Children's Misconceptions as Barriers to Learning Stock-and-Flow Modeling

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ABSTRACT
Research has shown that people have difficulties understanding dynamic behavior. In an attempt to better understand the nature of these difficulties, we have developed a new modeling tool and conducted an exploratory study with young children. The modeling tool, called System Blocks, is a set of communicating plastic boxes with embedded computation that facilitates hands-on modeling and simulation of stock & flow structures. In the study, 5th grade students were asked to perform several assignments with System Blocks, dealing with concepts such as rates, accumulation, net-flow, and positive feedback. Our initial findings suggest there are common patterns in the way children think about dynamic behavior, which might account for some of the difficulties children as well as adults have when faced with dynamic behavior in general and stock & flow models in particular. These patterns include a tendency to prefer: quantity over process (stock over flow), sequential processes over simultaneous processes, and inflow over outflow.

INTRODUCTION
Research has shown that people's understanding of systems behavior is extremely poor (Booth-Sweeney & Sterman, 2000; Dorner, 1989; Resnick, 1994; Sterman, 1994). Booth-Sweeney & Sterman showed that business school students have a poor level of understanding of stock & flow relationships and time delays. Dorner used computer simulations in his experiments and showed how poorly people perform when dealing with real life problems with interdependent features. He argued that people rely on a primary mechanism of "extrapolating from the moment" when dealing with temporal patterns. Resnick showed how people assume centralized control for patterns they see in the world, when in fact many phenomena are self-organizing, coordinated without a coordinator. Sterman listed the different barriers to learning that organizations face, including misperception of feedback, flawed cognitive maps of causal relations, and more. Sterman recommendations for improving the learning process include: eliciting participants' knowledge, using simulation tools, and improving scientific reasoning skills.

Existing stock & flow simulation tools such as Stella (isee systems) and Vensim (Ventana Systems) are easy to use, but not easy enough to enable novices to model without training. Building on the body of work in constructionist research (Piaget, 1972; Papert 1980, 1991; Kafai and Resnick, 1996), the approach we took is to make dynamic processes visible and manipulable through physical interaction. Towards that end, we have developed System Blocks, a new hands-on modeling and simulation tool (Zuckerman & Resnick 2003). System Blocks were designed to provide an easier introduction to systems modeling and simulation. The blocks are physical, with knobs that enable real-time interaction with a running simulation. The dynamic behavior is represented using different mediums, including moving lights, sound, and a line graph. Special attention was given to create an "equation-less" modeling process, to prevent possible barriers to learning equations might cause.

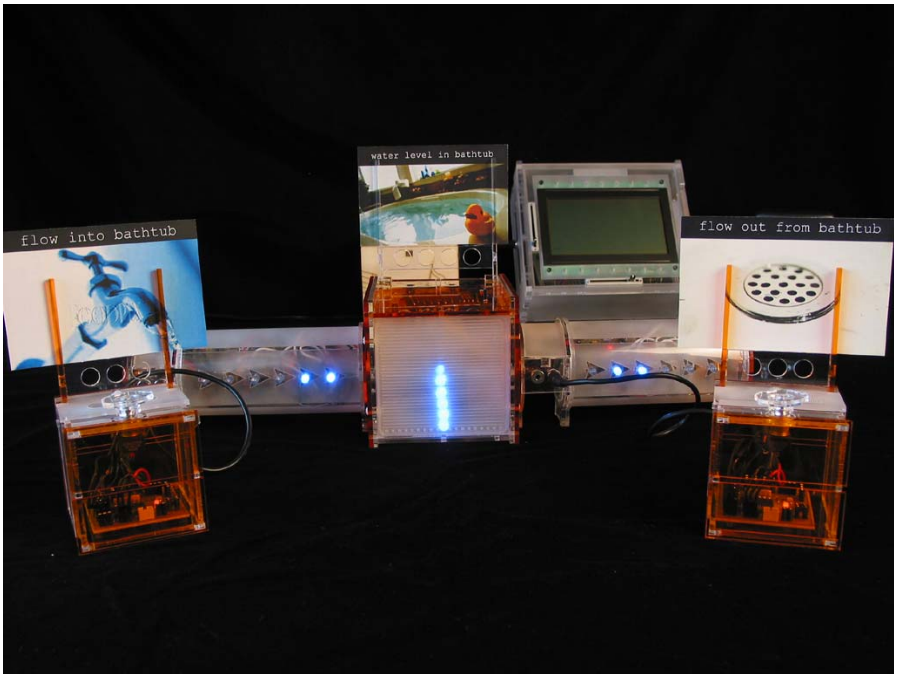

Figure 1. System Blocks simulating water flow through a bathtub

We conducted an exploratory study with ten 5th grade students. These students used System Blocks to interact with core system concepts. We conducted one-on-one interviews with the students while they used System Blocks to model and simulate systems that relate to their own lives. We observed how the 5th grade students show tendency towards sequential processes, and how the interactive simulation and the visibility of the simulated processes enabled them to recognize the simultaneous activity. In the same way, we observed how they interact and adapt their theories about concepts such as inflow, outflow, stock, net-flow, and positive feedback.

Based on our study we report on several misconceptions and tendencies, with regards to young children's understanding of systems concepts. In addition, we suggest two preliminary conclusions: (1) Multi-sensory representation of a system simulation can help children understand key systems concepts; for example, sound helped the children recognize rate-of-change in an accumulation process. (2) An iterative process of modeling and simulation, performed by the children themselves, might help children revise their current conception of dynamic behavior and help them adapt new theories based on their simulation experience.

Our findings are based on an exploratory study and a small sample. Nevertheless, the patterns we observed can be helpful pointers to some of the difficulties children and adults might have when trying to learn about the behavior of systems. Further study should be conducted to examine the nature of these tendencies and to further suggest practical strategies that can help people develop richer understanding of systems concepts.

EXTENDED EXAMPLE

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.

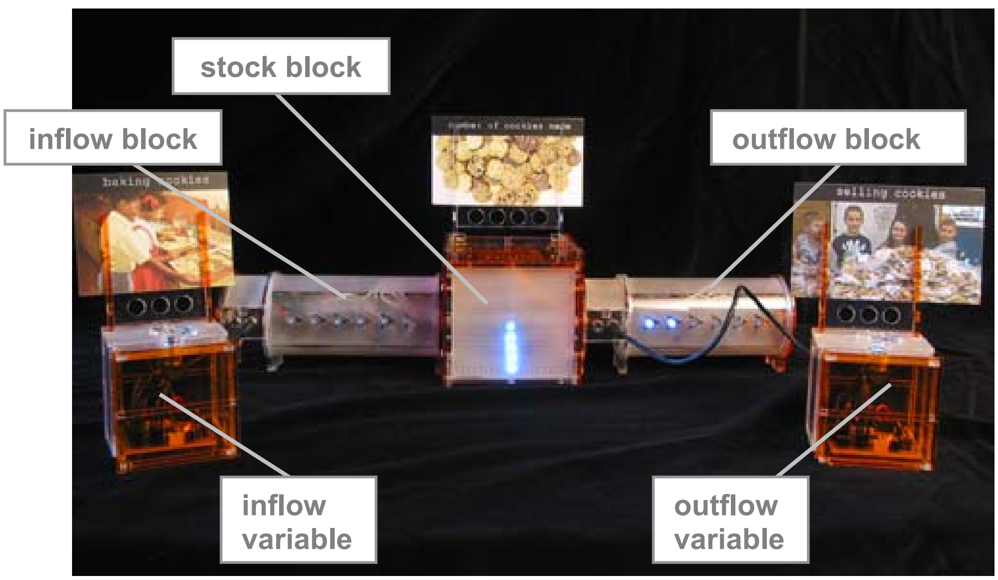

Figure 2. System Blocks simulating a "cookies store" example

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 cookies 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 can 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. In our study we have not modeled the time delay it takes to bake the cookies (“baking time”). System Blocks can model this time delay in the same way as any other stock & flow modeling tool, by adding an additional stock block for “number of cookies in oven” with a “cooking time” outflow.

METHOD AND DATA ANALYSIS

We conducted our empirical study with 5th grade students at 2 different schools: the Carlisle Public School in Carlisle, MA and the Baldwin Public School in Cambridge, MA (see Table 1). The goals of the study were to evaluate System Blocks as a new modeling and simulation tool, to surface any misconceptions children might hold about dynamic behavior, and to investigate the potential of an interactive simulation environment as a method to overcome these misconceptions.

Our research approach was a qualitative one. We used a clinical interviews approach where an interviewer presents brief, standard tasks to the students, and then probes the students' understanding based upon their response to the tasks.

The two groups of 5th grade students differ in their prior instruction in systems concepts. 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 Public 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

Table 1: Overview of schools where study was performed

The 5th grade interviews were conducted in 2 one-on-one sessions of 45 minutes each. The interviews incorporated a standard set of probes but they were loosely structured and designed to follow up on what the students said. The main activities in each interview were: (1) mapping of picture cards onto a simple inflow-stock-outflow structure. (2) Simulating the model and analyzing net-flow dynamics using moving lights and sound. (3) Analyzing net-flow dynamics using real-time line graph. (4) Analyzing models with simple positive-feedback loop. All sessions were videotaped for later analysis.

Table 3 lists some of the picture cards examples used during the sessions (both with and without positive feedback).

Inflow	Stock	Outflow
flow into bathtub 	water level in bathtub 	flow out from bathtub 
getting money 	amount of money saved 	spending money 

<table>
<tr>
<td>baking cookies
</td>
<td>number of cookies made
</td>
<td>eating cookies
</td>
</tr>
<tr>
<td>people get infected
</td>
<td>number of sick people
</td>
<td>healthy again
</td>
</tr>
<tr>
<td>hours per day spent watching TV
</td>
<td>interest in characters
interest in characters</td>
<td>doing other things
</td>
</tr>
<tr>
<td>people join the trend
people join the trend</td>
<td>number of people in the trend
number of people in the trend</td>
<td>people leave the trend
people leave the trend</td>
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Table 2: Examples of picture cards used during the sessions

OBSERVATIONS

The students reacted positively towards System Blocks as a modeling interface:

"I like the blocks much more than working on the computer. With the computer, 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 worked great."

The simulation capabilities of System Blocks were essential to the students' iterative 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 appeared as if they had 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 observed how System Blocks gives them a framework to test and revise their theories.

During the sessions I asked the students to generate their own examples. I asked them to think of examples that match the system structure we simulated of inflow, stock, and outflow. In addition, I asked them to pick examples that relate to their own lives. Table 3 lists the examples generated by the Carlisle students, and table 4 the ones generated by the Baldwin students. Table 5 lists selected pictures of the Baldwin students' examples.

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 status

Table 3: Carlisle 5th graders personal examples for real-life systems

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 book in the shelf	Bookshelf is filled	Children take the books
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 4: Baldwin 5th graders personal examples for real-life systems

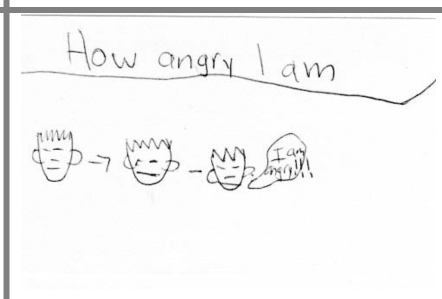
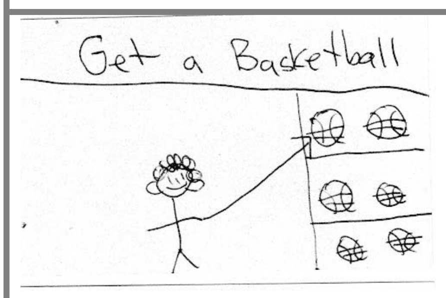
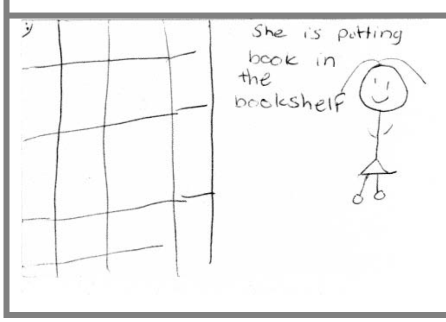
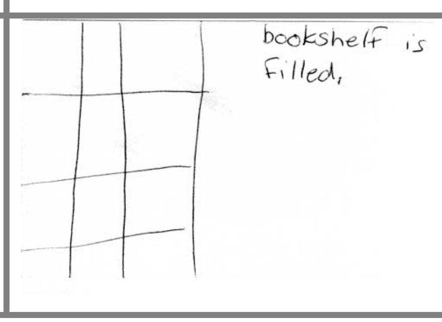
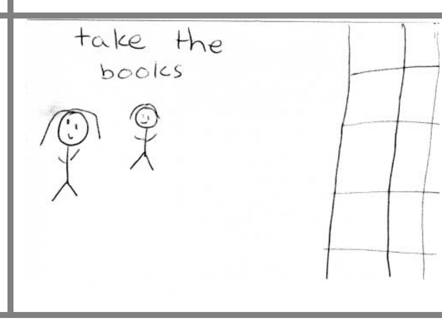
Inflow	Stock	Outflow
		
		
		

Table 5: Examples of drawings made by the Baldwin school students

Throughout the sessions we observed several misconceptions and tendencies students held about dynamic behavior in general and systems concepts in particular. Our observations are based on an exploratory study with a small sample, but nevertheless, the patterns observed might serve as helpful pointers to some of the difficulties people have when trying to learn about systems 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 over Simultaneously***: a tendency to think in a narrative way (beginning, middle, and end), A causes B then B causes C. Thinking about processes as if they happen one-at-a-time, rather than simultaneously. Occurred more with the Baldwin students (the group with no prior instruction).
- ***Quantity Over Process***: a tendency to favor quantity (something that can be counted) over process (an activity). When mapping real-life examples to Stock & Flow models, students that had this problem mixed the inflow (activity, process) with the stock (amount of something, quantity). Occurred more with the Carlisle students (the group with prior instruction).
- ***Inflow Over Outflow***: a tendency to give higher priority to the inflow rather than the outflow. When dealing with a problem, students with this tendency preferred to increase or decrease the inflow and did not pay enough attention to the outflow. Occurred more with the Carlisle students (the ones with prior instruction). When analyzing line graphs, students with this tendency connected the slope of the graph to the inflow, and completely ignored the influence of the outflow (the slope represents the net-flow, which is the difference between the inflow and the outflow). Occurred more with the Carlisle students (the group with prior instruction).
- ***Minor differences will not make a difference***: When minor differences exist between an inflow and an outflow, students ignored the change these differences would create over time, and assume the system would stay in balance or not change. No differences observed between the two student groups.
- ***Linear vs. curved***: students did not pay enough attention to the curvature of line graphs. They focused 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). This problem night be addressed by improving the way line graphs are presented to students. Teachers can pay more attention to line curvature, using computer-generated graphs when possible, and emphasize the difference between straight and curved graphs. Occurred more with the Carlisle students (the group with prior instruction).

DISCUSSION

Our findings are based on an exploratory study and a small sample, and should be regarded as such. We have showed that using System Blocks, both students with or without prior instruction in systems were capable of performing Stock & Flow modeling, simulation and analysis. Students were able to correctly map different real-life examples into Stock & Flow structures, and when errors were made, the interactive nature of System Blocks helped the students revise their models by themselves. In addition, students were able to map their own personal experiences to Stock & Flow structure. System Blocks were most effective in helping students understand the net-flow dynamics concept (that emphasizes simultaneous processes).

With regards to positive feedback, our observations suggest that 5th grade students are capable of learning feedback concepts (Zuckerman 2004). Further research should be done to prepare the relevant educational scaffolding to support learning of feedback concepts at a younger age.

Summarizing the misconceptions and tendencies, it seems that students with prior system thinking instruction had a tendency to favor inflow over outflow and quantity over process. On the other hand, they were faster to “shake off” the tendency for sequentially over simultaneously. It seems that System Blocks might help to decrease the number of misconceptions with regards to net-flow dynamics and graph curvature, if used when these concepts are introduced to students for the first time.

System Blocks offer a delicate integration of tangible, physical representation and abstract, dynamic behavior. The blocks are tangible, but represent abstract entities. The picture cards serve as an intuitive way to create analogies, mapping the abstract entities with real-life examples. 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.

In the interviews we played a key role as the facilitator, and could have directly influence the students’ performance. We challenged the students and at the same time might have guided them. It is not clear if a student working independently can yield the same results. 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 can be in a small group setting with a teacher as the facilitator, working with the proper educational materials.

In this paper we showed 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 we have used in our interviews. Nevertheless, our exploratory study suggests that one-on-one interaction with a student using an interactive simulation tool 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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