

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ABSTRACT

The world is complex and dynamic. Our lives and environment are constantly changing. We are surrounded by all types of interconnected, dynamic systems: ecosystems, financial markets, business processes, and social systems. Nevertheless, research has shown that people's understanding of dynamic behavior is extremely poor.

In this thesis I present System Blocks, a new learning technology that facilitates hands-on modeling and simulation of dynamic behavior. System Blocks, by making processes visible and manipulable, can help people learn about the core concepts of systems. System Blocks provide multiple representations of system behavior (using lights, sounds, and graphs), in order to support multiple learning styles and more playful explorations of dynamic processes.

I report on an exploratory study I conducted with ten 5th grade students and five preschool students. The students used System Blocks to model and simulate systems, and interacted with concepts that are traditionally considered "too hard" for pre-college students, such as net-flow dynamics and positive feedback. My findings suggest that using System Blocks as a modeling and simulation platform can provide students an opportunity to confront their misconceptions about dynamic behavior, and help students revise their mental models towards a deeper understanding of systems concepts.

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My Father, for seeding my deeply hidden passion for intellectual work, and for continuously believing in my creativity.

My Mother, for giving me the freedom to explore everything, including vital household items.

READER BIOGRAPHIES

MITCHEL RESNICK explores how new technologies both necessitate and facilitate deep changes in the ways people think and learn. Resnick's Lifelong Kindergarten group, at the MIT Media Lab, has developed a variety of educational tools, including the "programmable bricks" that were the basis for LEGO's award-winning MindStorms robotics construction kit. Resnick also led the development of StarLogo, a software toolkit for modeling decentralized systems. He is co-founder and principal investigator for the Media Lab's Digital Nations consortium. He also co-founded the Computer Clubhouse project, a network of after-school learning centers for youth from underserved communities, and co-developed The Virtual Fishtank, a million-dollar museum exhibit that helps children of all ages understand the working of complex systems. Resnick earned a B.S. in physics from Princeton University in 1978, and an M.S. and Ph.D. in computer science from MIT. Before pursuing his graduate degrees, he worked for five years as a science/technology journalist for Business Week magazine.

HIROSHI ISHII founded and directs the Tangible Media Group at the MIT Media Lab pursuing a new vision of Human Computer Interaction (HCI): "Tangible Bits." His team seeks to change the "painted bits" of GUIs to "tangible bits" by giving physical form to digital information. Ishii and his students have presented their vision of "Tangible Bits" at a variety of academic, industrial design, and artistic venues (including ACM SIGCHI, ACM SIGGRAPH, Industrial Design Society of America, and Ars Electronica), emphasizing that the development of tangible interfaces requires the rigor of both scientific and artistic review. Prior to MIT, between 1988-1994, Ishii led a CSCW research group at the NTT Human Interface Laboratories, where his team invented TeamWorkStation and ClearBoard. In 1993 and 1994, he was a visiting assistant professor at the University of Toronto, Canada. Ishii received B. E. degree in electronic engineering, M. E. and Ph. D. degrees in computer engineering from Hokkaido University, Japan, in 1978, 1980 and 1992, respectively.

TINA GROTZER is a Research Associate at Project Zero, Harvard Graduate School of Education. Her research focuses on topics at the intersection of cognition, development, and educational practice, such as the learnability of intelligence and how children develop causal models for complex science concepts. Tina is Co-Principal Investigator with colleague David Perkins on the Understandings of Consequence Project, funded by the National Science Foundation (NSF). The project has identified ways in which student explanations of scientific concepts have different forms of causality at the core than those of scientists. Tina received her EdD in 1993 and EdM in 1985 from Harvard University and her A.B. in Developmental Psychology from Vassar College in 1981.

PETER SENGE is a senior lecturer as MIT's Sloan School of Management. He has lectured extensively throughout the world, translating the abstract ideas of systems theory into tools for better understanding of economic and organizational change. He is the author of the widely acclaimed book, The Fifth Discipline: The Art and Practice of The Learning Organization (1990), introducing the theory of learning organizations. Since its publication, more than 750,000 copies have been sold. In 1997, Harvard Business Review identified it as one of the seminal management books of the past 75 years. The Journal of Business Strategy (September/October 1999) named Dr. Senge as one of the 24 people who had the greatest influence on business strategy over the last 100 years. The Financial Times (2000) named him as one of the world's "top management gurus." Business Week (October 2001) listed Peter as one of The Top (ten) Management Gurus. Peter Senge received a B.S. in engineering from Stanford University, an M.S. in social systems modeling and Ph.D. in management from MIT.

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CHAPTER 1. INTRODUCTION

The world is complex and dynamic. Our lives and environment are constantly changing. We are surrounded by all types of interconnected, dynamic systems: ecosystems, financial markets, business processes, and social systems. Our actions in the present often have unintended and unexpected long-term consequences we are responsible for but not aware of. For example, inner-city affordable housing projects can result in a long-term increase of the city's unemployment rate; unexpected increase in demand for a company's product can result in the company's bankruptcy; extreme diet can result in a long-term weight gain; farmers' use of pesticides can result in a long-term increase in the number of insects; population and economic growth can deplete the world's non-renewable resources and lead to long-term population and economic decline.

Research has shown that people's understanding of the dynamic behavior of systems is extremely poor (Dorner, 1989; Resnick, 1994; Sterman, 1994; Booth-Sweeney, 2000). People tend to focus on the short-term and direct consequences of actions, and ignore long-term and indirect consequences caused by time-delays and interconnectedness.

In the 20th century we experienced major advances in the way scientists understand dynamic behavior in natural and social systems. Different mathematical frameworks and modeling techniques have been successfully developed to better understand the behavior of systems.

But K-12 schools rarely introduce students to core concepts of systems such as circular causality, positive and negative feedback, stocks and flows, time delay, and unintended consequences. These concepts are considered "too hard" for K-12 students. System concepts are typically taught only at college and university levels, and only at engineering departments and selected business schools. By this age, students have already developed their own models of how the world works (through constructive processes in younger ages), and thus find it difficult to understand the behavior of systems.

In the past two decades, several software simulation environments have been developed to enable novices to model and simulate the behavior of systems. The goal of those endeavors was to develop tools that K-12 students can use, with no prior instruction in systems or advanced mathematical knowledge. StarLogo (Resnick, 1994), Stella (Richmond, 1987, 1992) and Model-It (goKnow Inc.) are a few examples.

The motivation to my work was the need for a simulation environment that can provide an easier introduction to systems modeling, making system concepts accessible to an even broader range of students. Building on the body of work in constructionist research (Piaget, 1972; Papert 1980, 1991; Kafai and Resnick, 1996), the approach I took is to make dynamic processes visible and manipulable through physical interaction. Towards that end I have developed System Blocks, a new digital manipulative for hands-on modeling and simulation of systems concepts. System Blocks supports the Stocks and Flows modeling technique that explores system behavior through continuous interaction of aggregated amounts (see Appendix A for an introduction to the Stocks and Flows modeling language).

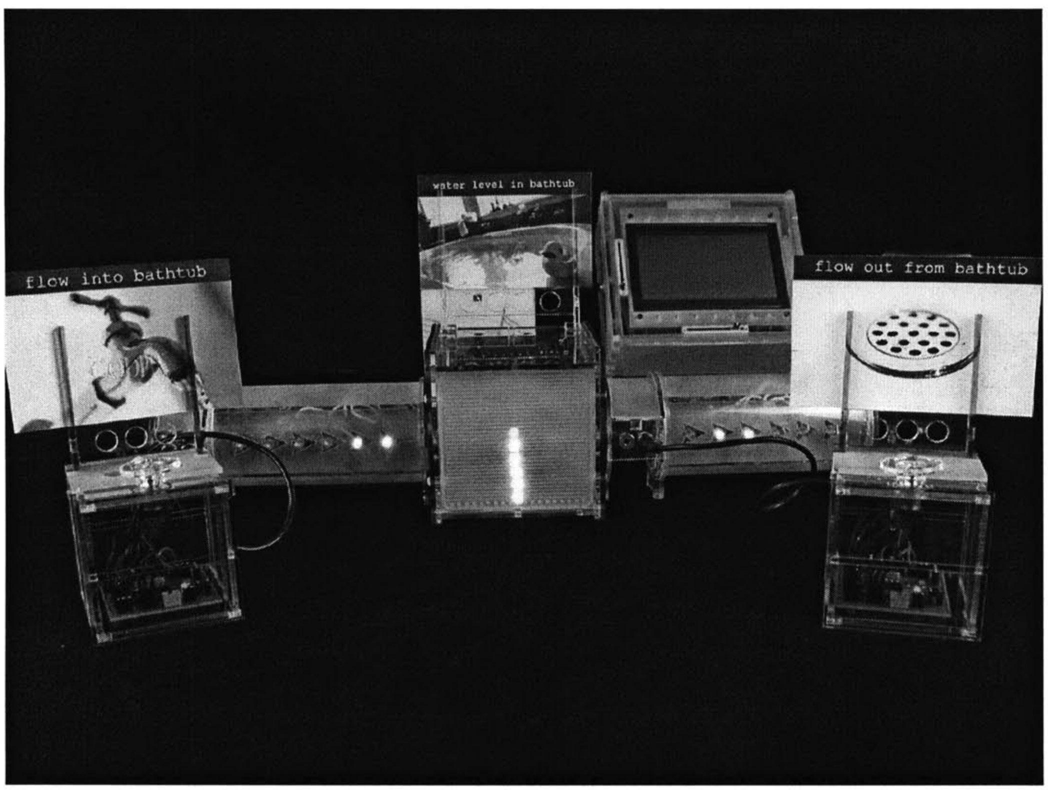

Figure 1. System Blocks simulating water flow through a bathtub

Using System Blocks, children and adults alike can model, simulate and analyze system structures by connecting physical blocks in different arrangements. System Blocks are designed to support the interweaving of concrete experiences and abstract reasoning, by helping students to connect core systems concepts with real-life examples. System Blocks were designed to support multiple styles of learning using a variety of multi-sensory representations including moving lights, sound, and real-time graph. System Blocks are a friendly, playful tool to physically model systems structures, examine the simulated behavior over time, and learn to identify fundamental structures in the systems around us.

I report on an exploratory study I conducted with ten 5th grade students and five preschool students. These students used System Blocks to interact with system concepts that are traditionally not taught at schools. I conducted one-on-one interviews with the students while they used System Blocks to model and simulate systems that relate to their own lives. I observed how the 5th grade students, with the appropriate tools and support, are able to learn concepts and techniques such as stocks and flows mapping, net-flow dynamics, and positive feedback to the extent that they can generate their own examples using these concepts. I observed how 4-year-old preschool students are capable of using System Blocks as a modeling and simulation tool, recognizing processes such as accumulation from a general representation of moving lights, and talking about real-life examples in systems terms.

I report on several misconceptions and tendencies I observed in my interviews, with regards to young children's understanding of systems concepts. A more comprehensive study should be done to examine the nature of these misconceptions and to define the strategies and educational scaffolding teachers should use to help students develop richer understanding of dynamic behavior.

My preliminary findings suggest that using System Blocks as a modeling and simulation platform can provide an opportunity for students to confront their misconceptions about dynamic behavior, and help students revise their mental models towards a deeper understanding of systems concept.

Consider the dynamic system modeled in Figure 2. Children participate in a "cookies store" activity at school, where they bake and sell cookies to school's students. Some students bake the cookies at the school kitchen and pass them to a cookies basket, while other students sell the cookies to other students.

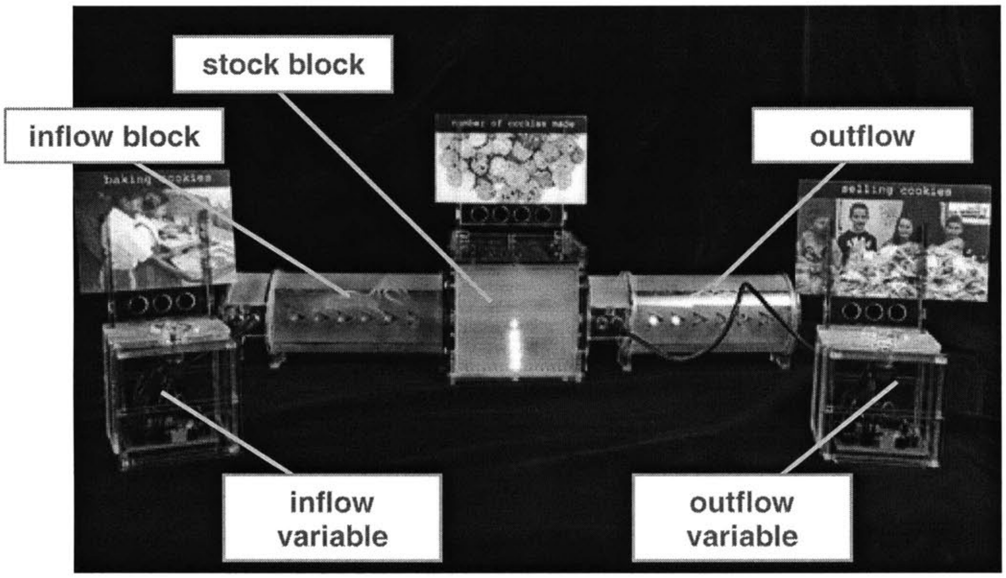

Figure 2. System Blocks simulating a "cookies store" example

This system behavior can be modeled using System Blocks (see Figure 2). The inflow block represents the "baking cookies" rate, the stock block represents the "number of cookies in basket", and the outflow block represents the "selling cookies" rate. When this model is simulated, students can play different scenarios and see how the system reacts. For example, increasing the inflow rate by turning the dial on the inflow variable block (baking more cookies) will increase the stock (number of cookies in basket). Increasing the outflow rate by turning dial on the outflow variable block (selling more cookies) will decrease the stock (number of cookies in basket). Further tinkering with System Blocks enables students to quickly get to the next step, analyzing net-flow dynamics: If the inflow is set to a higher rate than the outflow, the stock will increase; If the outflow is set to a higher rate than the inflow, the stock will decrease; finally, if the inflow and outflow are set to exactly the same rate, the stock level will not change and the system will remain in a state of dynamic equilibrium. In our cookie store example, dynamic equilibrium means the number of cookies in the basket stays constant, while cookies are being baked and sold all the time.

The above scenario represents a generic system structure. Other simplified real-life examples that fit this structure are a bank account balance, amount of homework left to do, pollution level in the atmosphere, and amount of calories in the body, to name a few.

If a stock represents "amount of calories in the body", then the inflow is "consuming calories" or "eating", and the outflow is "exercising". A person familiar with this generic structure would know that in order to decrease the amount of calories in the body and maintain a new balance one must pay attention to the inflow and outflow at the same time, and not focus only on one of them.

Building on this simple generic structure, consider the following next step: the students that bake the cookies want to make sure the cookies basket is always full. They watch the number of cookies in the basket, and they bake new cookies if this number decreases. This scenario describes a goal-seeking system. The goal is to keep the "actual number of cookies in basket" as close as possible to the "desired number of cookies in basket". The students are an integral part of the system. They monitor the goal (number of cookies in basket) and adjust the inflow (baking more cookies) based on the gap between the actual stock level and the desired level. For the sake of simplicity, we have not modeled the time delay it takes to bake the cookies ("baking time"). Adding an additional stock block will create the time delay, and the model will become the classic supply-chain model of a time delay between production and sales, which many managers struggle with.

This is one out of many real-life examples of dynamic behavior based with an underlying generic structure. If the simple structures will be taught at elementary and middle schools, high-school students might be ready to understand the more advanced structures, ones that produce goal-seeking, s-shaped or different oscillating behaviors.

CHAPTER 3. THEORY AND RATIONALE

System thinking is seeing the whole in addition to the parts; seeing the interaction between the parts and not only the parts; looking for key interventions that can modify a system behavior with minor interferences; and leveraging unintended consequences to enhance long-term stability.

In this chapter I will situate my research in three areas: cybernetics and systems theory; learning technologies; and studies of children's learning of dynamic behavior.

3.1 The Systems View of the World

During the 20th century we experienced major advancements in the way scientists understand the behavior of systems in natural and social systems. Different mathematical frameworks and modeling techniques have been successfully developed to better understand dynamic behavior in general and the behavior of systems in particular. The core concepts of systems were mathematically defined such as positive and negative feedback, stocks and flows, and time delays. Researchers have mapped the "generic systems structures" commonly observed in natural and social systems, structures that generate behaviors such as exponential growth and decay, goal seeking, oscillating or self-regulating behavior.

The feedback concept as a self-regulating mechanism in engineering systems is not a modern idea. In his book *Feedback Thought in Social Science and Systems Theory* (Richardson, 1991), George Richardson beautifully maps the evolution of the feedback concept throughout history. The first known feedback device is the float valve of Ktesibios, dated as early as 250 B.C. (Richardson, 1991 taken from Mayr, 1970). Ktesibios float valve was used to create a steady drip of water into a cylindrical vessel, enabling the construction of an accurate water clock.

The feedback concept in biological and social systems is a modern idea. The first published article linking biological and social systems with the engineers' concept of feedback is Rosenblueth, Wiener and Bigelow's 1943 paper *Behavior, Purpose and Teleology*.(Rosenblueth et al., 1943). Their definition of the term "feedback" is:

> The expression feed-back is used by engineers in two different senses. In a broad sense it may denote that some of the output energy of an apparatus is returned as input; an example is an electrical amplifier with feed-back. The feed-back is in these cases positive - the fraction of the output which reenters the object has the same sign as the original input signal. Positive feedback adds to the input signals, it does not correct them. The term feed-back is also employed in a more restricted sense to signify that the behavior of an object is controlled by the margin of error at which the object stands at a given time with reference to a relatively specific goal. The feed-back is then negative, that is, the signals from the goal are used to restrict outputs which would otherwise go beyond the goal. It is this second meaning of the term feed-back that is used here. All purposeful behavior may be considered to require negative feed-back. If a goal is to be attained, some signals from the goal are necessary at some time to direct the behavior.

In their paper they give examples for feedback in biological and social systems (as opposed to engineering systems) such as a cat pursuing a mouse, a bloodhound following an object, a person lifting a glass of water from table to mouth or the action of throwing a stone at a moving target.

In the years to follow many people were deeply influenced by the feedback and systems concepts. Most of those people had engineering background, and they started to apply these concepts to other disciplines. Wiener, Laszlo, and von Bertalanffy from the so-called Cybernetics thread were mostly focused on the philosophical, social and human direction, while Forrester tried to understand how feedback relates to economics and business systems.

Wiener

In 1948 Norbert Wiener published *Cybernetics: control and communication, in the animal and the machine* (Wiener, 1948) and defined a new field. The term cybernetics derives from the Greek word for steersman. At the core of cybernetics is the concept of feedback. Appropriately, the art of steersmanship is a feedback system that includes the person that steers the ship as an integral part of the system. Cybernetics studies how systems function, how they control their actions, how they communicate with other systems or with their own components. In 1954 Weiner published *The Human Use of Human Beings* (Weiner, 1954), where he broadened his vision from animals and machines to sociological systems, such as bureaucracy and factory. In the 1960's cybernetics as a discipline experienced a rapid rise followed by a swift decline. In recent years there was a second wave of cybernetics. "New" or "second order" cybernetics includes the observer as an integral part of the observed system, and deals with how observers construct models of the systems with which they interact.

Von Bertalanffy

In the 1940's, the biologist Ludwig Von Bertalanffy introduced General System Theory (Bertalanffy, 1955; 1968). Bertalanffy defined his theory as an interdisciplinary doctrine "elaborating principles and models that apply to systems in general, irrespective of their particular kind, element, and forces involved." General System Theory is the scientific exploration of "wholes" and "wholeness", and Bertalanffy emphasize that not so long ago before he introduced his theory these terms were considered metaphysical notions transcending the boundaries of science. General System Theory provides a possible approach toward the "unification of science", through the shared system structures found in different domains. Bertalanffy called them parallelisms or isomorphisms, and tried to define general-system properties such as hierarchic structure, stability, differentiation, steady states and goal directedness. The system view contrasts with the mechanistic view. As Bertalanffy said "The concept of 'system' consist a new 'paradigm',..... contrasting the blind laws of nature of the mechanistic world view and the world process as a Shakespearean tale told by an idiot, with an organismic outlook of the 'world as a great organization'."

Laszlo

In 1972 Ervin Laszlo published "Introduction to Systems Philosophy" and "The Systems View of The World" (Laszlo, 1972). According to Laszlo, atomistic and holistic ways of thinking have alternated in the history of Western science. Early scientific thinking was holistic but speculative, followed by a movement to empirical yet atomistic science. Laszlo defines the systems scientific view as the next choice, getting back to holistic concepts but using rigorous theories. He documents the rise of the systems theories after the breakdown of the mechanistic view of the world. According to Laszlo, the mechanistic world view, rooted in the Newtonian science, looks at the world as an "exquisitely designed giant mechanism, obeying elegant deterministic laws of motion." At the beginning of the twentieth century, sets of interacting relationship came to occupy the center of attention. For example, in the field of physics, where Newton's mechanistic theory was most successful, new theories rose such as relativity in field physics and quantum theory in microphysics. Throughout the 20th century we saw the beginning of a change towards the system view in the different sciences. In biology, the laws of physics were insufficient to explain the complex interactions that take place in a living organism. In the science of economics, the rise of a stock price could not be explained based on the actions of an individual stockbroker.

Forrester

In 1961, Jay Forrester published "Industrial Dynamics", presenting a "way to study the behavior of industrial systems to show how policies, decisions, structure, and delays are interrelated to influence growth and stability" (Forrester, 1961). Industrial Dynamics aims to integrate the separate areas in management – marketing, investment, research, personnel, production, and accounting.

Forrester credits the development of his work to his direct experiences. Those include direct management experience and exposure to commodity markets at his parents' farm and later on at the Lincoln Laboratory, as well as his graduate studies in Prof. Gordon Brown's Servomechanisms laboratory at MIT, where information-feedback concepts were developed, and through the opportunity he had to plan and direct the construction of Whirlwind I, the first high-speed electronic digital computer.

Forrester describes the construction of dynamic system models that can connect different components through continuous flow. The components include Levels, Flows, Decision Functions, Sources, Sinks, Auxiliary Variables, Parameters and Constants. Rate Equations define the mathematical behavior of the components, and the models plus equations can be complied and run through the DYNAMO compiler.

The result is a system behavior generated by the interactions of the model components. Simulations clarify that often interactions are more important than the components taken separately. Forrester's Dynamic System Models is a powerful technique that enables investigation of different policies, decision factor and scenarios by changing parameters in the model.

After "Industrial Dynamics" Forrester continued to develop his theory and created the System Dynamics field at MIT's Sloan school of management. He created models in different domains, including economics, urban policy and global policy, documented in his books "Principles of Systems", "Urban Dynamics" and "World Dynamics" among others.

3.2 Learning Technologies

In the last several decades there were many approaches to technology-supported learning. Most influential on my research were the constructionist approach to learning (Papert, 1991); the "digital manipulatives" approach that takes core concepts of traditional manipulatives and enhance them using embedded computation; and the modeling and simulation approach to learning.

System Blocks are a new manipulative as well as a new modeling & simulation tool. In this section I will describe some of the related work in these fields as well as projects that inspired me.

3.2.1 Digital Manipulatives

Manipulatives are widely used in Kindergartens and elementary schools to help children learn abstract concepts through hands-on play activity.

The American Heritage® Dictionary of the English Language defines manipulatives as: "any of various objects designed to be moved or arranged by hand as a means of developing motor skills or understanding abstractions, especially in mathematics".

NCREL Glossary of Education Terms and Acronyms defines manipulative as: Any physical object (e.g., blocks, toothpicks, coins) that can be used to represent or model a problem, situation or develop a mathematical concept.

Digital manipulatives share the same approach, of helping children learn through hands-on play activity, but use embedded computation to try and make abstract concept more visible and manipulable. If traditional manipulatives address concepts such as number, shape, color, area or texture, digital manipulatives address concepts such as emergence, acceleration, social networks, feedback and control, communication, differential geometry, and the behavior of systems.

3.2.1.1 The origins of manipulatives

Pestalozzi, a 19th century educationist, published a book at 1801 named "How Gertrude Teaches Her Children" (Pestalozzi, 1801), emphasizing that children should not be given ready-made answers but should arrive at answers themselves through self-activity. At 1805 Pestalozzi's founded a school in Yverdon, Switzerland that practiced his new vision to education.

Friedrich Froebel, an agriculture student, visited Froebel's school in the year it was founded and was inspired by Pestalozzi's educational ideas. Following this visit, Froebel formulated the "Kindergarten System" with emphasis on the use of special play materials ("gifts") in carefully defined activities ("occupations"). Froebel laid out his educational philosophy in his book "On the Education of Man" (Froebel, 1826; Brosterman, 1997). Froebel "gifts" were 20 carefully designed play materials, such as wooden blocks and dots, geometric paperboard pieces, and geometric metal pieces. The "gifts" and related "occupations" helped young children learn about color, form, geometry and physics through design and story telling activity. Froebel did not design the "gifts" to teach certain concepts, but rather to emphasize the "unification" of life and to help children appreciate "forms of life", "forms of knowledge", and "forms of beauty".

Maria Montessori was the first woman in Italy to qualify as a physician. She argued for teachers training along Froebelian lines, and developed a set of principles, which later became the "Montessori Method" (Montessori, 1916) and the foundation of her "Casa de Bambini". In her method, Montessori argued for "first the education of the senses, then the education of the intellect". In a program she developed for children with difficulties in reading and writing, she emphasized learning through repeating exercises "Looking becomes reading; touching becomes writing". Integral components of her method were the "Montessori Materials". In contrast to Froebel's gifts, Montessori's materials were designed to teach a specific concept. Montessori focused on selected areas for her manipulatives: Cultural, Language, Mathematics, and Sensorial. Cultural included animals and world puzzles; Language included alphabets, word kits, and grammar kits; Mathematics included number rods, number figures, fraction circles, multiplication boards etc.; Sensorial included wooden towers, stairs, cylinders, color tablets, sound cylinders, touch fabrics and more.

3.2.1.2 Beads, Balls, and Badges

Mitchel Resnick and researchers at the Lifelong Kindergarten group at MIT's Media Lab have introduced a set of digital manipulatives – computationally enhanced versions of traditional children's toys (Resnick et al. 1998). The new beads, balls, and badges help children explore a set of concepts that have previously been considered "too advanced" for children to learn.

The programmable beads helps children to create dynamic light patterns, and in the process learn about concepts such as emergent phenomena.

The BitBall, a programmable ball, uses its internal acceleration sensor to map acceleration in real-time to different mediums, such as sound and light. Children themselves change the BitBall programs and can customize the mapping. In the process of play and programming, children can learn about the abstract concept of acceleration in a playful way. Resnick reports that a group of university students could not apply their physics classroom knowledge to a real-world context: finding the top of a ball's trajectory based on its acceleration data alone. Using the BitBall they learned that it is impossible to find it from acceleration data alone.

The Thinking Tags, a computational version of the traditional nametag, enables children to become an integral part of a social network simulation. For example, infectious disease simulations that simulate a virus spread through a population. Students, in the process of the simulation game, learn about systems concepts and social networks ideas (see more on the Thinking Tags in section 3.2.2.4).

3.2.1.3 Programmable Bricks

In the last decade, a family of programmable bricks were developed at MIT's Media Lab. This research has led to the development of the "LEGO Mindstorms" product, a popular robotic construction kit.

The Cricket, perhaps the most fully developed digital manipulative, is the latest version in the programmable bricks family. The Cricket is a tiny computer, powered by a 9 volt battery, that receive information from sensors and control motors (Martin, 1994; Resnick, 1996a). Children can program Crickets to control the behavior of electro-mechanical LEGO creations, such as robotic creatures, kinetic sculptures, simple scientific instruments, and custom-made toys. As a digital manipulative, Crickets help children learn about feedback and control, and engage them in design and artistic activities that were not previously accessible only to engineers (Resnick, 2000).

Resnick reports (Resnick, 1996b) how children use Cricket to learn about concepts such as feedback and control (when creating a robotic dinosaur that attracts to flashing light) or about general principles of communication (when designing a "protocol" for communicating creatures).

3.2.1.4 Triangles, Curlybot, and Topobo

The Tangible Media Group at MIT's Media Lab has been a pioneer of innovative tangible interfaces for children and adults alike. Hiroshi Ishii, in his "Tangible Bits" vision (Ishii, 1997), emphasizes that our sophisticated skills for sensing and manipulating our physical environments are not employed by traditional computer interfaces (GUI – Graphical user Interfaces). Ishii's group aims to seamlessly couple the dual worlds of bits and atoms.

Below I briefly describe several projects of the Tangible Media Group that seems most relevant to the "Digital Manipulatives" framework.

Triangles (Matthew et al., 1998) is a new form of computer interface that uses physical objects to embody digital information. Triangles are a set of triangular-shaped plastic shapes, with embedded computation, that enable users to create both two and three-dimensional patterns. The triangles connect together both physically and digitally with magnetic, conducting connectors. Triangles were tested as a non-linear story telling tool, a media configuration system, and an artistic expression material.

Curlybot (Frei et al. 2000) is a toy that can record and playback physical motion. As one plays with it, it remembers how it has been moved and can replay that movement with all the intricacies of the original gesture; every pause, acceleration, and even the shaking in the user's hand, is recorded. Curlybot then repeats that gesture indefinitely creating beautiful and expressive patterns. Using Curlybot, children can explore mathematical concepts such as differential geometry, or computational concepts such as programming by example.

Topobo (Raffle and Parkes, 2004) is a 3D constructive assembly system embedded with kinetic memory, enabling people to record and playback physical motion. By snapping together a combination of Passive (static) and Active (motorized) components, people can quickly assemble dynamic forms like animals and skeletons. Pushing, pulling, twisting, and stretching the components can animate those forms. For example, a dog can be constructed and then taught to gesture and walk by twisting its body and legs. The dog will then repeat those movements and walk repeatedly. Topobo can help children gain better understanding of balance, center of mass, coordination, relative motion, and multiple degrees of freedom.

3.2.1.5 Electronic Duplo Blocks

Aimed at preschoolers, the Electronic Blocks (Wyeth, 2001) are tangible programming elements mounted inside LEGO Duplo blocks. Using sensor, logic, and action blocks young children create interactive devices such as a light block that activates when clapping or a motion block that moves when light is detected. The Electronics Blocks strength is in its simplicity, enabling very young children to independently create different devices and in the process explore core concepts of logic and programming. Wyeth reports that older children (elementary and middle school students) could build more sophisticated creations, such as towers of blocks that "talked" to each other, alarm clocks and cars that could count.

3.2.2 Simulation Tools for Learning of Dynamic Behavior

Generally speaking, there are two approaches to computer modeling. The first approach, sometimes described as "point prediction", aims to create models that predict the future and assist in decision-making based on those predictions. Typically, "point-predication" models try to include all the possible influences and tend to be large and complex. The second approach, sometimes described as "generating insights", aims to create smaller models that do not include all the possible influences, but include the core variables and influences. Many times, the process of modeling and simulating these models generate insights about the overall dynamic behavior.

Modeling for learning belongs to the "generating insights" approach. As many thinkers in the field say, no model is ever complete. The power of computer modeling is the process of modeling, and not the generated result. When modeling dynamic behavior, even simple models can generate behavior that shares similar dynamics of real-life phenomenon. Small models can be understood in a short period of time, and can be used as building blocks to understand bigger models. In addition, simulation of small models makes it easier to run different scenarios and identify the core influences in a particular phenomenon.

In the field of systems modeling there are two main modeling approaches, I would address them as the "individual-focused" and the "aggregate-focused".

> The "individual-focused" approach, such as agent-based modeling, starts with individual agents and show how the interactions between many agents form a dynamic system. The rules underlying the behavior of each individual agent can be very simple, but the resulting system can have a rather complex behavior.
>
> The "aggregate-focused" approach, such as stocks & flows modeling (see appendix A), starts with aggregated amounts that are the core components of a specific system and shows how continuous flow of material and information between this components determines the system's behavior over time. Specifically, feedback processes are identified and modeled as the core generators of systems behavior.

Both approaches can model similar problems in different ways. For example, the classic dynamics between predator and prey can be modeled in both approaches, to show the resulting oscillatory behavior. The following description describes the modeling guidelines in both approaches for a "rabbits eating grass" predator-prey system.

The "individual-focused" approach rules would be something like:
Rabbits wander around randomly. Grass grows randomly. When a rabbit bumps into some grass, it eats the grass and gains energy. If the rabbit gains enough energy, it reproduces. If it doesn't gain enough energy, it dies.

The "aggregate-focused" approach mapping would be something like:
Grass has an initial "population level", a "growth rate" and a "being eaten rate". Rabbits have an initial "population level", a "birth rate" and a "death rate". The relationship between the two populations is defined as: more Grass lead to more Rabbits (through increased "birth rate"), more Rabbits lead to less Grass (through increased "being eaten rate").

When both approaches are modeled and simulated, an oscillatory behavior is generated.

Below I review seven tools, targeted at novices, that facilitate modeling and simulation of dynamic behavior: STELLA®, Star Logo, Model-it™, Colella's Participatory Simulation, Patten's Sensetable, Gorton's Tangible Toolkit, and SimCalc.

3.2.2.1 STELLA

In 1987, Barry Richmond introduced STELLA, the first visual software tool for system dynamics modeling and simulation. STELLA makes it possible to model and simulate dynamic behavior using the Stocks and Flows modeling language. STELLA's main representations are a bar graph or a "behavior over time" graph. In addition, STELLA is designed with multiple layers, enabling teachers to create a presentation interface separated from the model and equations layers. This makes it easier to create "self-contained" exercises that use text and images to help students navigate and interact with pre-defined models. On the other hand, it puts another layer between the students and the modeling process.

In addition to developing STELLA, Richmond had a comprehensive vision for system thinking in K-12 education, and had a clear definition of the generic structures underlying system behavior (Richmond, 1992).

Today STELLA is used in K-12 education by an active community of teachers who see system thinking and dynamic modeling as an integral part of education. The main centers for system thinking in K-12 are the Waters Foundation (www.watersfoundation.org) and the Creative Learning Exchange (www.clexchange.org). These centers supply teachers with classroom case studies, example class materials and the relevant STELLA computer models. Schools that include system thinking as part of their standard studies perform participatory games that simulate system concepts in K to 5th grades and use the STELLA® software to model and simulate dynamic behavior in 6th to 12th grades. In most cases, system thinking is integrated to an existing subject, such as physics, science or literature (Hopkins, 1992).

System Blocks shares many themes with STELLA. The modeling language is very similar, as well as some of the representations and style of interaction. System Blocks differ from STELLA in its tangible interface, simplified modeling process that does not require equations, and multi-sensory representations such as the moving lights and the sound.

3.2.2.2 StarLogo

In 1993, Mitchel Resnick introduced StarLogo, a software simulation tool that makes it possible to crate microworlds with many interacting agents (Resnick, 1994). Using StarLogo, adults and children can gain better understanding of decentralized and self-organizing systems, as well as core concepts such as emergence. StarLogo can simulate real-life systems in different domains, including but not limited to biological, physical, sociological, and ecological systems. A 2D animated display area is StarLogo's main representation of the dynamic behavior, presenting each agent as a colored dot or icon. The result is a simple and effective visual experience that makes it easy to identify trends. For example, a traffic jam simulation makes it possible to see that jams can be created without any direct cause (such as car accident or police speed trap), but rather as a result of the different interactions between the moving cars.

3.2.2.3 Model-it

Model-It™ (goKnow Inc.) is a visual modeling and simulation tool enabling students to easily build, test, and evaluate qualitative models of dynamic behavior without needing to know the underlying calculus driving these models. Model-It™ provides meters and graphs for data visualization. Students can change values of one aspect of the model and immediately see the effects of that change throughout their model.

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Model-it™ uses a unique qualitative approach to modeling. For example, the relationship between two objects can be defined as "a slight increase in X causes a large increase in Y". This is an effective approach to introduce the power of modeling to students, enabling them to simulate a model they created without any math background.

System Blocks shares the "qualitative" approach to modeling, but goes one step further by enabling students to define the relationships between objects by the order they connect the different blocks.

3.2.2.4 Colella's Participatory simulations

At the Lifelong Kindergarten group at MIT's Media Lab, Colella introduced participatory, computer-mediated simulations of dynamic systems (Colella, 1998). Using Thinking Tags, computerized nametags that communicate with each other via infra-red, participants can be an active part of a social network simulation such as an epidemic spreading through a population.

From her study, Colella observed that the participatory activity was a motivating learning environment. Students helped each other, gather evidence, and build theories about the dynamics of the system. In addition, Colella reports that students were able to articulate the underlying rules of the disease simulation (Colella, 2001, p.30)

3.2.2.5 Sensetable

Sensetable is an interactive platform developed at the Tangible Media Group at MIT's Media Lab (Patten, 2001). Sensetable is a system that wirelessly tracks the positions of multiple objects on a flat display surface quickly and accurately. The tracked objects have a digital state, which can be controlled by physically modifying them using dials or tokens.

Several applications were created on top of the Sensetable platform, including business supply chain visualization using system dynamics simulation; IP networked design workbench; and CircuiTUI, an electronics circuit design and simulation tool.

The Sensetable is an innovative approach to merge tangible and on-screen interfaces. The CircuiTUI application is currently used in an educational setting at a university level introductory course to circuit design. The Sensetable platform enables modeling, simulation and presentations of dynamic behavior is a variety of fields, and has great potential as an educational technology.

System Blocks differ from Sensetable's system dynamics modeling application in its authentic implementation of the core Stocks & Flows components, in the visual and auditory representation of the dynamic processes, in the decentralized and embedded technical infrastructure, and in the different intended users.

3.2.2.6 Gorton's Tangible Toolkit

In 2002, Tim Gorton introduced "Tangible Toolkits for Reflective Systems Modeling" (Gorton, 2003). Gorton presents a hardware and software infrastructure that enables developers to create modeling toolkits for specific dynamic systems. Using his infrastructure, Gorton created two toolkits, one simulating mail flow in a USPS distribution facility, and the other simulating a computer network chat model. In two case studies performed with these toolkits, Gorton observed that the tangible and decentralized aspects of the toolkits promoted discussion, interaction, excitement and sense of ownership among the case studies' participants.

An early prototype of System Blocks was created using Gorton's infrastructure for an initial evaluation with children, and was an effective step in the design process towards System Blocks current technical infrastructure (see chapter 4 – Design and Implementation).

System Blocks shares some themes with Gorton's toolkits, but differs in the authentic implementation of the Stocks & Flows modeling language, the ability to model and simulate different types of systems with no need for programming or editing of equations, and the multi-sensory representations for the dynamic behavior.

3.2.2.7 SimCalc and Mathworld

The SimCalc project (Roschelle & Kaput, 1996) has taken a comprehensive approach to mathematics of change education, coupling new technology with a dedicated curriculum. At the core of the project is the Mathworlds software, developed at the University of Massachusetts. Mathworld links animated simulation to graphs of position vs. time, velocity vs. time, and acceleration vs. time. In addition, algebraic representations can redefine the graphs. For example, an elevators exercise enables student to define different velocity graphs and see how an animated elevator travels as a result.

Bowers and Doerr (in press) describe the learning value in the modeling & simulation process in Mathworld. Students engage in iterative cycles of modeling and revision, leveraging the visual feedback to test their hypotheses.

System Blocks shares the same approach of learning through iterative modeling and simulation cycles. In contrast to Mathworld, System Blocks are designed for a qualitative modeling process rather than an accurate one. In addition, System Blocks facilitates hands-on manipulation through its physical interface, and makes it possible to simulate many different real-life phenomenon rather than focusing on one domain.

3.3 Studies of Children's Learning of Dynamic Behavior

3.3.1 Mathematics of Change

Rate of change is an important concept in the mathematics of change area of study. It is one of the core concepts underlying calculus, and is an important base to our understanding of behavior over time. Rate of change has its basis in real-life experiences, such as the relationship between a car's speed and the distance it travels, or the cost per minute of call and the total bill. Rate of change concepts are traditionally hard to learn, even at high schools and colleges. Researchers (see below) have mapped some of the misconceptions students have in this domain, and suggest hands-on experiences and simulation technologies as a potential way to improve student's understanding.

My research focused on dynamic behavior and system structures, but have a lot in common with the rate of change concept. Below I review some of the findings in this well-researched field, as a background to the different challenges and misconceptions I observed in my evaluation.

Rubin and Nemirovsky in their paper *Cars, Computers and Air Pumps: Thoughts on the Roles of Physical and Computer Models in Learning the Central Concepts of Calculus* (Rubin and Nemirovsky, 1991) describe the popular misconceptions regarding rate of change concepts among high school algebra and physics students. They showed that students' predictions about rate or amount graphs tend to be based on the visual properties of one of the graphs, so if a velocity graph was a line students predicted the position graph should also be a line, or if a velocity graph was decreasing so should the position graph.

Hauger paper *Rate of Change Knowledge in High School and College Students* (Hauger, 1995), defines three types of rate of change knowledge: global, interval and point-wise. Hauger shows that students use prior rate of change knowledge (such as interval or average rate of change) to get at rate of change in general and instantaneous rate of change in particular. Hauger recommends that instruction in average rate of change should take place earlier than high school.

Turner, Wilhelm and Confrey argue in their paper *Exploring Rate of Change Through Technology with Elementary Students* (Turner et al, 2000), that "elementary students are clearly capable of thinking about and understanding concepts related to rate of change." The authors describe how 5th grade students used motion detectors and graphing software to create and analyze graphs of their bodies' velocities and changing positions. In addition, the authors explored with the students change in a banking context using interactive software representing a bank account.

Systems behavior is bringing a new dimension to the way we observe dynamic behavior. In the mathematics of change domain, the interest is on the resulting behavior. In systems, the interest is in the underlying mechanism and the relevant feedback processes. Table 1 lists the core graphs of dynamic behavior with their underlying mechanism as well as the resulting behavior. The graphs are taken from Nemirovsky's "seven basic shapes for continuous well behaved functions" (Nemirovsky 1997).

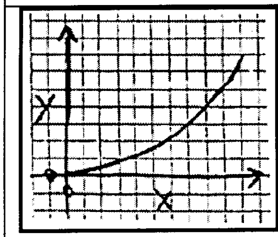
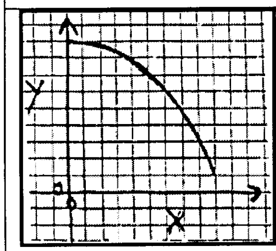
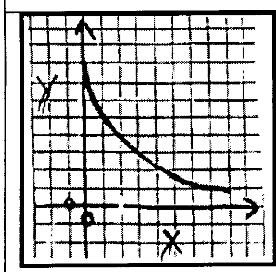
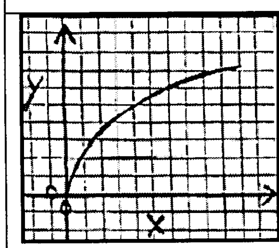
Dynamic Behavior	Underlying mechanism	Resulting behavior
	Reinforcing behavior. Positive feedback. Growth leads to more growth.	Increasing at an increasing rate.
	Reinforcing behavior. Positive feedback. Decay leads to more decay.	Decreasing at an increasing rate.
	Goal seeking behavior. Negative feedback. More decay leads to less decay.	Decreasing at a decreasing rate.
	Goal seeking behavior. Negative feedback. More growth leads to less growth.	Increasing at a decreasing rate.

Table 1: Definitions of dynamic behavior fundamentals

3.3.2 Causal Models

A number of researchers have defined complex causal concepts (e.g. Chi, 2000; Kalish, 1998; Perkins and Grotzer, 2000; Resnick, 1994; Wilensky & Resnick, 1999) involved in understanding various science concepts. For instance, Perkins and Grotzer (2000) developed a taxonomy of causal concepts characteristic of explanation in science. These causal concepts are inherent in systems thinking. This work has investigated the difficulties that students have in grasping complex causal concepts. For instance, Perkins and Grotzer (2000) found that students make a number of default assumptions about the nature of how causes and effects behave that impact students' ability to understand the scientific explanations, particularly when asked to reason at systems levels.

This research also shows that when given explicit opportunities to grapple with the underlying complex causalities and to discuss the nature of causality in the context of their science learning, students reveal greater understanding of complex causality and of the science concepts (Grotzer, 2000; Grotzer & Basca, 2003; Perkins & Grotzer, 2000).

Grotzer (2003) reports that research about the youngest students' understanding of the more complex forms of causality is sparse relative to that of simpler forms. Further, classrooms lack the needed educational scaffolding to support children's understanding of more complex forms of causality. Therefore it is difficult to assess what students' development of understanding might look like given optimal educational support.

If new tools and techniques would enable introduction and scaffolding of complex causality in classrooms, the progressions of children's understanding might look different.

CHAPTER 4. DESIGN AND IMPLEMENTATION

The design and implementation process took one intensive year, from September 2002 to September 2003. I spent the summer of 2002 reading about system thinking on one hand and playing with standard LEGO bricks, cricket programmable bricks and some Froebel manipulatives on the other hand. During this process the idea was formed, and in the next twelve months three System Blocks prototypes were created, each improving the underlying technology, the physical design, and the authenticity to the Stocks and Flows modeling language.

In this chapter I will present each one of the three prototypes, with emphasis on the following topics: the infrastructure underlying the prototype's technology; the principles I chose to implement and the scenarios that can be simulated using the prototype; the multi-sensory representations implemented; where the prototype was presented and what input I received; and my reflection on the design process.

Before the review of the different prototypes I will review my design guidelines that evolved throughout the design process.

4.1 Design Guidelines

The inspiration for designing a new digital manipulative came from three directions. First, the system philosophy that acts as a framework to understand the dynamic behavior around us. Second, the classic kindergarten and school physical manipulatives and the strong belief teachers have in manipulatives' ability to promote mental models development among young learners. Third, the "converging bits and atoms" theme at the Media Lab. Specifically, Ishii's Tangible Bits and Resnick's Digital Manipulatives visions.

The following design guidelines evolved throughout the project:

Learning Philosophy

Constructionism serves as the underlying learning philosophy. Specifically, the physical construction kit should help children construct models of dynamic behavior and test their models. In addition, the construction kit should enable children to model phenomenon that are meaningful to children's lives.

System Blocks should support multiple styles of learning. The dynamic behavior should be represented in different ways, using different sensory experiences such as auditory, visual or tactile.

Intended Users

Since System Thinking is a complex concept to understand, System Blocks should be designed as a teacher's tool. The blocks should not be designed as a free-play toy (for example, for children to play on their own at home), but should be designed as a directed-play toy, so a teacher or a parent can guide the child through the interactive learning process. Optimally, System Blocks should by use at classrooms, as the introduction to modeling and simulation part of a systems thinking curriculum.

The intended age range should be around 10-14 years old, the age of progression from concrete experiences to formal reasoning. Although middle school should be the main focus, System Blocks activities should be designed for all age ranges, including preschool and elementary students, high school students, as well as college students and adults.

Modeling Language

The blocks' modeling principles should be authentic to the Stocks and Flows modeling principles (see Appendix for an introduction to Stocks and Flows modeling). Implementing the same building blocks and underlying logic of Stocks and Flows modeling would enable children to apply what they learned using System Blocks to standard Stocks and Flows modeling software tools.

The dynamic behavior generated by System Blocks should be mathematically accurate when compared to standard System Dynamics simulation tools (see Appendix B for a comparison of System Blocks and Vensim® running an exponential decay simulation).

Technical architecture

System Blocks should be implemented as a decentralized system, with no global synchronization of the blocks. Blocks should not be aware of their neighbors. At every time step, each block will perform an internal operation, using neighboring blocks as input or output only. This is a simple yet robust architecture. It scales without compromising performance and can be easily extended with new functionality using new blocks' behaviors.

The blocks should communicate using cables and connectors rather than wirelessly, to enhance the causal relation between blocks and to resemble the standard Stock and Flow "arrows" metaphor.

The blocks should not carry batteries internally. Rather, power should be transferred from one block to the other, through the same cables that pass the data communication.

Usability and Understandability

Overall interaction with the system should be intuitive and simple. Physical gadgets such as buttons, sliders and dials should enable real-time interaction with the system. The type of connectors should enable a young child to connect and disconnect blocks with no adult assistance.

There should be no programming involved at any stage of the modeling or simulation process. The blocks' physical arrangement alone should determine the dynamic behavior. Equations should be needed at any stage of the modeling and simulation process. This puts simplicity on a higher priority than variety of models. System Blocks should not be able to model any model, rather, they should make it easier to model and simulate the core dynamic behaviors.

A fine balance should be kept between concrete and abstract. The blocks should be designed as a general modeling tool, with no specific example influencing the external shape or color etc. At the same time, the blocks should be able to represent many different examples, and should have a simple interface that "concretize the abstract" in some visual or textual form.

Input and output of the system should be at the same area. Representations of the dynamic behavior should be presented in the physical space, and not by using a desktop computer, which is external to the system.

Aesthetics

I believe aesthetics should be an essential part of any meaningful experience. When designing a new object, this object should be aesthetically pleasing. In a learning environment, specifically when dealing with "hard-to-learn" concepts, an aesthetic object can help to create an initial interest in the subject and enhance the motivation for learning the "deeper lesson". Therefore, System Blocks should be aesthetically pleasing, both for children and adults.

4.2 The First Prototype

The first prototype was implemented during September – October 2002.

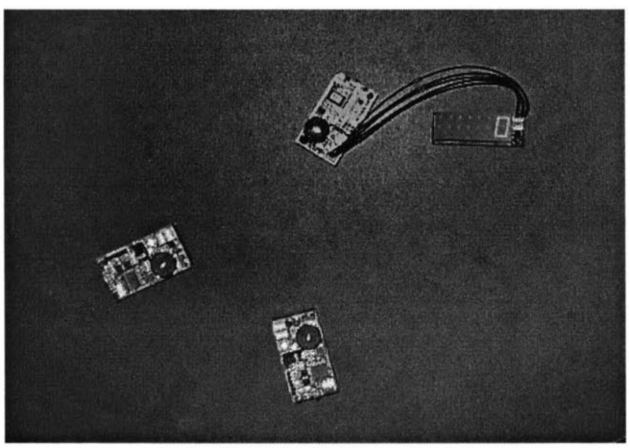


Figure 3: System Blocks first prototype using Crickets

4.2.1 Infrastructure

The first prototype was implemented using the Cricket programmable brick (Resnick et al., 1996b; Martin et al. 2000) as the hardware infrastructure and Cricket LOGO (Martin et al, 2000) as the software language. A simple decentralized architecture was implemented using the Cricket built-in Infra-

Red (IR) communication. Each block had an internal operation that was performed when new input was received.

4.2.2 Principles and Scenarios

Three blocks were implemented, representing inflow, stock, and outflow. The inflow and outflow Crickets had a rotary potentiometer installed as a dial to enable control over the rate of flow. Users could play with the dynamic concepts of flow and accumulation by turning the dials of the inflow and outflow and therefore controlling the stock level. Simple construction activity was possible using different combinations of the inflow, outflow and stock. For example, using only two blocks (inflow and stock) would enable a user to increase the stock level, but not to decrease it. Decreasing would be possible by adding the outflow block into the activity and positioning it in the right way. In addition, adding the outflow enabled users to experience dynamic equilibrium (when the inflow and outflow are set to the same rate). I used different scenarios to emphasize the dynamic behavior. One example was "pollution in the atmosphere" where we cannot control the outflow (the atmosphere cleans itself through natural processes). Our only option is to decrease the inflow (emissions). I created a simple simulation using a very low outflow value. Playing with this simulation showed that decreasing the inflow (emissions) would not decrease the level (pollution level), it will only decrease the rate at which the level is growing, but it will still keep growing (since the outflow is very low, most values of the inflow are still bigger than the outflow values).

4.2.3 Representations

A 4-digit display was connected to the stock block using the Cricket bus-device architecture. The display showed a real-time numeric representation of the current level of the stock.

4.2.4 Presentations & Reflections

System Blocks first prototype was presented to a few people from the educational community, a few teachers and a few children. I received interesting input that supported my design guidelines. The concept was appealing yet abstract, and I used several scenarios to communicate the concept, such as “saving money” with “income” as the inflow and “expenses” as the outflow, or homework example, with “homework left to do” as the stock, “teacher assigning homework” as the inflow and “doing homework” as the outflow. When I showed the homework example to an 11-year-old, he immediately said: “It reminds me of my allowance.” A teacher that saw the “saving money” simulation said “I can use this with my current activity in the classroom, to demonstrate the obesity problem using inflow as eating and outflow as exercising.”

System Blocks first prototype was an effective one. I got a first glimpse at building a hardware-based decentralized system and received good initial feedback. I learned that the examples I am using are a key factor in getting engagement, and that the real-time nature of the prototype's interaction is appealing to people. The overall experience encouraged me to continue and I decided to focus my efforts for the next prototype on physical communication instead of wireless. The IR-based wireless communication in this prototype was misleading and the causal relationship between the flows and the stock was not always clear. In addition, I decided to explore additional System Dynamics principles such as time-delays and feedback.

4.3 The second prototype

The second prototype was implemented during November – December 2002.

Figure 4: A 10-year-old child plays with System Blocks second prototype

4.3.1 Infrastructure

The second prototype was implemented using the Tower, a modular prototyping toolkit developed at the Grassroots Invention group at the Media Lab (Lyon 2003; Gorton 2003). I selected the Tower for two main reasons. First, it enabled wire-based communication using the serial communication layer developed by Tim Gorton. Second, it used LOGO as the software language, so I could quickly implement the basic functionality using almost the same code I used for the first prototype. The Tower has many built-in features and libraries and enabled quick prototyping. The drawbacks to using the Tower were its high cost, support for only 8-bit serial communication, large physical size and the need for batteries at each unit. Overall, using a prototyping system such as the Tower was an effective experience and allowed me to focus on other areas in my design process, specifically adding new Stocks and Flows principles; improving the overall user experience; and adding multi-sensory representations of the dynamic behavior.

4.3.2 Principles and Scenarios

Five types of blocks were implemented. Each block has input ports and output cables. Each block may be connected to several blocks and back to itself. The blocks can be connected in different arrangements, forming different systems.

The Sender – has a button mounted on the wooden case. Each time the button is clicked - the number "one" is sent to the next block through the output cables. This block has no equivalent in the Stock & Flow language.

The Accumulator – has "plus" and "minus" ports (plus for "inflow" and minus for "outflow"). When input is received from one of the ports, this input is added to or subtracted from the accumulated level. Then, the new level is sent to the next block through the output cables. This block represented the Stock principle.

The Delay – has a dial mounted on the wooden case. The dial controls the number of seconds to delay. When a new input is received, the block holds it for X seconds (as set by the dial) and then sends the same value as the input to the next block through the output cables. The delay principle is instrumental in system thinking. In Stocks and Flows modeling there is no "delay" building block, rather, delays are created using additional stocks.

The Multiplier – has a dial mounted on the wooden case. The dial controls the "multiplication factor". When a new input is received, the block multiplies the input with the "multiplication factor" and then sends the result to the next block through the output cables. This block is equivalent to the Variable principle in Stock & Flow modeling, using a multiplication equation with a user-controlled variable for the multiplication factor.

The Converter – for every input received, this block sends out the number "one" through the output cables. So every input is converted to "one".

I used several scenarios with this prototype. Mainly, I focused on feedback behavior. The feedback behavior was not in the classic form of Stock & Flow modeling, but a simplified way that I thought would be easier to understand.

Scenario 1 – Feedback loop, linear growth

Consider the blocks arrangement in Figure 5. The Sender block starts the process. One click on the Sender red button sends the number (1) to the next block – the accumulator block. The Accumulator block receives the (1) and adds it to the current level (0 + 1 = 1). Then, the Accumulator block sends its current level (1) to the next block – the Delay block. The Delay block holds the number for two seconds and then sends it to the next block, the Converter. The converter receives (1), changes it to (1) and sends it to the next block – which happens to be the Accumulator block again. The Converter block is connected to the Accumulator block "plus" port. The Accumulator receives (1) and adds it to its current level (1 + 1 = 2), and in turn sends its current value (2) to the next block – the Delay block again, and so on.

The resulting behavior simulates linear growth, which can be noticed by the digits changing on the Accumulator internal display (1, 2, 3, 4, 5...), with a delay of two seconds between each update.

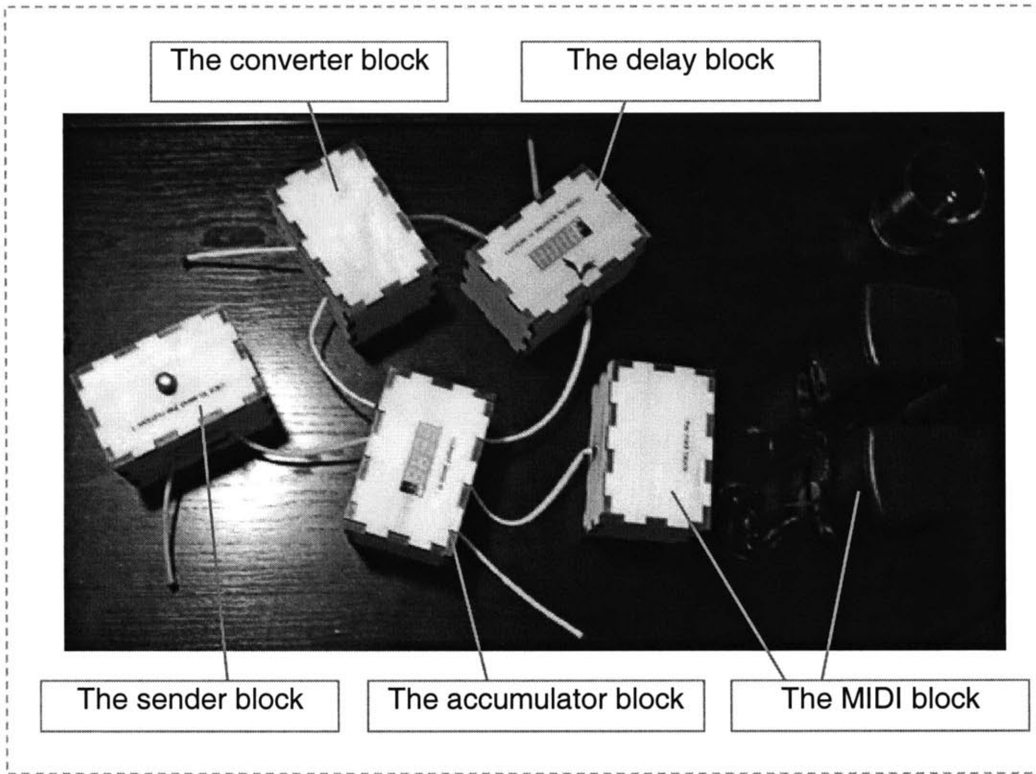


Figure 5: A "reinforcing feedback loop" simulation using the second prototype

Scenario 2 – Feedback loop, exponential growth

Consider the same arrangement in Figure 5, only without the Converter block. This time, the output from the Accumulator will pass through the Delay block and back into the Accumulator, with no change to the number (in Scenario 1 the Converter changed any number to the number 1). The result is exponential growth (1, 2, 4, 8, 16, 32, 64...). In every cycle the Accumulator adds its current value to itself, with a delay of two seconds between each update.

4.3.3 Representations

The Accumulator block has a numeric display using a 4-digit display mounted on the wooden box. This serves as a numerical representation of the

Accumulator (stock) current level, which also represents the "state" of the system (in a simple one-stock system).

For this prototype I developed a sound representation, using the MIDI format. The MIDI block can receive input from any other block and translate the received number into the equivalent MIDI note (range is 0-127). For Scenario 1 mentioned above (linear growth – 1,2,3,4,5…), the MIDI block will play a scale going up from 1 to 127, which sounds like an incremental pitch change. In my initial evaluation I found that the sound is an effective representation for dynamic behavior, and children identified increase or decrease behavior based on the sound they hear.

4.3.4 Presentations and Reflections

The second prototype was presented to key people in the system dynamics community as well as researchers in the education community: Jay Forrester, the founder of the System Dynamics field; Peter Senge, author of the Fifth Discipline (Senge, 1991) and a key thinker in the field; Linda Booth Sweeney, a researcher at Harvard Graduate School of Education specializing in System Thinking and education; David Perkins and Tina Grotzer, principal investigators at Harvard Project Zero, specializing in aspects of complex causality and children's understanding of causal models; Hiroshii Ishii and members of the Tangible Media Group at MIT's Media Lab; and several PhD students from the system dynamics group at MIT's Sloan school of management.

In April 2003, System Blocks were presented at the CHI 03 conference for Computer-Human Interaction (Zuckerman & Resnick, 2003a).

The input I received on the second prototype was positive and constructive. The System Dynamics professionals recommended to keep the blocks principles authentic to Stock & Flow principles, and to improve the timing mechanism and algorithms to create a mathematically accurate tool. The educational researchers recommended to work on multiple representations

and to enable customization of the blocks with specific content examples to shift from abstract to concrete.
The CHI audience appreciated the construction activity and the sound output, and people recommended to enhance the concept of flow using moving lights on the cables.

I performed an initial evaluation using second prototype. Four children, 4, 6, 10 and 13 years old, played with the blocks individually for 45 minutes to an hour. I conducted interviews with the children while they played and tried to understand what was clear, what was hard to understand and what they thought about the experience. All the children were engaged for the whole period, and reported that it was fun and exciting. The 10 years old compared the activity to playing a video game. All of the children (including the 4 year old) succeeded to increase or decrease the Accumulator by connecting the sender to the "plus" or "minus" ports respectively (the younger children called the ports "the one that makes it go up" and "the one that makes it go down"). The delay concept was very hard for all of them. The older children could use it after I explained what it does; for the younger ones it was harder. The feedback behavior was intriguing for all of them, since the blocks started to "work on their own". The younger children could not repeat it, but the older ones could, and also gave a few examples, like a home fountain where the water feeds back into the pump (a circular causality with no feedback, but a good start). The numbers display on the Accumulator was easy to understand, but made the children focus on numbers, and they thought the blocks were about math. This made them focus on the incremental behavior and not the overall behavior of the system. The sound representation was very well received. The children found it intriguing and the younger ones used it to identify increase or decrease instead of the numbers display.

System Blocks second prototype was a successful one. The wired-based communication proved to be effective and playful. The blocks were aesthetically pleasing and children found them to be play objects, in spite of the abstraction level. The Systems principles I implemented did not correspond with a specific modeling language, and made it challenging to simulate real-life examples that can be meaningful to the children.

I decided to develop a dedicated Printed Circuit Board (PCB) that would be small and support all the features I need, including 16-bit number system and power transfer between blocks. In addition, I decided to implement a timing system and algorithms that would be mathematically accurate and authenticate to the Stocks and Flows modeling language. I wanted to find creative ways to "concretize the abstract" and add a way to represent meaningful examples, and I hoped to develop additional representations for the dynamic behavior.

4.4 The Final Prototype

The final prototype was implemented during January – August 2003.

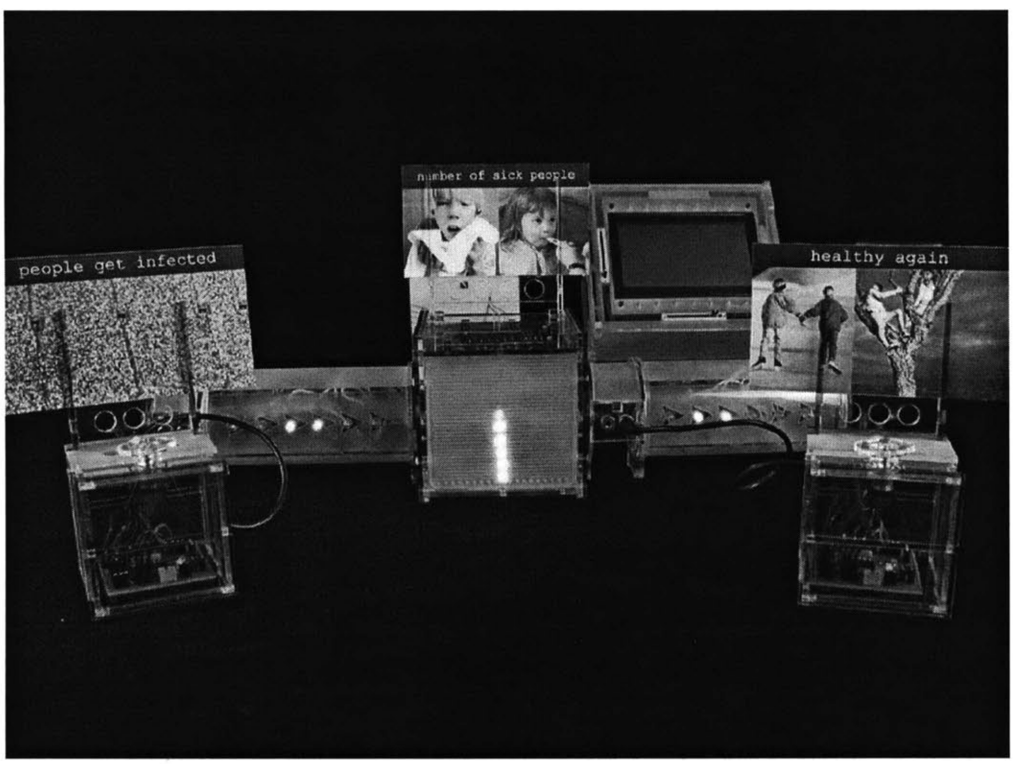


Figure 6: System Blocks final prototype, simulating the spread of a virus

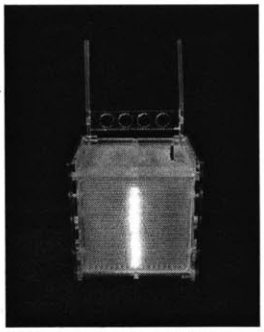
4.4.1 Infrastructure

The final prototype hardware infrastructure was a dedicated Printed Circuit Board (PCB) designed with the PIC microprocessor using the Logochip environment (Mikhak, Silverman, Berg 2002). The dedicated PCB was designed to fit the needs of this project. The main features of the PCB are: 16-bit number system, serial communication between boards, four input ports and two output ports, power transfer between boards, low level pin control, analog to digital sensor ports, and a convenient programming language and environment. During the Spring and Summer semesters of 2003, several MIT undergraduate researchers assisted me in the iterative process of design, layout, fabrication and testing of several PCBs, until we reached our goal of a 2"x2" board that performs all the required operations.

Using the 16-bit number system and the convenient Logo programming language I was able to implement a decentralized system, authentic to the Stocks and Flows modeling language, and mathematically accurate when compared to standard system dynamic software tools (see Appendix B). I created a non-integers number infrastructure that was instrumental for any negative feedback behavior. The power transfer between boards worked effectively and one battery pack was enough to power the whole set of boards. The serial communication enabled wire-based communication between the boards. The multiple input ports enabled certain blocks to receive data from several blocks at once, which is essential for the stock block accumulation process.

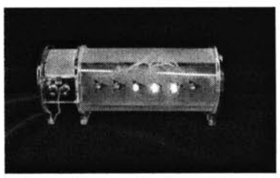
4.4.2 Principles and Scenarios

Five types of modeling blocks were created. This time, the blocks are authentic to the Stock & Flow language. Each block has input ports and output ports. Each block may be connected to other blocks if their connectors match. The blocks can be connected in Stock & Flow arrangements, forming simple systems.



Stock

An acrylic box with a line of 10 LEDs mounted at the front face. Receives input only from the flow blocks, either as inflow or outflow. Can receive input from both flows at the same time. The stock internal operation is to integrate the inputs at every time step, display the result using the line of LEDs and send it through the output ports, located at the back of the box. The stock has a linear slider mounted on the top face that determines the stock's initial value.

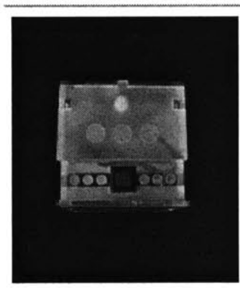


Flow

An acrylic cylinder with a line of 6 LEDs mounted at the front face. Receives input from the variable or stock blocks. Can receive input from four blocks at the same time. Sends output only to the stock block. The flow internal operation is to multiply the inputs at every time step, display the result as a relative speed of moving lights using the line of LEDs, and send it through the output ports, located at both sides of the pipe.

Variable: constant continuous

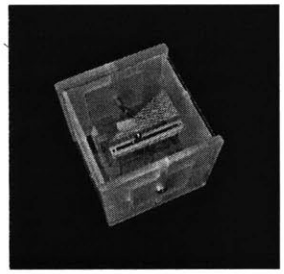
An acrylic box, half the size of the stock, with a dial mounted on the top face. Does not receive input. The constant continuous internal operation is to send numbers through the output port at a continuous rate of 0.1 second. The value to be sent is determined at every time step from the dial position, and can range between 0.00 and 1.20, at a 0.05 step.



Variable: constant discrete

An acrylic box, half the size of the stock, with a push button mounted on the top face. Does not receive input. Sends a constant value through the output ports. Every time the button is clicked, the number 1.00 is being sent.

Variable: gap



An acrylic box, 2/3 the size of the stock, with a linear slider mounted on the top face. Receives input from a variable or a stock block. The gap internal operation is to subtract the received input from a constant value and send the result through the output port. The constant value is determined at every time step from the linear slider position, and can range between 0 and 80 at a 0.5 step.

Compared with standard Stock & Flow modeling software tools, System Blocks has limited functionality. Some of these limitations are: equations can not be changed, so flow is always a multiplication of its inputs and stock is always simple integration of its flows; the number of inputs into a flow or a stock is limited; variables are essential because constants can not be inserted into equations; the number system is limited to 5 digits, with limited accuracy of 2 digits after the decimal point; the time step in the system (dt) is fixed as 0.1 second; division operation is not available, which limits the variety of possible models and makes it harder to create easy-to-understand variables.

The following Figures show a comparison between System Blocks modeling and Vensim® Stocks & Flows modeling using simple systems.

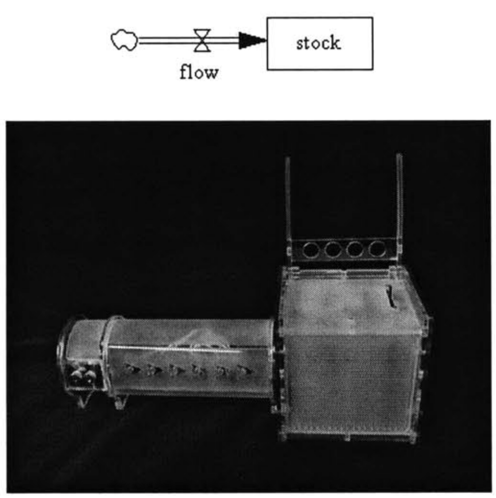


Figure 7: Inflow and stock using Vensim® and System Blocks

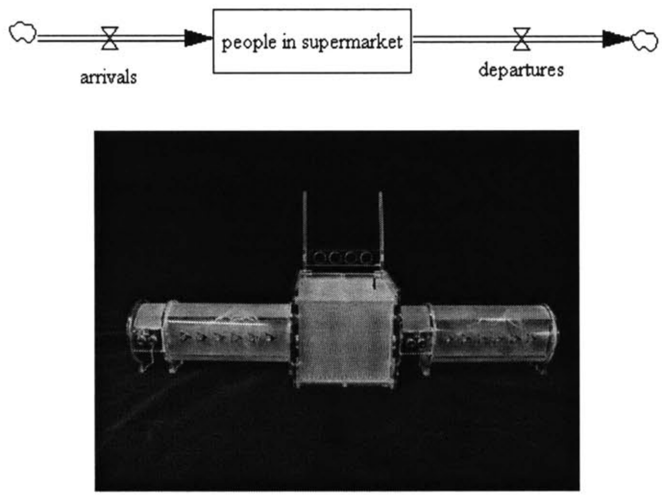
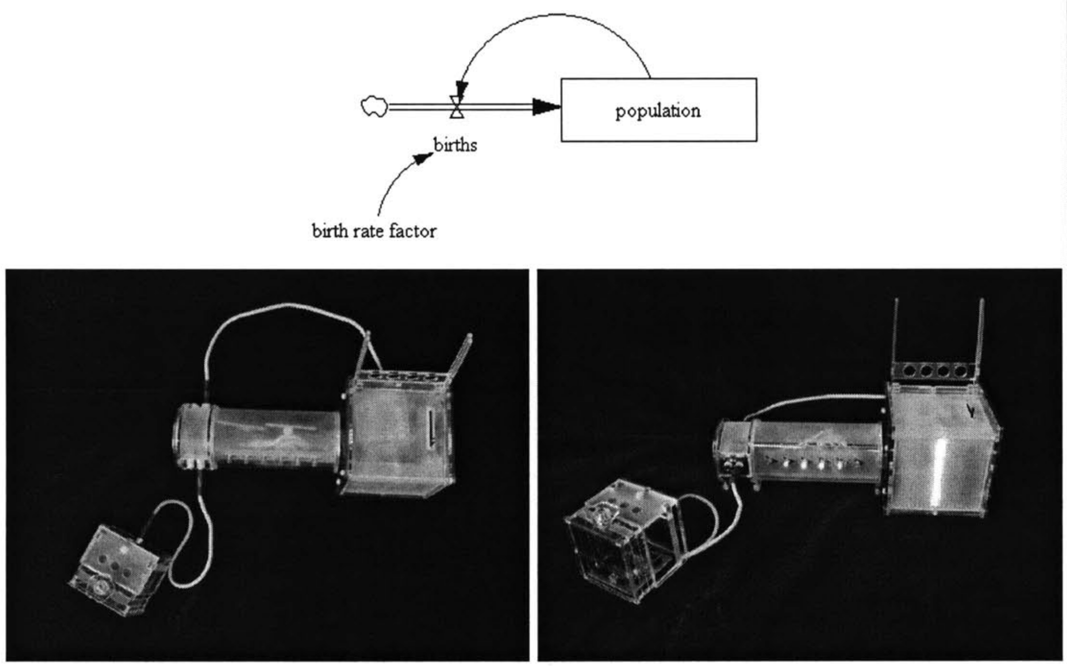


Figure 8: Inflow, stock, and outflow using Vensim® and System Blocks



Not simulated

Simulated

Figure 9: Positive feedback using Vensim® and System Blocks

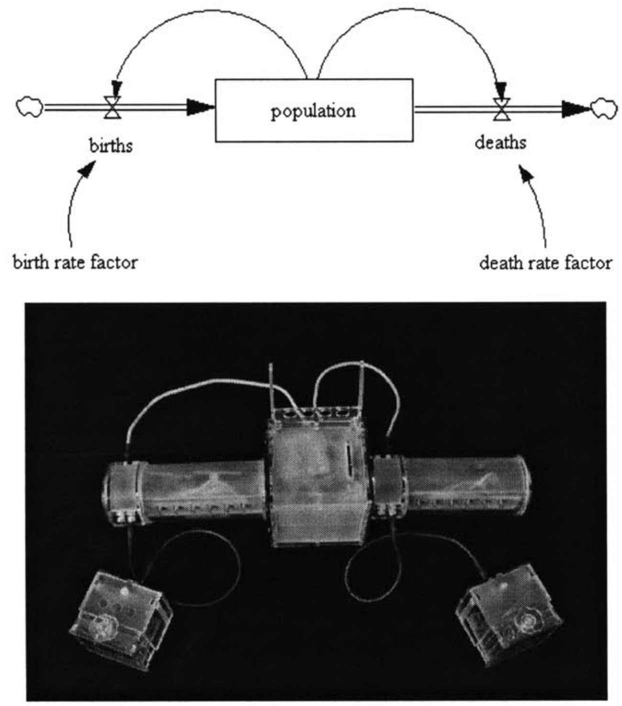


Figure 10: Population dynamics using Vensim® and System Blocks

4.4.3 Representations

Multiple representations can enhance the learning experience. Some of the representations used by Stella® and Vensim® are a graph, a bar graph or a table of numbers. In System Blocks we have implemented several "Representation" blocks.

Using the same PCB developed for System Blocks, and interfacing with other electronic devices, four representations devices were created to convey the dynamic behavior: an LCD graph, a number display probe, a physical movement unit and an improved MIDI-based sound.

Representation blocks can be connected to any other block using the connection cables. Generally speaking, a system behavior is represented by the behavior of its main stock, so the most common usage is to connect a representation block to the model main stock.

4.4.3.1 LCD Graph

The LCD graph display was created using a Hyundai graphic display module with an on-board controller. The LCD has a large display area of 256 pixels width on 128 pixels height. Leveraging the low-level pin control of System Blocks PCB and the Logo chip environment, an interface was created to translate the value received through the serial input into a dot on the LCD. The result was a cheap screen that draws a graph in real-time from the continuous stream of values received from any System Block, at the system rate which is 10 times a second.

The 256X128 display area is limited, and can not display larger-scale dynamic behaviors, such as oscillation or even exponential growth. To tackle this problem, two sliders were mounted to manually scale and offset the incoming input. This made it possible to fit any dynamic behavior into the screen area. The offset feature was to divide the received input by a constant, controlled by the slider. The scale feature was to add a constant to the received input. Since the sliders are mounted on the graph display box surface, it is easy to change these constants to control offset and scale in real-time and see the desired range on the limited screen.

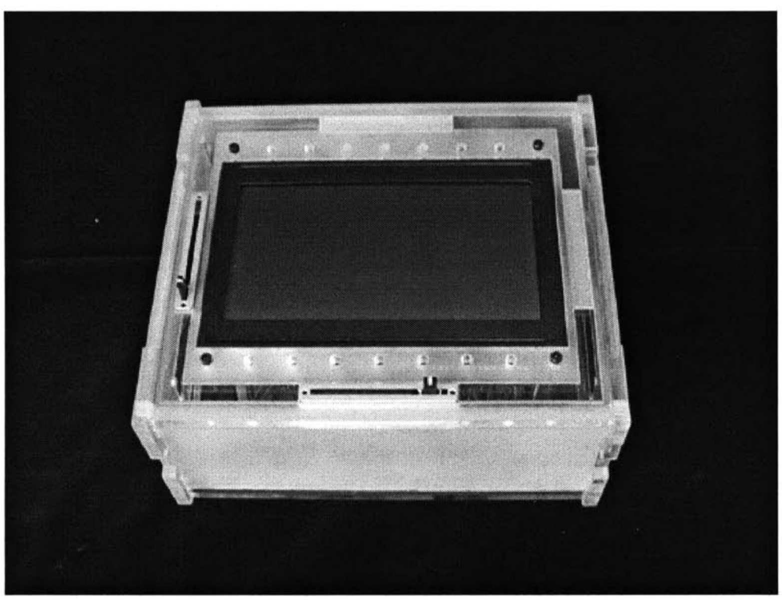


Figure 11: Graph display using an LCD screen

4.4.3.2 Number Display Probe

The easiest representation to implement is a number display. Numbers are the data flowing through the different System Blocks 10 times a second. Numbers can convey the system status at a given moment, but are less useful to understand behavior over time. One of my experiences with the second prototype and a number display was that children immediately think it is about math. Also, they focus on a momentary view of the system, and miss the overall behavior. From those reasons, I decided to make the number display a separate unit and not a default unit mounted into the blocks.

Two number display units were created, using a multi-digit 7-segment LED display. One unit has 7 digits and the other 4 digits. Leveraging the low-level pin control of System Blocks PCB and the Logo chip environment, an interface was created to translate the value received through the serial input into digits on the LED display. The 7-digit unit can display a signed 16-bit number. The 4-digit unit can display an unsigned 4 digit number, representing a decimal number in the format of ab.cd

The number display probe can be activated in two ways, using a cable connection like all the other blocks, or using short range infrared. The short-range infrared communication enables children to "hover" the display probe above any block, and see the "numbers inside" that block changing in real time. IR LEDs were installed inside the blocks, transmitting the current block value 10 times a second. Another IR LED was installed inside the display probe, receiving the data from the transmitters when the probe is placed closed enough to the transmitting block.

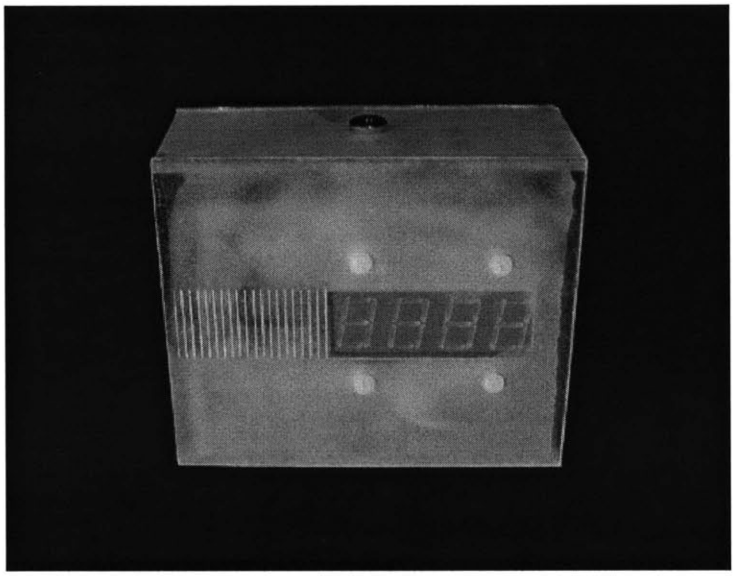


Figure 12: Number display probe

4.4.3.3 Physical Movement Unit

Stepper motors enable accurate physical movement. Programming a System Blocks PCB to control the stepper motor resulted in an accurate translation of the stock level into accurate step-rotation. Using the appropriate gears, a linear-actuator was created to convert the rotational movement into linear movement. This enabled a physical representation of the stock level using a piece of material that moved up or down in correlation to the stock's current level.

A limitation of the physical movement unit is the time it takes the motor to move to a desired step. The unwanted result is that the physical level if not in synch with the system level. A possible way to bypass the problem might be to use a servo motor with a different gear mechanism that will move up and down.

An interesting implementation can be a child-size platform that moves up and down using linear actuation. A child could stand on the platform and feel the movement of the level, be it linear increase or exponential decay. Extra attention should be put into the choice of motors to ensure synchronization with the system's performance.

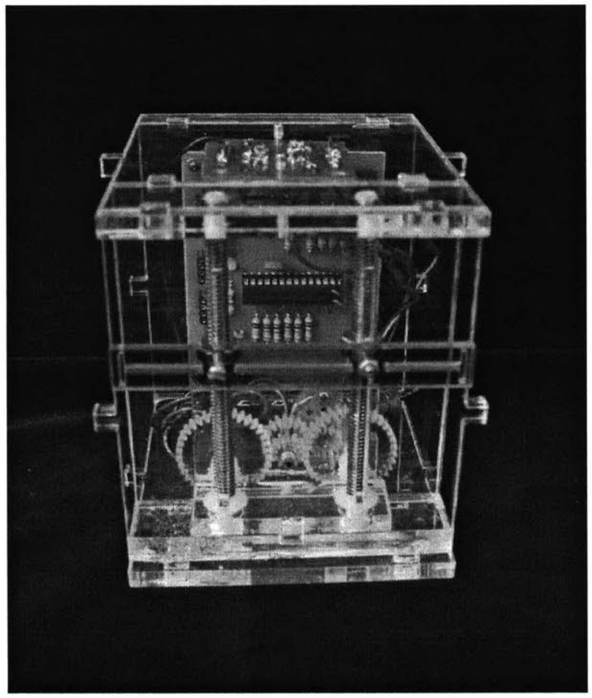


Figure 13: Physical movement unit, using a stepper motor

4.4.3.4 MIDI-based sound

The MIDI-based sound was implemented using the Cricket MIDI bus-device. The bus-device protocol was implemented in the System Blocks PCB, so it can communicate with Cricket bus-devices. The MIDI format can play notes using different instruments, on a scale that ranges from 0-127. The numbers to be played are received through the PCB 16-bit serial connection and mapped to the relevant notes. Numbers above 127 are ignored.

When using the sound as a representation, you hear a piano playing upscale or downscale, based on the system's behavior. The note represents the current level of the stock, and the tempo (the time between each two notes) represents the rate of change or the net flow into the stock. This is a simple and effective mapping, capturing the two most important factors of accumulation (level and rate of change).

At a state of dynamic equilibrium, the level does not change, but the inflow and outflow are active and flowing at the same rate, so the rate of change can be represented. I tested two different approaches for this state. One is to play the same note (unchanged level) again and again, at a tempo of the rate of change. This approach is the most logical one, but the result was unpleasant (hearing the same note playing again and again). The other approach was to not play anything, so the silence is a sign that equilibrium is reached. This approach was pleasant, but did not communicate the rate of change.

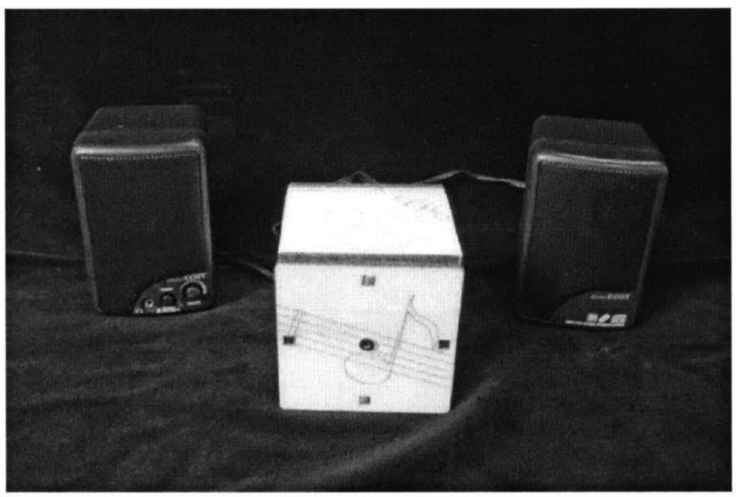


Figure 14: MIDI-based sound

4.4.4 Presentations and Reflections

System Blocks final prototype was presented in several events.

At June 2003 I was invited to present at the Waters Foundation action research meeting, a gathering of K-12 mentors and teachers focused on system thinking and dynamic modeling in K-12 education. The teachers thought System Blocks are appropriate for a classroom setting, and invited me to conduct an evaluation of System Blocks at the Carlisle school in Massachusetts. While I presented to the teachers, following my demonstration of first-order negative feedback, a discussion evolved regarding weather what I presented was negative or positive feedback. It turned out that many of the teachers had some confusion regarding negative feedback, and System Blocks tangible demonstration helped to clarify the misconception.

At July 2003 I presented System Blocks at the 2003 International System Dynamics Conference in NYC (Zuckerman & Resnick, 2003b). This event is targeted at system dynamics experts from academia and consulting businesses all over the world. Both academia and business related people showed interest, and gave interesting input. Specifically, business consultants commented that System Blocks might be useful with their clients and colleagues, and not only with children.

At October 2003 I had the opportunity to present the blocks to John Sterman and the System Dynamics Group at MIT's Sloan School of Management. The system dynamics experts evaluated the blocks, were satisfied with the mathematical operations and the authenticity to the Stocks and Flows language, and recommended to add a few more blocks, such as a comparator to enable simulation of more complex models such as the dynamic structure of the famous beer game.

CHAPTER 5. EVALUATION

I conducted an empirical study of System Blocks at 3 different schools in Massachusetts, with 5th grade and preschool students. The study took place at the Carlisle Public School in Carlisle (5th grade students), the Baldwin Public School in Cambridge (5th grade students), and the MIT Technology Children Center (preschool students).

The goal of the study was to evaluate if a tangible modeling and simulation tool such as System Blocks can help young children understand the core concepts behind dynamic behavior. These concepts include stocks & flows, linear dynamics, and positive feedback. Traditionally, these concepts are considered "too hard" for elementary and middle school students, and are taught only at high school or university level, if taught at all.

My hypothesis is that a hands-on modeling and simulation experience that focuses on overall behavior and not on accurate values, using multi-sensory representations of dynamic behavior, will make system concepts more accessible to young children.

My research approach is a qualitative one. I used a clinical interviews approach where I presented brief, standard tasks to the students, and then probed the students' understanding based upon their response to the tasks.

I studied different aspects with the different age groups. With the 5th graders I conducted comprehensive individual interviews, and tried to probe their way of thinking about dynamic behavior through tasks in different areas.

With the preschoolers I conducted short individual interviews, to investigate if they are able to connect real-life examples with the simulated dynamic behavior.

In the interviews, I hoped to create an environment for the students to confront their own misconceptions and tendencies. I planned different activities for the sessions, that encourage the students to explain the dynamics of a given situation, then simulate that problem using System Blocks and see if the simulated behavior is different than their explanation. The blocks can facilitate an iterative process of self-evaluation of one's theories about dynamic behavior.

This method follows the tradition of Piagetian activities and interviews where subjects are shown particular events or transformations, which they either assimilate into their current conceptual structure or accommodate by revising their conceptual structures. Variations of this approach can be found in other current research. For example, Grotzer calls them RECAST activities (**Re**veals **Ca**usal **St**ructure). RECAST activities are designed to help students revise how they perceive the nature of the causality involved in an event, therefore, they help students address misconceptions that derive from deeper structural knowledge (Grotzer 2002).

The two groups of 5th grade students I interviewed differ in their prior instruction in systems concepts (see Table 2). The Carlisle Public School is part of the "Waters Foundation" program, where systems thinking concepts are introduced and used starting at elementary school. The Baldwin Pubic School students had no prior instruction in systems concepts.

Grade level	**School name**	**socio-economic status**	**Prior instruction in systems concepts**	**Number of participants**
5th grade	Carlisle	High	Prior instruction. Part of the "Waters Foundation" program. Familiarity with Stocks and Flows and Behavior Over Time Graphs.	5 students
5th grade	Baldwin	Mixed	No prior instruction.	5 students
Preschool	MIT TCC	Mixed	No prior instruction.	5 students

Table 2: Overview of schools where study was performed

In the following sections I describe each of the three studies. I present my method, data analysis, interviews activities, interviews results, and my conclusions for each of the studies.

5.1 Fifth Grade Study

I interviewed 10 students in total, 5 from each school. As I mentioned above, the Carlisle Public School students had prior instruction in system concepts. In the elementary grades they were introduced to Behavior Over Time Graphs, describing different activities over time. In 4th grade they were introduced to the Stocks and Flows modeling language using the STELLA software. They had not been introduced to the net-flow dynamics or positive feedback concepts. The Baldwin Public School students had no prior instruction in systems concepts. In the 4th grade they were briefly introduced to "over time graph", but none of the Baldwin students I interviewed could draw a graph before we started the sessions.

I started the study at the Carlisle Public School in order to learn how children with some familiarity in system thinking talk about systems. In addition, I wanted to use Carlisle students' performance as a benchmark for the Baldwin students.

5.1.1 Method and data analysis

I conducted multiple one-on-one sessions with each of the students. Each student was interviewed for 2-3 sessions of 45 - 60 minutes each. In total I conducted around 20 hours of interview time. All sessions were video-taped and audio-taped for later analysis.

The interviews incorporated a standard set of probes but they were loosely structured and designed to follow up on what the students said. In each interview the student performed the following modeling and simulation activities using System Blocks:

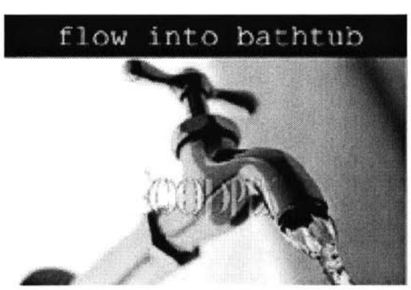
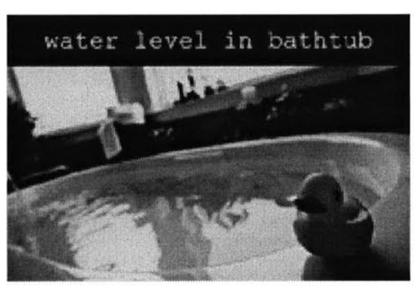
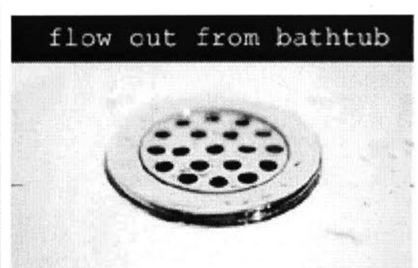
- Introduction to modeling and simulation
- Simulation analysis, net-flow dynamics
- Graphing net-flow dynamics
- Introduction to positive feedback and exponential growth

In the following paragraphs I will describe each of the four activities conducted with each student. The same activities were conducted in both schools. I started with simple introduction to modeling and simulation using the blocks, focused on net-flow dynamics, using the sounds and graph representations (on top of the default moving lights). I continued with introduction to positive feedback behavior, including graphing of the generated exponential behavior.

5.1.1.1 Modeling and simulation

In the modeling activity I wanted to evaluate how the students maps real-life examples to simple Stocks and Flows structures. I prepared sets of index cards with pictures and text describing different real-life examples (see Table 3). Each set had 3 cards: one for the inflow, one for the stock and one for the outflow. I started without simulation, asking the students to put the cards in the order that makes sense to them. For example, the bathtub example cards are: "flow into bathtub", “water level in bathtub”, “flow out from bathtub”. I handed the cards to the students in no particular order, and they placed them on top of the blocks, in the special “card holder” mounted on each block. I did not use the terms stocks or flows at this stage, I just handed them the cards and watched what order made sense to them.

Table 3 lists the different examples using a smaller version of the picture cards.

Inflow	Stock	Outflow
flow into bathtub	water level in bathtub	flow out from bathtub
		

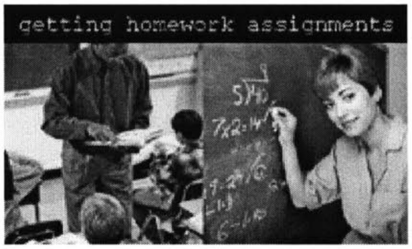
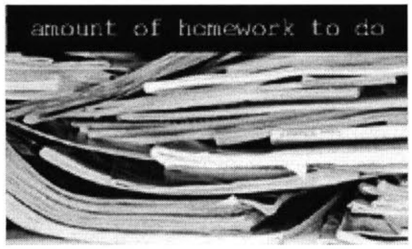
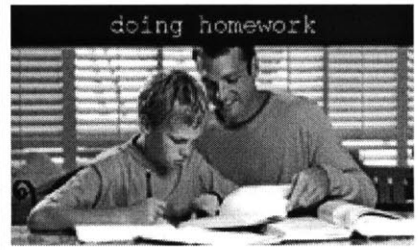
getting homework assignments 	amount of homework to do 	doing homework 
getting money 	amount of money saved 	spending money 
things that make you angry things that make you angry	how angry are you? how angry are you?	things that calm you down things that calm you down
baking cookies 	number of cookies made 	eating cookies 

Table 3: Real-life systems using picture cards

I started with a real demonstration of water flowing from one measuring cup to another measuring cup. I emphasized how one cup is full, the other one is empty, and when I tilt the full cup water flows from one cup to the other. I let the students do the same operation on their own.

I introduced the blocks, starting with two stock blocks, one flow block and a variable block. Together with the student, we modeled the measuring cups activity using the blocks, watching how the light moves into the stock at a rate determined by the dial of the variable block. I spent some time mapping what each block represents: stocks blocks are the measuring cups; the flow block is the water flowing from one cup to the other; the variable block is the angle of tilt that causes the water to flow.

To model the bathtub example we used the relevant picture cards and defined the blocks as inflow of water with a faucet valve, outflow of water with a drain valve, and a bathtub. The student connected the inflow and outflow to the bathtub stock and added the variables to each flow. Now the bathtub model was ready for a simple simulation.

I asked the students to simulate the bathtub model using the variable dials, and at the same time explain what happens using "bathtub terms". I did not guide the students as to what dial to use first (inflow or outflow), and did not mention that both can be operated together. At this point, I allowed the students to play with the blocks, observing their behavior and waiting for the moment where they try to operate both dials together. After that moment, I asked the student to switch cards and map other examples, such as the cookies or the anger examples (see Table 3 above). The students were very expressive, explaining what each block represents and what happens in each simulation.

At the end of the modeling activity I handed the students blank cards, asking them to write up an example that behaves in the same way as our simulations. I encouraged them to use an event or activity from their own life, something that they care about.

5.1.1.2 Net-flow dynamics

Net-flow dynamics is the influence of both the inflow and the outflow on the stock. The sum of (+inflow) and (-outflow) is the net-flow. If the net-flow is positive, the stock will increase. If the net-flow is negative, the stock will decrease. Paying attention to only one of the flows would not explain the behavior of the stock. In this activity I wanted to evaluate if the students can gain abstract understanding and some intuition of net-flow dynamics. My definition for "abstract understanding of simple net-flow dynamics" is the ability to answer to the following questions:

1. If an inflow is faster/greater than the outflow, the stock will _______

2. If an outflow is faster/greater than the inflow, the stock will _______

3. If an inflow and an outflow are the same, the stock will _______

In order to promote understanding of this concept I encouraged the students to use System Blocks and run different scenarios on the models they just simulated in the earlier activity. For example, using the cookies example, I asked the student to make the "number of cookies made" go up or down. I asked if there are other ways this could be done, and than observed how the students explore (for example, one successful strategy is decreasing the outflow instead of increasing the inflow). I gave the students simple challenges that emphasize the relationship between the inflow and outflow, and how paying attention to just one of them would not give an accurate picture of the stock's behavior.

At some point during this activity I connected the sound representation to the stock. I hoped that the sound would promote better understanding of the net-flow concept or the rate-of-change concept, because the sounds had 2 clear characteristics, the pitch and tempo of the played notes.

I asked the student to switch between different examples, including the examples the students created on their own. I hoped to reach a point were the student could remove the cards completely, and work with the abstract blocks, explaining net-flow dynamics in stock and flows terms, without any specific example.

5.1.1.3 Graphing

In the graphing activity I wanted to evaluate if the students could transfer their understanding of net-flow dynamics using moving lights and the sound representations to the standard way of representing such behavior – using graphs of behavior over time. I connected the graph display representation to the stock. I let the students play for a while with the new representation, to see what they came up with. I asked them to go through the same activity we just did with the lights representation, run different scenarios, make the stock increase or decrease at different speeds. In some cases I used the sounds and graph representation together, to have a transition fro a familiar representations (sound) to the new one (graph). I encouraged the students to investigate how the graph represents the stock, inflow, outflow and net-flow.

When I had the impression the students started to understand the graph representation, I asked them to draw some graphs on paper, each time describing a different activity. For example, a stock increasing at some rate and then the rate increases.

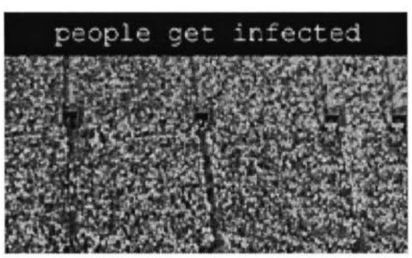
At this point the students had experienced the 3 different representations (moving lights, sound, and graph). I asked them if they had a preferred representation, what they thought are the pros and cons of each one, and if they had any idea for new representations I should build.

5.1.1.4 Positive Feedback

In the positive feedback activity I wanted to evaluate if the students can understand the positive feedback concepts. Positive feedback is circular causality with amplification. If A causes B and B causes A, positive feedback will happen if the more there is A, than there is more B, and the more there is B, there is more A. For example, if A is the "number of people getting infected every day" and B is "total number of sick people".

Since the students were already familiar with modeling, simulation and graphing using System Blocks, I could introduce the new concept and contrast the simulated behavior with the non-feedback behavior the students saw earlier.

I started with new sets of picture cards that represent phenomena with simple positive feedback behavior, where the stock is feeding-back to the inflow. For example, the spread of a virus is a phenomenon with positive feedback behavior. More sick people leads to more people getting infected, which in turn leads to more sick people etc. In the same way, the more time a day you spend watching TV, the interest you have in your favorite show's characters will increase, which in turn will cause you to watch more TV, which will increase your interest even more etc. Table 4 lists the different cards I used for positive feedback examples.

Inflow	Stock	Outflow
people get infected 	number of sick people 	healthy again 
hours per day spent watching TV 	interest in characters interest in characters	doing other things 

people join the trend	number of people in the trend	people leave the trend
people join the trend	number of people in the trend	people leave the trend

Table 4: Positive feedback systems using picture cards

In order to model the feedback behavior, I showed students how to connect a cable from the stock back into the inflow. I emphasized the circular causality, and asked the students to simulate the new model. The simulation is impressive, because the inflow is increasing in speed over and over until the lights move extremely fast, much faster than the students could simulate using the dial in the linear dynamics models. I emphasized that the only change we made is adding the circular connection between the stock and the inflow, all the rest stayed exactly as it was. In addition, I asked the students to try and use the outflow to stop the stock from increasing. In previous models it was possible, and the students simulated it several times. This time, the exponential growth could not be stopped, and the outflow made almost no difference. I pointed out that acting quickly can make a difference, and asked the students to increase the outflow very quickly, immediately after they noticed the stock was starting to grow. The students saw that acting quickly can stop the growth. I connected the activity to a real-life example using the SARS epidemic example that was brought to an end due to quick response.

I continued and added the graph display representations, so the students could see what exponential growth looks like using a graph representation. I asked about the differences between the current curved graph and the previous linear graphs, and asked the students to draw a few graphs, some with feedback and some without.

Finally, I asked the student if the feedback behavior reminds them of anything, and if they want to write an example of their own.

5.1.2 Observations and Analysis – Carlisle Students

In this section I will describe in length my observations and analysis of Carlisle's 5th grade students interviews (students with prior systems instruction). In section 5.1.3 I will describe my analysis for Baldwin's 5th grade students (students with no prior instruction). My observations and analysis are based on the interaction with the students during the sessions, and the videotapes analysis.

My observations and preliminary findings suggest that Carlisle's students were able to operate System Blocks, and were successful at associating the moving lights to flow or accumulation of real-life examples. The students mapped tangible (cookies, homework) and intangible (anger) examples, and nobody said "but it is just lights blinking, where is the water you are talking about?" It seemed that the picture cards work well as the "bridge" between the abstract and the concrete.

The "confronting misconceptions" framework worked well. Over and over I observed students making assumptions about the expected behavior, then simulating on their own, finding out that the behavior is different than their expectation, and immediately inventing or adapting a new theory to match the observed behavior.

In a sense, this interactive process provided a setting for what Eleanor Duckworth [Duckworth, 1996] refers to as "wonderful ideas".

The following section describes my observations and analysis of the students' performance in the different activities.

5.1.2.1 Findings - modeling and simulation

The picture cards were an effective way to evaluate students mapping ability. Some students got it all right, and some made a few errors.

The pattern I noticed in the errors was a mix-up between the inflow and the stock. For example, in the anger example ("things that make you angry", "how angry are you?", "things that calm you down") two students positioned the "how angry are you?" before the "things that make you angry". When I asked why, one student said that first he is angry, then things make him angry, and then things calm him down. This behavior might be interpreted as a tendency to favor narrative causality over simultaneous processes (see section 5.1.2.2), and to favor quantities over processes. This type of error occurred several times with different students in the card modeling activity. During the feedback activity, I observed the same error with the virus spread example ("people get infected", "number of sick people", "health again"). Two students positioned the "number of sick people" as the inflow and "people get infected" as the stock. There can be several reasons for this error. The specific examples I worked with and the "left-to-right" operation of the System Blocks might have influenced students' placement of the cards. Further study should be done to fully understand it, but based on my observations, I would define it as a tendency to favor a quantity over process. I call it the ***"Quantity-Over-Process"*** habit. Some students feel more comfortable with a quantity of something (which can be counted), and give it higher priority over processes (which are by definition dynamic). This results in a tendency to start a causal connection with the entity, especially when the processes involved are less tangible ("getting infected" or "getting angry" might be harder than "baking cookies " or "getting homework assignments").

The modeling activity was immediately followed by a simulation activity. The student with the "Quantity-Over-Process" error in the "anger" example simulated her model and started to tell the story. While she turned the inflow dial, she started to explain what happens: "first I am not angry, now I turn the dial and become more angry, now the 'things that make me angry' start to go up.....oops...can I please change this cards?" and immediately switched the "how angry are you?" with the "things that make you angry" card. It was a quick and effective process in which System Blocks helped her to confront her own misconception. After she switched the cards, I asked her why she switched them. She said: "it did not seem right, first things make me angry, then I get angry".

At the end of the modeling and simulation activity I asked the students to write their own examples on blank cards. It was not easy for most of them, and I observed some restlessness. After they wrote their examples, I asked them to simulate it and describe the simulation. One student decided to change the text on the cards during the simulation process. Table 5 lists the students' examples (in their exact words, taken from the cards), including any changes made during simulation. Some examples do not have outflow, which is possible.

Student's gender	**Inflow**	**Stock**	**Outflow**
Male 1	Reading over a week	Books read	- no outflow
Male 2	How many minutes I read a day	Pages I have already read	- no outflow
Female 1	Getting books from library	# of books I have	Returning books
Female 2	Speed I am running	Total number of Min I ran. ***Later changed to***: Total yards	- no outflow
Male 3	Responsibility of me caring for my current pets	Total chances of me getting another pet	Grandma's health (mental)

Table 5: Carlisle 5th graders personal examples for real-life systems

As we can see from Table 5, the examples vary in complexity. I asked the students to try and come up with new examples, not ones we have

discussed or ones they heard from a teacher at school. For some students it took more time than others to think about an example.
The “speed I am running” example was generated quickly because this particular student loves to run. She runs every day in the evening, so this is personally meaningful for her. She always runs a fixed distance, and she keeps a record of her total time, so if she runs faster she finishes her run quickly. This is why her intuition was to choose the stock as “total number of minutes I ran”. While simulating, she started to see it does not make sense, because the speed (inflow) made the time (stock) accumulate, meaning the faster you run it will take you more time, which does not make sense. I suggested that she think about what will happen if her daily run would be for a fixed amount of time, like 15 minutes, and then think what is accumulating if she runs faster. She thought about it for while, and then said it should be the total yards she is running, and changed the text on the card. This example is directly related to the rate-of-change concept in the mathematics of change.

Another interesting example is the last one in the table, the “chances of me getting another pet” example. This student made a connection between how responsible he is with his current pets, his chances to get another pet, and his grandmother’s mental health situation. He explained, that his grandmother’s health situation is instable, and if her instability would increase, his mother would have to spend more time with his grandmother and therefore would have less time to take care of his pets while he is at school. I assume this student was able to connect different influences in this way due to his system thinking studies at earlier grades.

This type of example presents how stocks and flows mapping can help lay out the different variables influencing a desired goal, which leads to realistic views of a situation and higher chances of achieving the desired goal.

5.1.2.2 Findings – net-flow dynamics

My goal in this activity was to evaluate if the students can understand the core concept of net-flow dynamics in a qualitative way. The nature of a tangible interface like System Blocks enables students to watch the process of inflow and outflow, and to operate both flows at once, using two hands. There were differences in the students' comfort level with regards to operating both inflow and outflow simultaneously. Some students did it on their own, at an early stage of the session. Others operated them sequentially, one at a time, and I had to encourage then to investigate what happens both flows are active at the same time. I identified this difference as a tendency toward ***"sequential causality"*** rather than ***"simultaneous causality"***. Other researchers have previously identified this tendency. Grotzer called it "Sequential versus Simultaneous" Causality (Grotzer, 2000), Resnick called it "synchronization bugs" (Resnick, 1991), Feltovich et al. (1997) called it "Sequentiality/Simultaneity".

After a short training with System Blocks, the students that favored "sequential causality" had no problem operating both flows at once. It might be that most of the interfaces children are exposed to promote sequential operations rather than simultaneous operations.

Throughout the activity I encouraged the students to explore net-flow dynamics situations by giving them challenges. Starting with an empty stock, I asked them to fill the stock half way. At this point I asked them to work with both inflow and outflow together. When they reached some level of simultaneous flow, I asked: "can you make the stock increase?" Most students immediately reached to the inflow dial and increased it. But some reached to the outflow, and decreased it. I identify this difference as ***"inflow-before-outflow"*** habit. It might be connected to "sequential over simultaneous" tendency, and to a more general tendency to favor "narrative causality". I observed this happening more in scenarios that are narrative based. For example, in the "anger" example, one of the students explained how his younger brother makes him angry by getting into his room and messing up his stuff. When I asked what calms him down (the outflow in this model), he said: "I will call my mom and she will take my brother away, or I will close the door so he can not come in". This solution is based on decreasing the inflow, not increasing the outflow. After I encouraged the student to find something that calms him down, he said: "reading a book calms me down", and increased the outflow instead of decreasing the inflow. I observed the same tendency is the "Baking Cookies" example, and in the simulation that had no example, just the abstract blocks.

Many factors can be the cause for this tendency. The specific examples I worked with can influence the priority students give to each activity (for a student simulating the cookies example, it is more likely to influence how many cookies are baked vs. how many people eat the cookies). In addition, when I introduced the blocks I used the inflow first to increase the stock and the outflow second to decrease the stock. Still, my observations suggest that the tendency exists. The same tendency occur in common adult behavior. For example, when people start a diet, there is a tendency to favor an extreme diet over increasing physical activity. When dealing with budget problems, people prefer to try and earn more rather than spend less.

If both the tendencies of the young children and the adults share similar problems in understanding of causal structures, proper activities and simulations at young age might contribute. Further research should be done in this area to clearly define the tendency and the role of simulations as possible solutions.

I continued to challenge the students towards a core concept of net-flow dynamics: dynamic equilibrium. I asked the students: "can you make the stock stay half full, and not change?" Most students started with an empty stock, filled it up using the inflow and stopped when it was half full. This is a valid answer, and I challenged them again: "do you think there is a way to have the inflow running but keep the stock half full?" Some students got it quickly. Some were very surprised by the challenge, and their immediate reaction was "it's not possible". After further tinkering with blocks and playing with the simulation, all students succeeded to maintain dynamic equilibrium.

During this activity, one of the students explained what happens: "the stock is not changing because the inflow and outflow are almost the same." I asked if she thinks they need to be almost the same or exactly the same, and she answered "almost the same". All of the students had a similar answer. I call this the ***"minor differences will not change the balance"*** misconception. Students ignored the accumulation process, where small amounts accumulate over time. It might be connected to our tendency to focus on current, short term situations, and underestimate long-term effect. It is closely related to what Grotzer and Bell called "focus on the current situation rather than on processes or patterns of effects" such as accumulation or exponential growth (Grotzer & Bell, 1999).

Following this discussion, I asked the student to simulate a situation where the inflow and outflow are almost the same, but not exactly. She quickly simulated it, and said "you see, the stock does not change". We waited a little and watched the lights on the stock. After a few second, we saw that the light became a little brighter, which represents a small increase in the stock. We waited a little longer, and we saw further increase in the stock. The student was surprised and said: "after a long time, it does make a difference". I asked her if she can think of an example for this situation, and she said: "if I earn $1.05 every day, and spend $1 every day, after a long time I will save a lot of money".

At the end of this activity, all students answered correctly the following questions about the core concept of net-flow linear dynamics:

1. If an inflow is faster/greater than the outflow, the stock will *increase*

2. If an outflow is faster/greater than the inflow, the stock will *decrease*

3. If an inflow and an outflow are the same, the stock will *not change*

5.1.2.3 Findings - graphing

Some students loved the graph from the moment I added it, and some preferred the other representations. Based on later discussions with the students, I determined that the ones who had prior problems understanding graphs at school preferred to work with the lights and sound, and the ones who were good with graphs were happy to see how the blocks can connect to a medium they are already familiar with.

The graph adds a "short term memory" of the dynamic behavior, of about 25 seconds. This helped the students see small differences in the stock level (the height of the graph line) and the stock rate of change (the slope of the graph). Some of the students quickly noted that the graph made it easy to see that even minor differences between inflow and outflow change the stock.

I asked them to go through the same activity we did in the previous activity, and all of the students were quick to control the graph using the inflow and outflow dials. They made the graph go up or down at different rates, and enjoyed to view the immediate reaction in the display.

I asked what characteristic of the graph represents the stock. I received a variety of answers. Some students got it right and said that the height represents the stock, and could also show how it would be measured using numbers on an imaginary Y-axis (the graph display has no axis or numbers at all). Others were confused, they could easily say when the stock goes up or down, but had a hard time separating the height and slope of the line, so they referred to the graph as a whole. After a few simulations where the students explored the graph on their own, changing the inflow and outflow and watching the graph and the lights at the same time, all students could say that the height of the line represents the stock. I continued and this time asked what the slope represents. All of the students were confident it represents the inflow, and neglected the fact that the outflow influences the slope as well. I call this error ***"slope-as-inflow"***. It seems connected to the "inflow-before-outflow" tendency described earlier, where students give higher priority to inflow, and to the difficulty in grasping the net-flow concept.

I followed this error with a challenge, and asked the students to use the outflow and see if it is being represented in the graph. They saw how the height decreases and how the slope changes when they increase or decrease the outflow. They seemed confused, and finally determined the slope represents both the inflow and the outflow, but could not explain exactly how. At the end of the session I repeated the questions. Most of the students said the slope represents the inflow. I think further research should be done in this area, clearly identifying the causes for this difficulty.

5.1.2.4 Findings - positive feedback

Modeling positive feedback examples turned out to bring out the same errors as the previous models. Some students got it right and some switched the stock with the inflow (the ***"quantity-over-process"*** error). As I listed earlier, in the infectious disease example, the inflow is "people get infected" (process) and the stock is "number of sick people" (quantity). This is a trickier situation, because there is feedback and the stock influences back to the inflow, so one can see the stock as the starting point for the process. Still, people have to get infected first in order to become sick, and several students got it right. Further research should be done to better understand this error. A good direction can be to prepare examples that range in difficulty level (from tangible/intangible and feedback/no feedback point of view), and see if the increased difficulty level leads students to favor stock over inflow.

All students could explain the concept of positive feedback after I simulated it. They could explain in their own words how more sick people leads to more people getting infected, and more people getting infected leads to more sick people. Generating their own examples was harder. Only one student managed to connect it with his own example, he said: "it's like in sports, every once in a while there is a new sport and more and more people join it".

When I simulated positive feedback and the inflow lights moved at a very high speed, students' reaction was different than previous simulations. They seemed excited, and their energy level increased. Some students got up from their chairs and used hand gestures to express the circular activity. One student said: "it is going faster and faster", another said: "it is going faster on its own".

In Mindstorms (Papert, 1980 p.74), Seymour Papert describes the excitement the recursion concept evoked among students, and how it touches the idea of going on forever. It might be that feedback has some of the same characteristics as recursion.

The simulation showed effectively how a small change in a system's structure can drastically influence the system behavior. I asked the students to use the outflow and try to stop the stock from increasing. They couldn't, and one student explained it: "there is no feedback on the outflow, so it can not compete with the inflow".

Some students asked to connect the sound block to hear how the feedback behavior sounds. One student reaction was "it is growing so quickly..."

Adding the graph display, students could see the exponential growth curve. The reactions were: "It is curved", "It is growing much faster", or "It grows higher than before". The students simulated the exponential growth several times, with different growth rates each time (setting the dial to different values). They saw how the growth curve starts slowly and suddenly picks up, but always, for different inflow values the curve has the same general shape. I asked them to draw two graphs, one with positive feedback and one without positive feedback. All of them drew a linear line with a small growth rate for the no-feedback and an exponential one for the positive feedback.

During the discussion on the linear vs. curved graphs, I observed that the students do not make a clear distinction between them. When they draw a graph on the whiteboard, they do not pay enough attention to the line characteristics. Using the graph display, the differences between linear and curved are very clear, but when drawing graphs by hand, these differences can be blurred. I asked some of the teachers at the school if they emphasize this difference, and they did not. I participated in one of the classes where "behavior over time graphs" were presented, in the context of filling a bathtub. The teacher presented 3 graphs, two somewhat linear one with different slopes, and one exponential. I worry experiences like this might seed misconceptions about graphs. From mathematical point of view, the difference between linear and curved is well-defined (net-flow constant vs. net-flow changing). A possible way to address this problem might be including simulation of graphs at the first time graphs are introduced to students, and continue by giving careful attention to the slopes when drawing graphs by hand and connecting back to the simulated graphs.

5.1.3 Observations and Analysis – Baldwin Students

In this section I will describe my observations and analysis of Baldwin's 5th grade students interviews (students with no prior systems instruction). Since I have already reviewed in length (in section 5.1.2) my preliminary findings from Carlisle's interview, and the Baldwin interviews were performed in the exact same format, I will keep focus in this section on the main findings and the differences between the two groups.

5.1.3.1 Findings - modeling and simulation

My preliminary findings suggest that all of Baldwin's students understood the blocks' operations, were able to associate the moving lights to flow or accumulation of real-life examples, and understood the mapping from the real "water flow and measuring cup" activity to the stock, flow, and variable blocks of System Blocks.

The students performed very well in mapping the picture cards to the stock and flows structure. Compared with Carlisle's students, I observed fewer occurrences of the "Quantity-Over-Process" tendency (this is surprising, since the Carlisle's students are the ones with the prior background). There was only one occurrence, in the "anger" example, where one of the Baldwin students mapped the "how angry are you?" before the "things that make you angry". As in the previous cases, when she simulated the model and explained what is going on, she identified the problem on her own and asked to switch the cards.

On the other hand, I observed more occurrences of the "Sequentially vs. Simultaneously" tendency. In the "generate your own example" exercise, this tendency happened often. Most of the examples were in narrative form (A leads to B leads to C), rather than inflow/stock/outflow (A leads to accumulation of B, C leads to decrease in C). Table 6 lists the different examples.

Student	Inflow	Stock	Outflow
Male 1	Getting a basketball	Practice	How good you are
Male 2	When I win games	How much I won	- no outflow
Female 1	Putting books on shelf	Bookshelf filling up	Children taking books from shelf

Female 2	How much I dance	How much I get tired	How I feel after
Male 3	Buying a LEGO set	Putting it together	Finish and play with it

Table 6: Baldwin 5th graders personal examples for real-life systems

Apart from one girl, that generated a great example (the bookshelf), all other students generated a sequential, narrative-influenced example. Following this exercise I tried to focus the activities on this area, asking the children to simulate and explain their examples. In most cases, it was harder to "shake off" the tendency for "sequential thinking" than it was with the Carlisle students. It took them more simulations to be convinced that there is a problem in their example, and some discussions and encouragements to help them come up with an idea for correcting it. When I asked them to generate another example, only one more student got it right, and the other 3 could not "shake off" their tendency towards sequential, narrative examples.

A more comprehensive study should be done in this area, but my preliminary findings suggest that the "sequentially vs. simultaneously" styles of thinking could be addressed with 5th graders, and help young children get familiar with different causal model early, before they become "protective" of a sequential, narrative style of thinking.

In addition, my study suggests that some factors in Carlisle students' prior instruction caused for more "Quantity-Over-Process" tendency. One explanation might be the "Causal Loop Diagrams" (CLD) that they learn at elementary school. CLD are drawings of causal arrows between variable of a problem, and are an important tool in system thinking. The problem might be that in CLDs, most variables are quantities of something, and therefore the students are used to starting a causal chain with a quantity. Further study should be done with the Carlisle teachers to better understand this tendency.

5.1.3.2 Findings – Net-flow Dynamics

Baldwin students' performance in the net-flow dynamics activity was not substantially different than the Carlisle students'. Some students were naturally good at it, and started to operate both flows simultaneously on their own. Others preferred to operate them one-by-one, until I encouraged them to try both simultaneously. After a few simulations, those students could operate both flows. At the end of this session, all students answered correctly to the general net-flow dynamics questions (inflow faster than outflow will cause the stock to increase etc.).

5.1.3.3 Findings – Graphing

Baldwin's students had very little experience with line graphs in 4th grade. When I asked them to draw a graph of water filling a bathtub (before the graph activity), only one student drew a line graph. Two other students drew pictures of bathtubs in different states with arrows between them, one other student drew an arrow going up, and another student drew a straight line.

During the activity, all students had no problem connecting the light and sound familiar representations with the new unfamiliar graph representation. They simulated growth and decay several times, and explained that the height of the graph is the amount of water in the bathtub, and that when the line goes up the bathtub is filling up and when the line goes down the bathtub drains.

Explaining the slope of the line was harder. During the simulations some of the students got it, especially when working together with the sound representation. After the session, I asked the students to draw a line graph and explain what the height and slope represent. All of them drew a line graph, 4 were correct about the height, and only one was correct about the slope.

Further study should be done in this important area, where Stocks and Flows connect to the mathematics of change.

5.1.3.4 Findings – Positive Feedback

Since I spent more time with these students on the previous sessions, I had time to do the feedback activity only with 2 students. These 2 students mapped the feedback example cards correctly (people get infected, number of sick people, healthy again). It seemed they understood the loop concept, and as with the Carlisle students, were very excited to see the positive feedback in action.

When I added the graph representation to display the exponential growth, the difference was clear. It might be that they had never seen a curved graph before, and it was clear to them that it is growing faster than the linear graph. On the other hand, I could not spend much time on this concept, and I doubt if they remembered any of it later.

5.1.4 Discussion of Findings - Fifth Grade Study

My preliminary findings suggests that System Blocks are effective in helping 5th grade students learn about the core concepts of systems thinking and dynamic behavior, such as Stocks and Flows modeling, net-flow dynamics, and positive feedback. In addition, System Blocks can contribute to the understanding of core concepts of the mathematics of change, and can help student refine their understanding of rate-of-change concepts using the standard line graph representation.

In this section I discuss my research findings from different angles: System Blocks as a new interface; the learning process facilitated by System Blocks; the generality and abstraction level of System Blocks; the list of students' misconceptions and tendencies; the differences observed between students with and without prior instruction; and the limitations of System Blocks.

The interface. Students stated they enjoyed all the sessions, that System Blocks were fun to use, and that it was much easier and more effective than the STELLA software tool (see section 6.1 for students' quotes on that topic). I noticed that the two-hands interface was effective in promoting simultaneous activity. The different representations (moving lights, sound, and graph) were effective in giving a qualitative representation of dynamic behavior. Different students had different preferences; one preferred the graph while others preferred the sound or lights. One student explained that all the representations are good but for different stages in the learning process. He thought that the lights are good for beginning, then the sound and then the graph ("coincidently" this is exactly the order they were presented to him). Students were very engaged throughout the sessions.

The learning process. The simulation capabilities of System Blocks were essential to the interactive cycle of having a theory, testing it out, and revising the theory. This process of testing and revising confronted students with their own misconceptions time after time, and was effective in helping them use their own senses and observations to come up with a new theory. They did it quickly. It seems they have no problem changing their theories. This is a core benefit of System Blocks. A simulation that can be operated by the student alone is critical to help students revise their theories when they fail. Without a simulation tool, student could hold to their false theories, or drop them but adopt new false theories. In my activities with the students I repeatedly saw how System Blocks gives them a framework to test and revise their theories on. Future work should be done on students' ability to transfer what they learned using System Blocks to a new context, without using System Blocks at all.

The abstraction level. System Blocks facilitate a constant shift between concrete and abstract. The blocks are tangible, but represent abstract entities. The picture cards are a very small step towards concreteness, but nevertheless seemed to work effectively. When working with System Blocks, it is clear that the cards are only temporary representations. Still, the students had no problem shifting between different domains in a matter of minutes - from physical examples such as water flowing and cookies baked to emotional examples such as level of anger to social networks examples such as trends and diseases. In the same way that children build a castle from LEGO or wooden blocks and pretend it is a castle, they can pretend a box is a bathtub and blinking lights are flow of water.

Students' misconceptions and tendencies. Throughout the sessions I observed several misconceptions and tendencies students expressed about dynamic behavior and system concepts. There were surprising differences in the type of tendencies between the students with and without prior instruction. System Blocks were effective in surfacing those tendencies with both groups of students.

- *Sequentially vs. Simultaneously:* a tendency to think in a narrative way, A causes B then B causes C. Thinking about processes as if they happen one-at-a-time. Others are more comfortable with processes happening simultaneously. Occurred more with the Baldwin students (the ones with no prior instruction)
- *Quantity Over Process:* a tendency to favor quantity over process. When mapping real-life examples to Stocks and Flows models, students that had this problem switched between the inflow (activity, process) and the stock (amount of something, quantity). Occurred more with the Carlisle students (the ones with prior instruction).
- *Inflow Over Outflow:* a tendency to give higher priority to the inflow rather than the outflow. When they deal with a problem, they tend to increase or decrease the inflow and not pay enough attention to the outflow. Occurred more with the Carlisle students (the ones with prior instruction). When analyzing line graphs, students tend to connect the slope of the graph with the inflow, and ignore the influence of the outflow (the slope represents the net-flow, which

is the sum of inflow and outflow). Occurred more with the Carlisle students (the ones with prior instruction).

- *Minor differences will not change the balance:* When minor differences exist between an inflow and an outflow, students tend to ignore the change these differences would create over time, and assume the system would stay in balance or not change. Might be connected to common tendency people have to focus on short-term processes rather than long-term ones. No differences observed between the two student groups.
- *Linear vs. curved:* students do not pay enough attention to the curvature of a line graph. Students' tend to focus more on the direction of the graph (going up or down), and not so much on the curvature. From mathematical (and real-life implications) point of view, there is a major difference between linear and curved growth (or decay). It seems that this problem can be easily addressed by improving the way line graphs are presented to students. Teachers should pay more attention to line curvature, and should use computer-generated graphs when possible to make sure the curvature is accurate. Occurred more with the Carlisle students (the ones with prior instruction).

The above misconceptions and tendencies are based on a small sample, exploratory study. Nevertheless, the patterns I have observed can be helpful pointers to some of the difficulties students might have when trying to learn about dynamic behavior.

Summarizing the difficulties, it seems that students with prior system thinking instruction had a tendency to favor inflow over outflow, quantity over process. Further study should be done to identify the potential causes for this tendency.

On the other hand, students with prior instruction were faster to "shake off" the tendency for sequentially over simultaneously. Further study should be done to identify the earliest age that simultaneous concepts could be introduced to children.

In addition, it seems that System Blocks is an effective tool to introduce systems concepts for the first time, and can help to decrease the number of misconceptions with regards to net-flow dynamics and graph shapes.

With regards to positive feedback, my findings suggest hat 5th grade students are perfectly capable of learning this concept. Further work should be done to prepare the relevant educational scaffolding to support learning of feedback concepts at a younger age.

The limitations. System Blocks were effective in a one-on-one process. An effective part of the learning process was students' ability to test and revise their theories. This was an individual process for each student. The process took different amounts of time for each one, and was a part of "trust relationship" that was created between the student and the blocks.
In a group setting, it is hard to tell if System Blocks can be as effective. Different students have different ways of thinking about dynamic behavior, and if some students are more dominant than others when operating the System Blocks, the less dominant students would not be able to test and revise their theories.

In the interviews I conducted, I played an important role. I facilitated the activities, the discussions, I challenged the students etc. It is not clear if a student working independently can yield the same results. On the other hand, after the first sessions the students seemed to be familiar with the blocks and with the type of activities to the extent that they might be able to work independently with the proper educational materials.

In a classroom environment, teachers would play the role of the facilitator. Teachers have a great deal of knowledge about their students' character, style of learning, and behavior in a group setting. Further study should be done to evaluate how effective System Blocks are in a small group setting with a teacher as the facilitator, working with the proper educational materials.

5.2 Preschool Study

I performed another exploratory study, a smaller one, with preschoolers. I wanted to explore how very young children react to System Blocks and if it is at all possible for them to connect System Blocks simulations with real-life examples. I decided to conduct interview sessions with preschoolers.

5.2.1 Method and Data Analysis

I interviewed 5 Preschool students at the MIT child-care center (MIT's Technology Children Center). The children ranged in age from 3 ½ to 4 ½ years old. The gender distribution was 3 females and 2 males.

I used a similar framework to the 5th graders, of one-on-one interviews, but with one session per child, and shorter session length of around 15 - 30 minutes, based on the child's level of interest.

I planned two activities for the preschool session. I started with a water flow example, using a real faucet and a measuring cup. I asked the children to turn the faucet on and fill the measuring cup. While they were performing the activity, I asked them to describe what happens. We performed this activity several times, each time I asked the children to turn the faucet more or less, so they experienced how the measuring cup can be filled at different speeds.

Immediately following the water flow activity we turned to a nearby table where the System Blocks were arranged in an inflow/stock arrangement (no outflow). I placed the measuring cup on top of the stock block, and placed a picture card of a "faucet" on the inflow block. I asked the children if they can imagine that the large box (stock) is representing the measuring cup, and that the small box with the dial and the picture card represents the faucet handle. I turned on the blocks' power, and asked the child to turn the dial on. We watched together how the lights move on the flow block and how the lights accumulate on the stock block. I asked the children to explain what is happening, and we discussed it for a while. Based on the child's interest and level of understanding, I added the outflow block and placed the rest of the "bathtub" example picture cards. At some point I added the sound representations, to see how the children react to it and if it helps them understand the concepts of accumulation. If appropriate I continued with additional examples including the "baking cookies" example, the "getting money" example, and the "things that make you angry" example.

5.2.2 Observations and Analysis – Preschool Students

The Preschool students' level of understanding varied greatly. To clarify my findings, I mapped their level of understanding based on the following areas:

1. Recognize – ability to recognize and state the direction in which the lights are accumulating. Say either "going up" or "going down" for the lights or sound representations.
2. Concretize - ability to pretend the lights represent a real-life example. Say "water is going up" or "the bathtub is full" or "no more cookies" when performing a simulation.
3. Control – ability to control the state of the stock using the inflow and outflow dials. Use either inflow or outflow when challenged to increase or decrease the stock.
4. Map – ability to map a real-life example to Stock & Flows structure using the picture cards. Emphasis both on associating the cards as well as the order in which there are placed.
5. Create – ability to generate a personal example and map it to Stock & Flows structure.

Here are descriptions of 2 sessions, the first with a 4 years old boy (pseudo name "Henry"), and the second with a 4 years old girl (pseudo name "Felicity").

Henry, a 4 years old boy enjoyed the real water example. We moved to the table with the blocks, and started with the inflow-to-stock simulation, using the faucet picture card on the inflow and the physical measuring cup on the stock. I asked him to turn the inflow dial and explain what happens. First he said "the lights are blinking" looking at the flow block lights. For the stock lights he said "going up". I asked what is going up, and he said "the lights are going up". I asked if he can pretend the lights are water, and started the simulation again. Looking at the flow block, he said: "the light are blinking". Looking at the stock block, he said: "going up". I asked what is going up, and he said "the water". I continued and connected the outflow block. I showed Henry the bathtub example picture cards. I mapped the cards and explained what each represent. I started another simulation and asked him to fill the bathtub. He reached to the inflow and filled it. I helped him stop the inflow when it was full. I asked him to drain the bathtub, and he immediately reached to the outflow and drained it. Henry said "got off", "no more water". I presented him the cookies example, explained him the text on each card, and asked him to place them on the blocks. He mapped "baking cookies" as inflow, "eating cookies" as stock, and "number of cookies" as outflow. We simulated it. I asked Henry to explain what happens. He said: "goes up". I asked what is going up, he said "the cookies" and started to count up the number of LEDs "1 cookie, 2 cookies, 3 cookies…" I asked him to make the number of cookies go down, he reached to the outflow without hesitation and did it. I added the sound representation and asked what happens. He said: "it gets louder". I presented him the "anger" example (things hat make you angry, how angry are you, things that come you down). I mapped it and asked him to simulate. He turned the inflow and said "going up". I asked what is going up, and he said: "anger is going up". I asked him if he could generate his own example. He wanted to make a cookies example. I gave him blank cards to draw on, and asked him to tell me what to write as their labels. His example in the order he created it: "making cookies" for inflow, "eating cookies" for stock, "all done with cookies" for outflow. We simulated Henry's example, and I tried to guide him to confront his error (as I did with the 5th graders), but he could not pay attention. I asked Henry what he thinks about the blocks, and he said: "I like the blocks in the block area better, because I can build with them".

Summary of Henry's session:

- Recognize - at the first simulation he could not recognize accumulation. From the second simulation on he could, both for lights and sound.
- Concretize – after I asked Henry to pretend the lights are water, he successfully talked about water, cookies, and anger when watching the accumulating lights.
- Control – Henry used both inflow and outflow dials without hesitation to control the accumulation direction.
- Map and Use – It seems Henry has a tendency for the sequentially, narrative causality rather than simultaneously. Both his mapping order and placement shows it, as well as his explanation for his own generated cookies example: "first they make the cookies, then they eat the cookies, then they are all done with the cookies".

Felicity, a 4-year-old girl, asked to hold the blocks and feel them when she first saw them. We performed the real water flow demonstration and moved to the table with System Blocks. We started with the inflow-to-stock simulation, using the faucet picture card on the inflow block and the physical measuring cup on the stock block. I asked Felicity to turn on the inflow dial and explain what happens. She watched the lights move in the flow block, and immediately said: "the water moved through this one". She intuitively recognized the direction of flow and connected it with water. She also recognized the direction of accumulation and said: "the water is going up". She was not sure which direction she should turn the inflow dial to turn it on, and seemed not so confident using it. I added the outflow and placed the bathtub picture cards. She filled the bathtub and then drained it. She said: "no more water" when the stock was empty. She was still hesitant with both inflow and outflow dials. She was interested in the picture cards and wanted to see more examples. I showed her the cookies example, and I mapped it to the inflow, stock and outflow. Before we simulated, she guessed that turning the inflow will "make more cookies". When we started the simulation, she saw the moving blue lights and said: "the water came back". I asked if she can pretend the lights are cookies and she did it. I asked her to turn the outflow dial, she did and said: "the cookies are going down because the children are eating them". She asked for more examples, I showed her the money example and mapped it. She simulated and said: "no more money because the people are using it to buy stuff". I presented the anger example and mapped it. She simulated and said: "I become angry because this went all the way up". Several times during the simulation she confused outflow with inflow, and reached for the inflow when trying to decrease the stock. I asked her to generate her own example. She loved the idea and started to draw on the blank picture cards. She started with a princess, and placed it on the inflow block. Then she drew a bed with a sleeping princess, and placed it on the outflow block. Then she drew the same bed, with the princess seating on the bed, and placed it on the stock block. I asked her to simulate and explain. She simulated and said: "going to sleep, getting awake again". "asleep, awake, asleep, awake". I asked felicity what she thinks about the blocks. She said: "it's cool". I asked why, and she said: "because I learned new things". I asked what she learned, and she said: "sometimes you are making cookies and sometimes you are eating cookies, sometimes you are getting money and sometimes you are buying things".

Summary of Felicity's session:

- Recognize – immediately recognized direction, both accumulation and flow.
- Concretize – intuitively pretended the light is water. In the cookies example she continued to connect the lights to water, and needed a second to connect it with the cookies.
- Control – was not confident with inflow and outflow dials. Several times reached for inflow instead of outflow. Might have the "inflow over outflow" tendency?
- Map – did not have the chance to map because I did the entire mapping for her. The order I used when I mapped was inflow, stock, outflow.
- Create – was very comfortable generating an example (the "awake, asleep, awake, asleep" dynamics). Her mapping order was inflow first, then outflow, and only then stock. She mapped the processes before the quantity.

5.2.3 Discussion of Findings - Preschool Study

My preliminary findings suggest that 4-year-old preschool students have initial understanding of systems related concepts. On one hand, some preschoolers could not recognize the accumulation concept from the moving lights, and could not concretize the blocks and connect them with real-life examples. On the other hand, several preschoolers could connect the moving lights with real-life examples and could even generate their own examples.

Table 7 presents a summary of my findings from the preschoolers' interviews, organized according to the areas I defined at the previous section.

	Recognize	**Concretize**	**Control**	**Map**	**Use**
Age 3.5 y. Female.	No for lights. Yes for sound.	No.	NA. Asked to go play.	NA. Asked to go play.	NA. Asked to go play.
Age 4 y. Female.	Yes for lights. NA for sound (I did not use it).	Yes. Examples: water, cookies, money, anger.	Yes Inflow. No outflow.	NA. I mapped the examples for her.	Yes. No errors. Example was: Princess "sleepingness" level. Order was: inflow, outflow, stock.
Age 4.5 y. Female.	Yes for lights. NA for sound (I did not use it).	Yes. Examples: water, cookies.	Yes Inflow. No outflow.	Yes. No errors. Order was: inflow, outflow, stock.	Na. Asked to go play.
Age 4 y. Male.	Yes. Both lights and sound.	Yes. Examples: water, cookies, anger.	Yes. Both inflow and outflow.	Yes, with errors. Mixed stock with outflow. Order was: inflow, stock, outflow. Sequentially tendency.	Yes. Sequentially tendency. Map a cookies example. Mapped: Inflow for "making cookies". Stock for "eating cookies". Outflow for "all done with cookies".
Age 4.5 y. Male.	Yes. Both lights and sound.	So so. Said "lights are going up" several times.	Yes. Both inflow and outflow.	Yes, with errors. Mixed stock with outflow. Order was: inflow, stock, outflow.	No. Could not think of any example.

Table 7: Summary of findings – preschoolers' interviews

CHAPTER 6. DISCUSSION AND FUTURE WORK

In my thesis I have presented System Blocks, a new platform for hands-on modeling, simulation, and learning of systems behavior. I reported on an exploratory study with middle school and preschool students, and presented the potential of System Blocks as a new interactive learning technology in the areas of systems behavior and the mathematics of change.

In sections 5.1.3 and 5.2.3 I have presented my research findings. Listed in the same sections are various misconceptions and tendencies I observed in students' understanding of systems concepts and dynamic behavior.

In the following section, I review my research in a broader context. I discuss the role of tangibility in the learning process; I list a few suggestions how to better support learning of system concepts; and I point to possible next steps that extends System Blocks towards a family of "process manipulatives".

6.1 Tangibility in the Learning Process

As I have reviewed in chapter 3, educators and researchers emphasize the importance of physical interaction in the learning process (Froebel, Montessori, Piaget). Nevertheless, it is not common to see technology-based physical interaction in today's schools. Interaction with technology in a learning environment is usually performed using the standard mouse, keyboard, and screen.

The tangibility aspect of System Blocks promoted discussion, and was effective in surfacing students' mental models and exposing misconceptions. Students had to choose which card to match to which block, and when they did, they could explain why they did it. When they started a simulation, they explained what should be happening, based on their mental model or assumption. When the simulation behaved differently than expected, I observed different reactions. Some students were quiet for while, than asked to switch the cards. Other started to talk, expressing their surprise but also immediately adapting a new theory and explaining to me what happened. I doubt I could get such live and active responses using a software tool on a computer screen.

When I asked 5th grade students to compare System Blocks with a software simulation tool or a computer game, their opinions were straightforward:

> "I am a person that likes to do things with my hands. With a regular software on the computer, it's always just clicking buttons. With the blocks I can feel what I'm doing. I like it much more."

> "I like the blocks much more than STELLA. With STELLA, you click buttons and insert numbers and then a window opens and you see the result. With the blocks, I can see the flow, I can change this dial and see the lights move faster."

> "I think the lights and the sound are very helpful. Also the graph is helpful, but I like the sound better. Starting with the lights, and then hearing the sound, and then seeing the graph was great."

In my exploratory study I conducted one-on-one interviews with students. A more comprehensive study should be done to evaluate System Blocks effectiveness in a group setting, either a full classroom or small-group clusters. I have started to explore this direction in a 3rd grade classroom setting. I have presented System Blocks to twenty 3rd grade students, presenting a Stocks and Flows model of a story they have reviewed in class (Dr. Seuss's The Lorax). The class presentation was followed by a short small groups activity. My preliminary findings suggest that small groups (4-5 students per group) might be an effective way to get the students used to the new interface. At the same time, I think it is instrumental to the learning process to enable each child to model and simulate individually, so misconceptions and tendencies could surface.

In my research I have not directly compared System Blocks and a software tool. Future study should be done in that area, for example, comparing similar modeling and simulation tasks between System Blocks and STELLA™ or Vensim®, and evaluating if the different interfaces lead to different levels of understanding among children or adults.

6.2 Learning Systems Concepts

As I have reviewed in chapters 2 and 3, common systems structures appear in many day-to-day experiences. Understanding the core concepts of systems and dynamic behavior can be a useful tool of thought for children and adults alike, and can serve people in different aspects of life.

My preliminary 5th grade research findings suggest that using System Blocks, students with or without prior instruction in systems concepts are capable of performing Stocks and Flows modeling, mapping, and simulation on their own. Students were able to correctly map different real-life examples into Stocks and Flows structures, and when errors were made, a short simulation helped the students understand by themselves what is wrong and how to change it. In addition, students were able to map their own personal experiences to Stocks and Flows structure (see section 5.1.2.1 and 5.1.3.1). System Blocks were most effective in helping students understand the net-flow dynamics concept (that emphasizes simultaneous processes).

My preliminary Preschool research findings suggest that 4-year-old children are capable of using System Blocks as a modeling and simulation tool. A few minutes of hands-on simulation was sufficient for 4 out of 5 children to recognize the accumulation process using the moving lights representation. A few additional simulations and the children could explain the system behavior of real-life examples, such as water flow through a bathtub or cookies being baked and eaten. Most important, some of the misconceptions and tendency observed with the 5th grade students appeared with the preschoolers as well. System Blocks has the potential to address these tendencies at a very young age, and provide young children an opportunity to confront their misconceptions about dynamic behavior, helping them to revise their mental models towards a deeper understanding of systems concept.

Future work should be done to create a systems thinking curriculum, covering all grade levels and focused on the generic structures of systems found in nature and in social systems. System Blocks could be used as the introductory modeling and simulation platform for the lower grades, and a software tool with more advanced modeling capabilities could be used in the higher grades. The curriculum should include activities that connect systems structures to real-life phenomena that the children can associate with. Kindergarten students could play with simulations of pre-built models with picture cards of simple systems (such as the cookies example described in chapter 2), using sound as the main representation. Elementary students could start modeling simple examples to Stocks and Flows structures, and manipulate linear graphs. Middle school students could map their own examples, and learn about positive and negative feedback and the differences between linear and exponential graphs. High school students could play with second order feedback behavior, and learn to identify more advanced systems structures, such as goal seeking, oscillating, and self-regulating systems. System Blocks are able to simulate such systems, and these advanced models could be used as a transition from System Blocks simulations to the more advanced software-based simulation tools, such as STELLA or Vensim.

System Blocks could be used in other areas in addition to K-12 education. Many businesses practice modeling and simulation of different business scenarios, in an effort to understand the dynamic behavior related to their business. Following the "modeling for insights" philosophy rather than "modeling for accurate predictions" (see section 3.2.2), executives and managers could use System Blocks to generate insights about their business dynamics. In addition, System Blocks can promote group learning. A group of co-workers can perform modeling of a problem together, when each employee represents her view in the business. The tangibility of System Blocks and the picture cards interface could promote discussion, and will surface the individual mental models each worker holds, leading to a "shared mental model" (Senge, 1991).

6.3 Towards a Family of "Process Manipulatives"

My research and the development of System Blocks can be viewed as the first step towards a family of "process manipulatives", a set of computational objects that make dynamic processes more visible, manipulable and accessible.

As I have reviewed in section 3.3.1, the mathematics of change is a "high profile" area in high school and college mathematics. In my research I showed some of the common themes between systems behavior and the mathematics of change, such as rate-of-change and behavior-over-time graphs. A new set of blocks could be developed to target the "hard concepts" of mathematics of change. With an appropriate curriculum, these "Rate-of-Change Blocks" could be introduced to young students, as early as kindergarten, seeding the core rate-of-change concepts. In the same approach of the "systems behavior across-grades curriculum" mentioned above, the rate-of-change curriculum could gradually develop from kindergarten to high school, introducing more advanced concepts as students' understanding grow. New peripheral technologies could be developed for the "Rate-of-Change Blocks" to support the current methods used at schools. For example, new "sensor blocks" could detect a student's body motion and input it into the system, the graph display could be improved to support printing and display of multiple graphs on a desktop computer, an interface could be developed to display the rate-of-change as an animated character etc. In the same way that System Blocks were not designed to replace existing system simulation software tools, but were rather designed to serve as a hands-on introduction at a younger age, the "Rate-of-Change Blocks" should not replace existing rate-of-change technologies, but rather assist to introduce these concepts at a younger age.

In addition, a new set of "Causality Blocks" could be developed to make it possible for young children to play with different forms of causality. Special attention should be given to "simultaneous causality" over "sequential causality", as the groundwork for developing better understanding of dynamic behavior. Children as young as 3 years old could start using "Causality Block", breaking new grounds for future studies in young children's understanding of causal models.

In the systems domain, future "process manipulatives" can focus on concepts such as negative feedback, emergence, and time-delays to make them more visible, manipulable, and accessible using hands-on interfaces.

6.4 General Conclusion

In this thesis I described how System Blocks provide students an opportunity to confront their misconceptions about dynamic behavior through a hands-on, interactive process of modeling and simulation. Many factors can be the cause for students' misconceptions and tendencies, including prior instruction, prior life experiences, the design of System Blocks interface or the specific examples I have used in my interviews. Nevertheless, my exploratory study suggests that one-on-one interaction with a "process manipulative" such as System Blocks can help students confront their current conceptions about dynamic behavior, and provide students an opportunity to revise their mental models towards a deeper understanding of systems concepts.

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FIGURES AND TABLES

APPENDIX A. STOCKS AND FLOWS

Introduction to Stocks and Flows Modeling Language

In this section I will describe the system dynamics Stocks and Flows modeling language and will briefly describe the math behind it. Stocks and Flows modeling was initially called Levels and Rates, but currently the common terminology is Stocks & Flows (S&F). System Dynamics researchers, practitioners, and teachers all use this modeling technique to model and simulate dynamic systems. There are several software modeling tools that support S&F modeling and simulation. The leading ones are STELLA® by High Performance Inc. (STELLA) and Vensim® by Ventana Systems (Vensim). The following introduction is a high-level overview of the concepts I find the most relevant to my research, and is aimed at readers that have no prior instruction in system dynamics modeling. Several books and software tutorial were used as a reference to create this introduction, and can be reviewed for a more thorough introduction to the field. (Roberts N. et al. 1983, Introduction to Computer Simulation: A System Dynamics Modeling Approach, Chapter 13; Sterman J. 200, Business Dynamics).

A.1 Stocks and Flows

A stock is a quantity or a level that accumulates over time. A flow is a rate, an activity, or movement that contributes to the change in a stock. For example, population is a stock and the number of babies born per year is a flow. Similarly, the amount of water in a bathtub is a stock, and the amount of water flowing in or out from the bathtub per second is a flow. Forrester originated the stock and flow diagramming conventions in 1961. Figure 15 shows the standard symbols of a stock and a flow (using Vensim® symbols). In this case, the flow is flowing into the stock and therefore called flow-in. A stock is represented by a rectangle (which is supposed to resemble a box or a bathtub) and a flow by an arrow with a valve (which is supposed to resemble a faucet, controlling the flow of water into a bathtub).

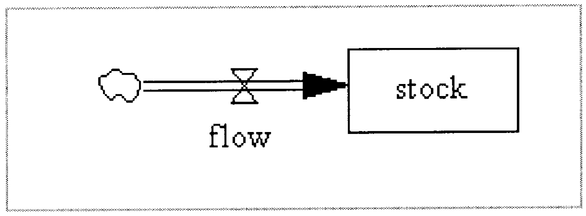


Figure 15: Flow into stock (inflow)

Figure 16 shows that the number of people arriving per hour influences the number of people in the supermarket. The flow of people arriving at the supermarket increases the stock of people in the supermarket, in the same way that a flow of water increases the level of water (stock) in the bathtub.

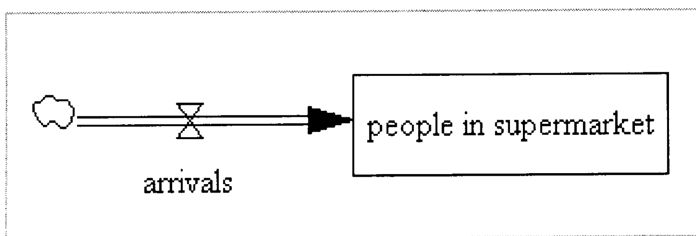


Figure 16: Flow of arrivals influences stock

Figure 17 goes another step in trying to model the behavior of the 'number of people in supermarket' system. The stock of people in the supermarket at any given time is influenced both by the number of people arriving per hour and the number of people departing per hour (or any other time unit). The arrival rate is added to the stock (number of people in the supermarket), and the departure rate is subtracted from the stock.

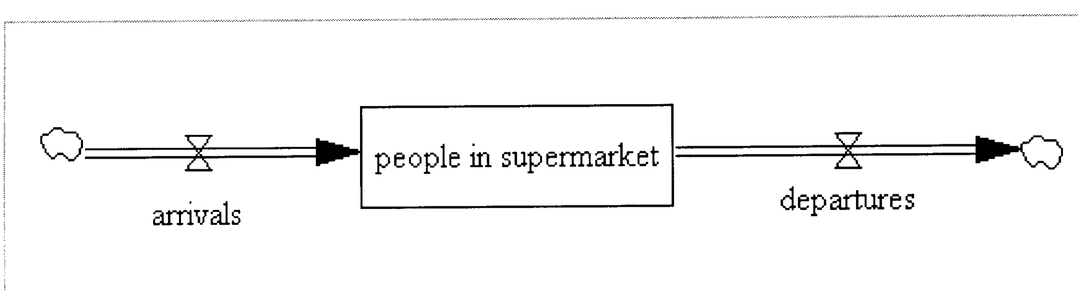


Figure 17: Inflow of arrivals as well as outflow of departures influences the stock

A.2 Feedback Loops

Figure 18 shows a model with a feedback loop, using the population growth system. "Population" is the stock, and "births" is the flow-in. The rate of births influences the population level, in the same way that arrival rate influences the level of people in the supermarket. But, in the population system, there is another cause-and-effect relationship that influences the number of people in a population. People give birth; therefore the number of people influences the birth rate. More people will lead to more births, which in turn will lead to **more** people. This cause-and-effect relationship is called positive feedback, and is depicted in the model using an arrow that connects the population stock back to the births flow. Positive feedback generates exponential growth or exponential decay. The flow is adding a fraction of the stock to the stock in every time step, and this fraction is an ever-increasing number, because the stock is increasing. A positive feedback loop is also called "reinforcing loop".

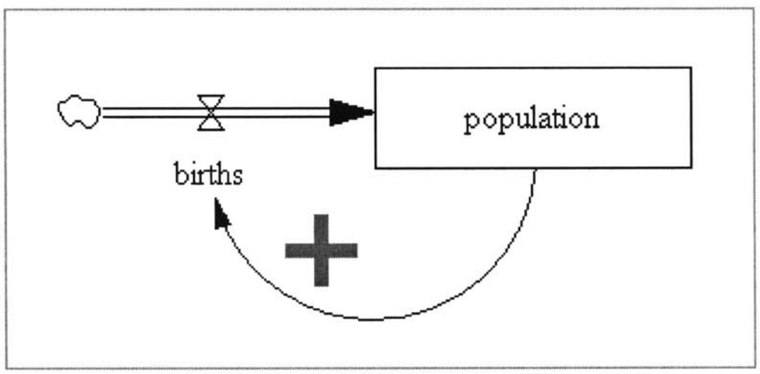


Figure 18: Positive feedback

There are two types of "flows" defined in S&F modeling, "material flow" and "information flow". In Figure 18 above "material flow" is the flow of births into the stock (depicted by the symbol of the "pipe" arrow with the valve), while "information flow" is the flow from the stock back to the births flow (depicted by the symbol of a regular thin arrow).

The following two examples show how a model can grow in two different directions, each focusing on different aspects of the same phenomenon.

Example 1 - figure 19 below includes the influence of deaths on the population stock. In the same way that departures influenced the stock of people in the supermarket, the deaths will cause the number of people in the population to decrease. When we think of the relationship between population and deaths, we learn that there is another cause-and-effect relationship other than the obvious one of "deaths decrease the population level". The larger a population is, the larger the number of deaths per unit time. There are several reasons for this effect, but maybe the most obvious one is that more people means more people getting older means more people dying. Other effects might be that more people means higher infection rate of deadly diseases; more people means more deadly accidents; more people means more violence etc. In line with the "insights-generating" modeling school of thought, we are not interested in mapping all the possible influences, but rather in capturing the core dynamic behavior of this system. To model the relationship between the population stock and the deaths flow, we examine the causality over time. More people will lead to more deaths, which in turn will lead to **less** people. This cause-effect-relationship is called negative feedback and is depicted in the model using an arrow that connects the population stock to the deaths flow. More in the stock leads to less in the stock. In calculus terms, this will be defined as "decreasing at a decreasing rate".

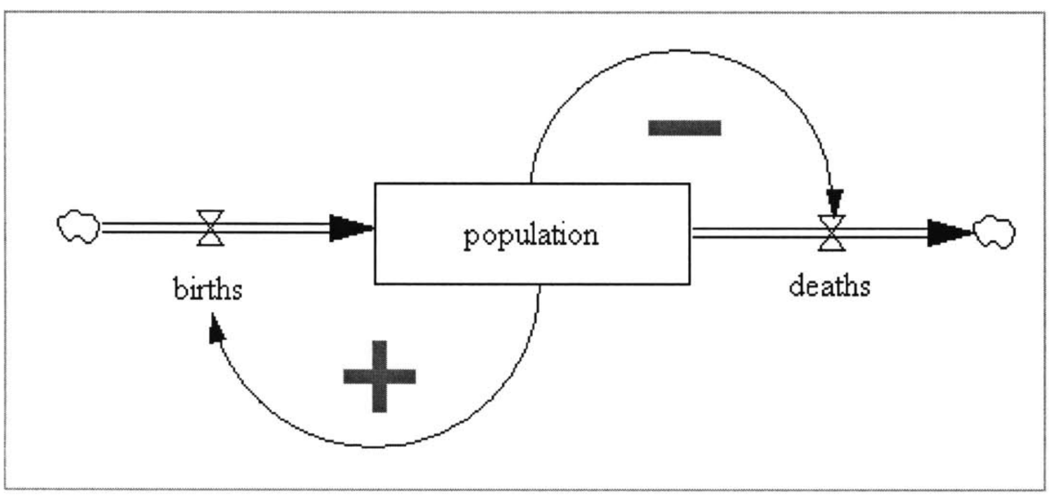


Figure 19: Positive and negative feedback in a population model

Example 2 – figure 20 below shows another possible view of population dynamics. Starting from the same model as example 1 (population and births rate), this model developed in a different direction than example 1 to model another aspect of population dynamics. When children are born, they need to mature before they can contribute to the births rate. In this model the population is separated into two different levels, adults (people biologically mature enough to contribute to the birth process) and children (people too young to contribute to the birth process). In this case, the positive feedback we had in the previous model (between population and births rate) connects between the "Adults" level and the births rate into the "Children" level. A new negative feedback exists between the "Children" level and the "Children Maturing" rate, because more children leads to more children maturing, which in turn leads to less children. We can see that in the same way that in example 1 more people leads to less people (because of the deaths rate), in this case more children leads to less children (because of the children maturing rate).

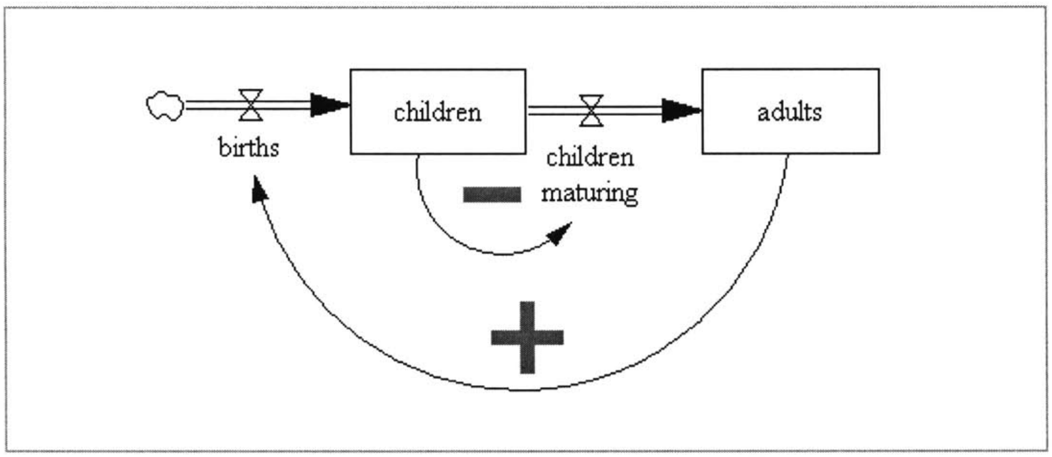


Figure 20: A simple maturing population model

A.3 Variables

When equations are added to a model, the equation parameters can be "hard-coded" as part of the equation. For example, in a population model, the "births" equation can have the form of: BIRTHS = 0.2 * POPULATION, when 0.2 is the birth rate fraction, or birth rate factor. In a specific population, this factor can be measured from historical data and added to the equation. This method can be effective for specific scenarios with historical data, but is insufficient in most cases. In programming languages, variables can be used to allow real-time interaction with procedures or functions. In the same way, Variables are used in Stock and Flow modeling to send data into equations in real-time. Figure 21 shows the same population model as in figure 19 above, but with two variables as inputs into the "births" and "deaths" flows.

In this case, the "births" equation can have the form of: BIRTHS = BIRTH RATE FACTOR * POPULATION.

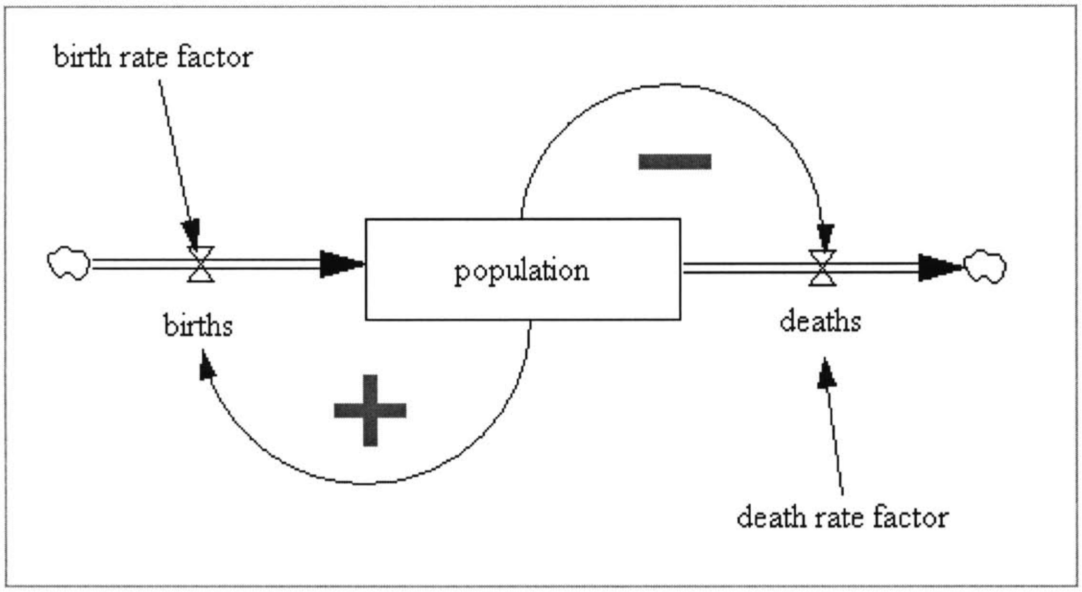


Figure 21: Variables as external input into flows

Variables can be used to send constant, user-generated, or model-generated data:

Constants would be "hard-coded" numbers that are inserted by the modeler in the model creation process. For example, in the population model above, "birth rate factor" can be set using the equation BIRTH RATE FACTOR = 0.2.

User-generated data would be user-interface gadgets in the form of sliders or dials that enables viewers of the simulated model to interact with the variable values in real-time, and therefore interact with the model equations in real-time. This is a very powerful feature that enhances the ability to test different scenarios in a model. For example, in the population model, "birth rate factor" can be defined as a range of values between 0 and 2 with an increment of 0.1. Figure 22 shows the population model at simulation time, where a user-interface slider is automatically generated for each variable.

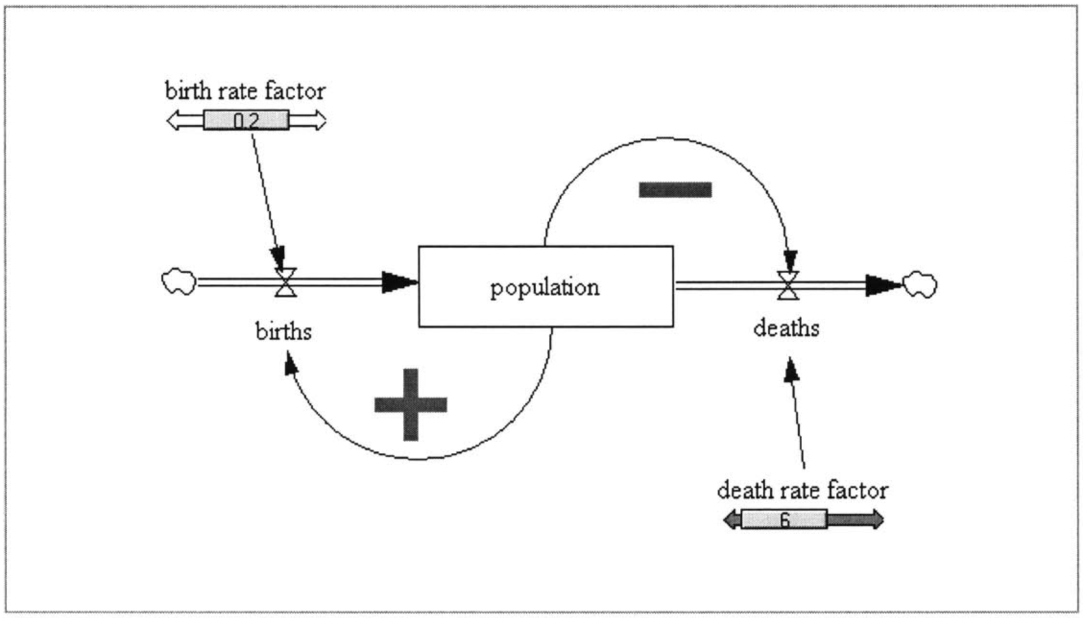


Figure 22: At simulation time, sliders enable real-time interaction with the model

Model-generated data would be variables that take other variables into account. These variables can be part of simple or complex feedback loops and are essential to the modeling process. Figure 23 shows a simple model of the positive feedback in cigarettes addiction, where the "cigarettes smoked" level affects the "need for cigarettes" variable.

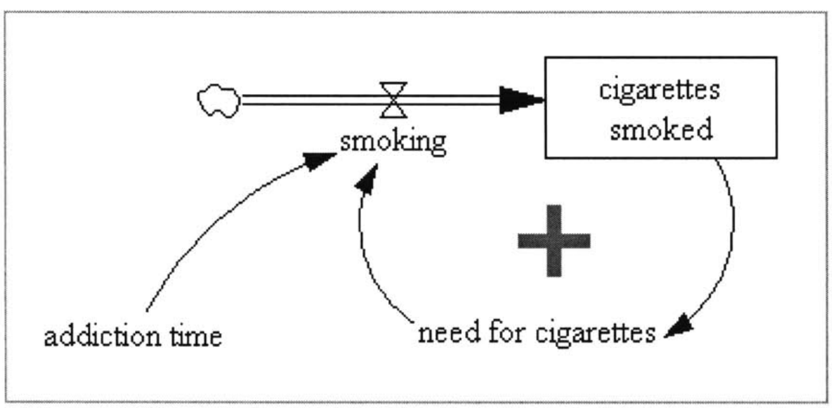


Figure 23: Variables can be part of feedback loops

A.4 Simulation

The idea behind simulation is to examine how a modeled system behaves over time. Comparing a simulated behavior of a modeled system to real-life behavior of the same system can help determine if a model is valid. Analysis makes it possible to review different scenarios or set of assumptions that have not occurred yet or cannot be checked without risk to the system stability. A simulation can generate insights about the risks or benefits of different sets of assumptions.

A graph is a convenient way to review the dynamic behavior generated by a simulated model. Graphs show the behavior of a system over time, and can help the viewers to identify trends in the dynamic behavior. Figure 24 shows two graphs generated when tracking the behavior of the "population" stock over two periods, using the simple population model above. The variables for this simulation were set as 0.125 for the "birth rate factor" and 81 for the "death rate factor" (acts as the average age level in the population).

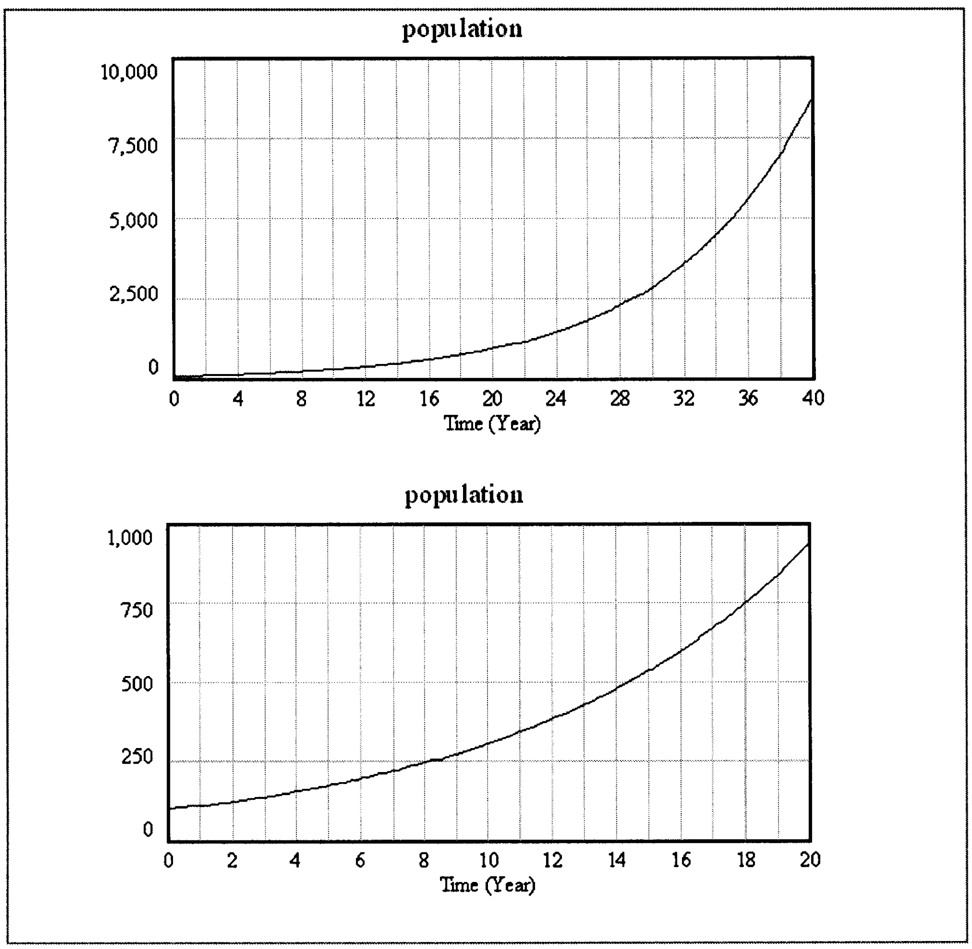


Figure 24: Population growth simulation using Vensim® over 20 and 40 years

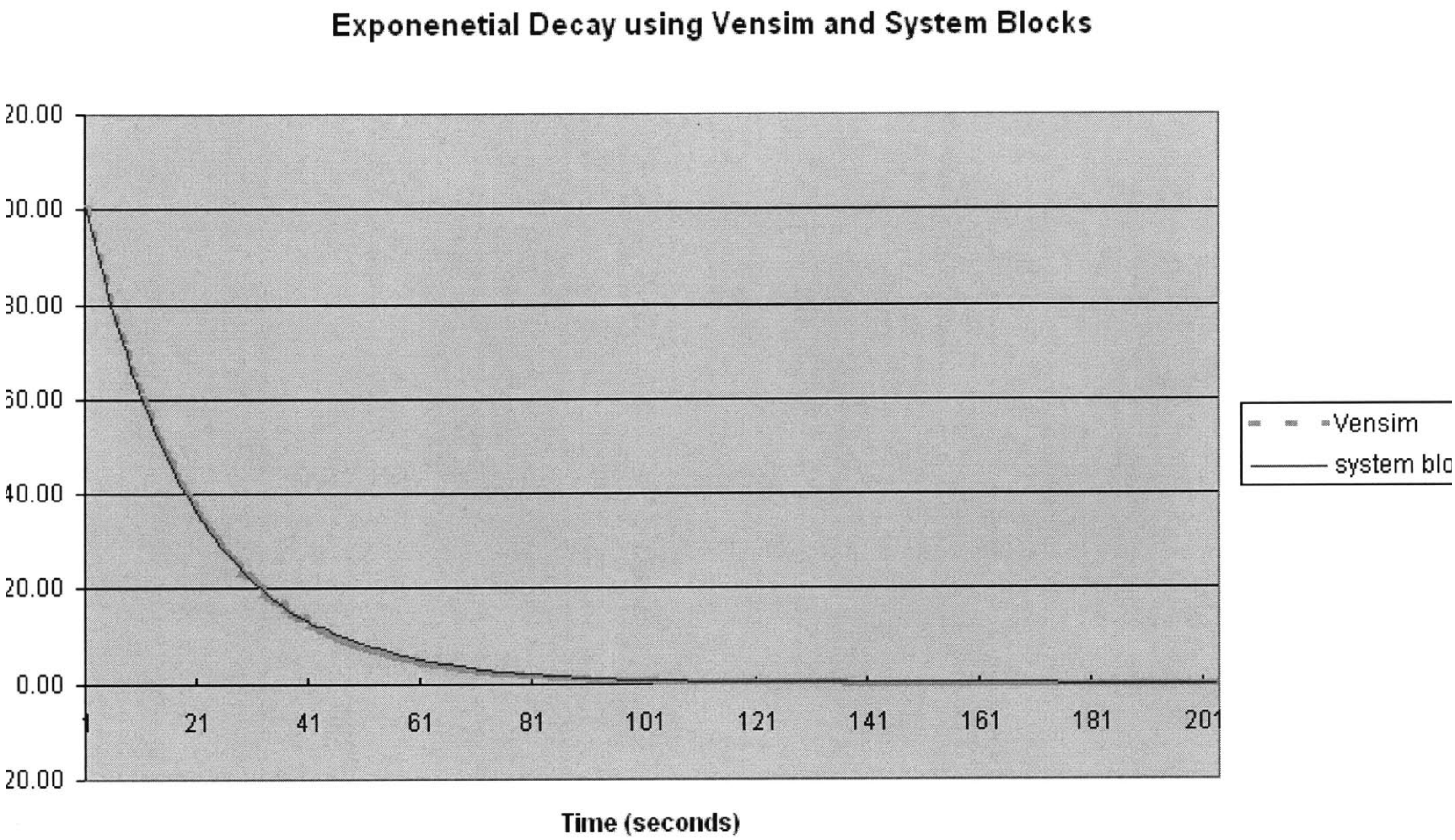


Figure 27: Exponential decay comparison, System Blocks vs. Vensim®

APPENDIX C. SYSTEM BLOCKS PCB

System Blocks 2"X2" Printed Circuit Board (SBPCB) was developed using the Eagle Layout Editor, a software tool developed by CadSoft for schematic capture and printed circuit board design.

SBPCB is based on the PIC 16F876 microprocessor and the logochip environment, developed by Bakhtiar Mikhak, Brian Silverman, and Robbie Berg (Mikhak, Silverman, Berg 2002).

The main features of SBPCB are: 16-bit number system, serial communication between boards, four input ports and two output ports, power transfer between boards, low level pin control, analog to digital sensor ports, and a convenient programming language and programming environment.

Below are pictures of the actual PCB, the top component layout, and the bottom component layout.

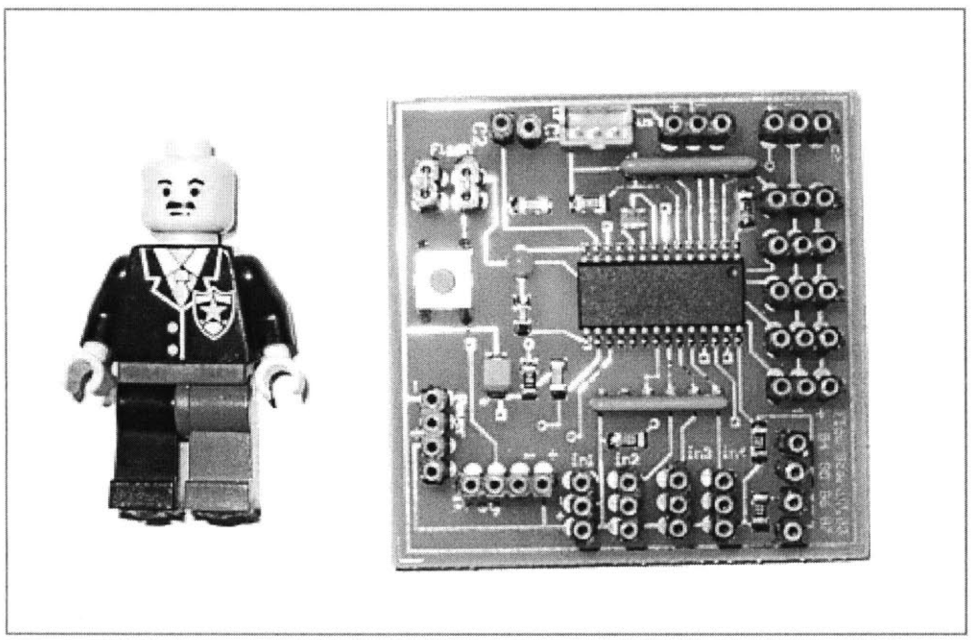


Figure 28: Picture of System Blocks PCB

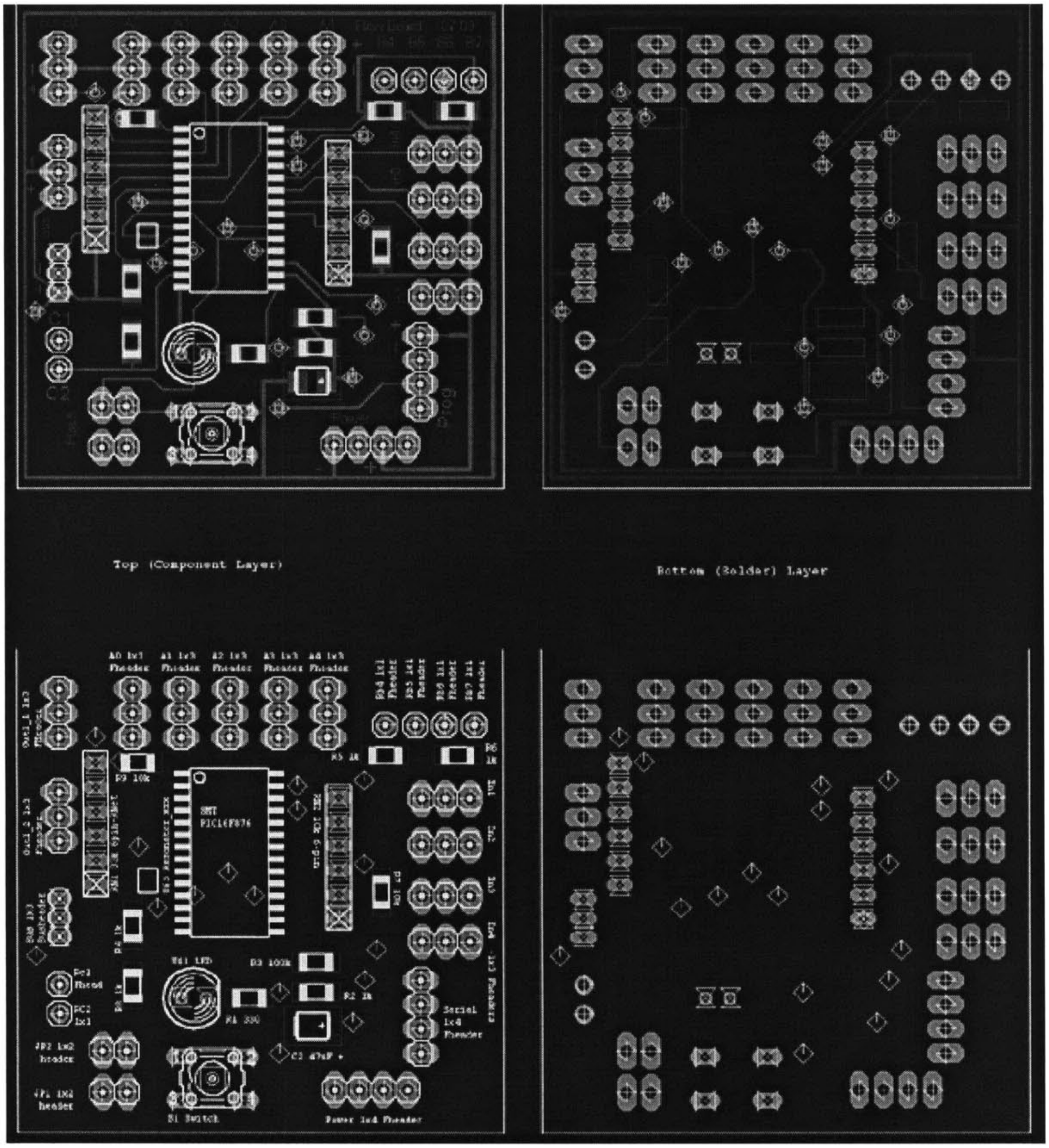
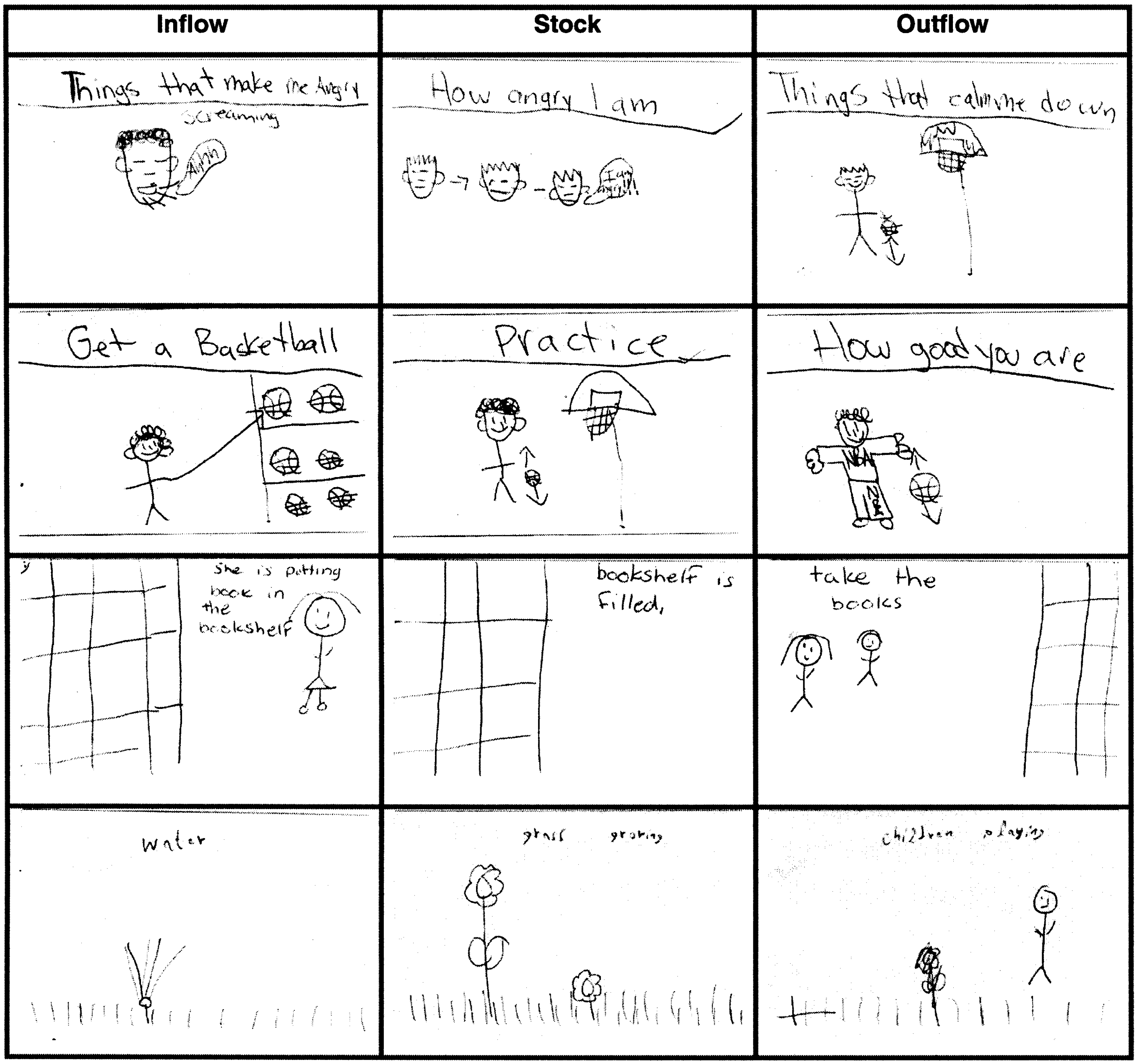


Figure 29: System Blocks PCB component layout

APPENDIX D. PICTURES OF CHILDREN'S EXAMPLES

The following are selected pictures of the systems examples generated by the 5th grade students during my interviews with them. I asked the students to think of examples that relate to their own lives, and write or draw them on blank index cards. The examples are supposed to match the system structure we simulated using System Blocks of inflow, stock, and outflow.



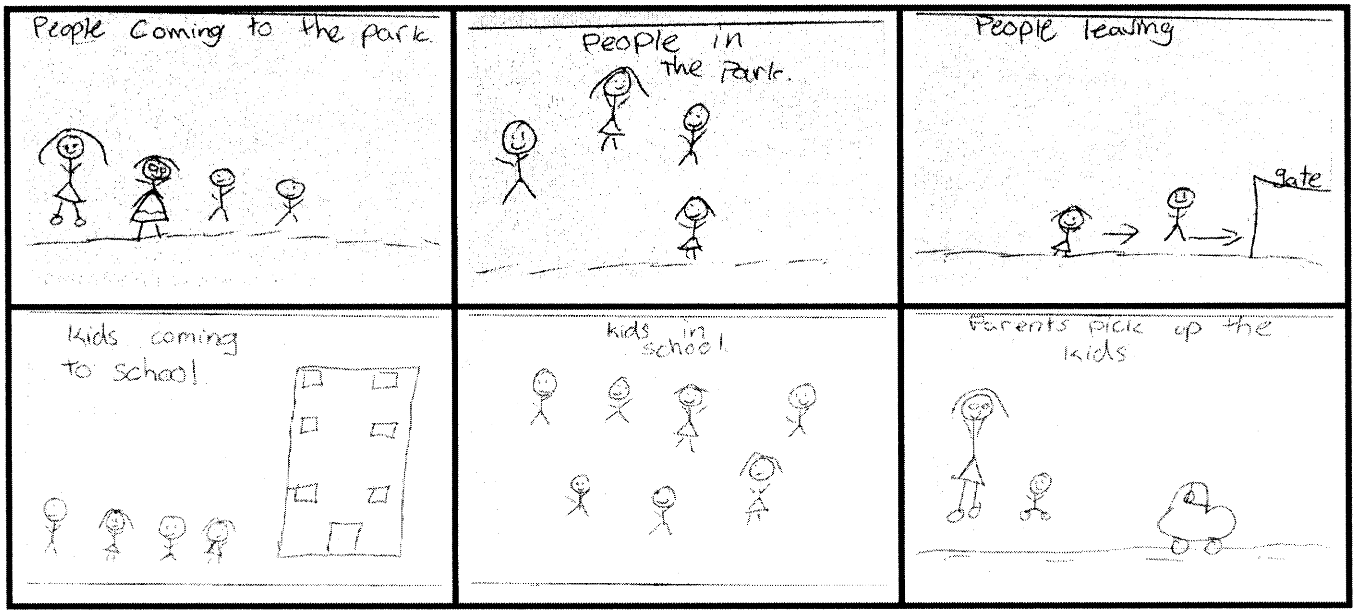


Figure 30: Drawings of systems made by 5th grade students while using System Blocks