FlowBlocks as a Conceptual Bridge Between Understanding the Structure and Behavior of a Complex Causal System

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ABSTRACT*: Complexity exists in the world all around us. While it has garnered the focus of scientists in forms such as quantum mechanics and chaos theory, complexity also exists in the every day world. For instance, in order to understand the transmission of a common cold, one needs to understand probabilistic causation, branching causal patterns, and distributed agency. In this paper we argue that students need opportunities to learn the causal concepts related to complexity and we review research in support of this assertion. We introduce a set of materials called "FlowBlocks" that are designed to give children the opportunity to explore complex causal relationships and their analogical relationships to real world systems. We go on to share exploratory research that we conducted using FlowBlocks and to discuss what the finding suggest for learning about the nature of complexity.*

Introduction: Learning About Complexity And Systems Concepts

Research shows that very young children hold fragile developing concepts related to forms of complex causality and yet, the science education literature repeatedly shows that students of all ages tend to make simplifying default assumptions about the nature of causality that undermine learning (Grotzer, 2003). The problematic nature of these assumptions is particularly evident in concepts that have obvious systems-thinking aspects, such as ecosystems relationships or the spread of disease, but can also be problematic for learning "everyday science concepts" (Grotzer, 2004).

Hmelo, Holton, and Kolodner (2000) introduced the Structure-Behavior-Function framework (SBF) in the context of complex systems. Borrowed from systems approaches to artificial intelligence (Goel & Chandrasekran, 1989), it draws distinctions between structures, functions, and behaviors of systems and the connections between them to illuminate types of reasoning about systems. According to Hmelo and colleagues (2000), *structure* refers to the actual physical structures of a system, such as the lungs and alveoli, *function* refers to the purpose of the system or subsystem, so the transport of oxygen throughout the body, and behavior refers to the *dynamic* mechanisms and processes that enable the structures to carry out their function. Hmelo and colleagues (2003) found that students were more likely to perceive the structural aspects of a system and to miss the behavioral or functional aspects.

Building on this earlier work, we hypothesize that particular kinds of learning scaffolds may help children bridge between the different SBF layers, specifically the structural and the behavioral layer. Our assumption is that people's tendency to focus on the structural layer is rooted in children's early learning of causal models. Children learn about causality from interaction with the physical world around them, acquiring knowledge through the senses. Since the senses perceive the physical, visible world, children naturally develop a good understanding of simple causal models, models that can explain children's interaction with the physical world. For example, playing with physical objects such as blocks or stones help children learn about direct cause-and-effect: one pushes the block, and the block moves. Andersson (1986) referred to this as the experiential gestalt of causation (EGC) and argued that students extend the primitive notion, learned in infancy, of an agent that physically affects an object to a sense of "the nearer, the greater the effect" to difficulties in learning various science concepts. Water, sand, and other natural materials help children refine these understandings. But the same interactions create an over-emphasis on direct, short-term, visible cause-and-effect relationships. The natural world is full of more complex cause-and-effect relationships, such as the water cycle and photosynthesis. But the processes underlying these causal relationships are invisible to the human senses. Therefore, people's intuitive reasoning is about the visible and the physical, rather than the invisible interacting processes.

FlowBlocks: New Type of Educational Technology

In exploring the question "How might scaffolding impact children's ability to grasp different levels within a system?" we introduced FlowBlocks, a learning technology designed at the MIT Media Lab (Zuckerman, Arida, and Resnick, 2005). FlowBlocks are a set of physical blocks, each with embedded computation, that snap together using magnetic connectors. Children connect the blocks in different arrangement, and then send a light signal through the blocks, creating a visible chain reaction of 'moving lights'. Just like LEGO® bricks, that help children experience how different arrangements can result in different physical structures (a house, car, train, or person), FlowBlocks help children experience how different arrangements can result in different causal structures (a linear chain reaction, circular chain reaction, reinforcing chain reaction, or probabilistic causation).

We reasoned that FlowBlocks might bridge children's intuitive reasoning about the structural layer to the more advanced reasoning about the behavioral layer. The design of FlowBlocks makes the behavioral layer visible (the moving lights), along with the structural layer (the physical blocks), so children can acquire new causal-models and develop a new intuition in a gradual process, at their own pace, in the same way that an infant learns about direct cause-and-effect through play with physical objects. In part, whether or not children are able to learn about systems using FlowBlocks depends upon their ability to see them analogically—as more than just a set of blocks, but as a structural and/or behavioral analogy to how systems in the world work. In order to draw an analogy, one must be able to see a relationship between whole systems of connected relations and to match them—to find structural alignment (Gentner, 1983).

Methodology

Design. In order to consider how scaffolding impacted students' ability to grasp the structural, behavioral, and analogical aspects of complex systems concepts, we conducted an exploratory study focused on children's ability to make the transition between physical or structural components of a system to behavioral or processes within a system. We did not focus on how children responded to functional aspects of a system as in the earlier research (Hmelo et al., 2003).

Participants. Fourth and fifth grade students (n = 18) from an elementary school in Cambridge, MA with an ethnically and socio-economically diverse population participated in the study. The students received no formal exposure to systems-thinking or complex causality concepts. Eight fifth graders, with even representation from each gender, and ten fourth graders, with a higher representation of girls (eight girls and two boys) comprised the interviewees. Classroom teachers selected the students for participation. Teachers were asked to select students who were average achievers from those who had returned parental permission slips.

Procedure. Each student participated in one 50-60 minute session exploring FlowBlocks with one other student of the same age and gender, and an interviewer who is a graduate student at MIT. The students were paired with another student to encourage communication between them and offer a window into their thinking with minimal researcher probing. Each session was videotaped for later analysis.

The interview technique proceeded from little researcher support (highly open-ended) to increasingly scaffolded questioning. The interview was comprised of three sections as follows. In the first part of the session, the students were given a basic introduction to the blocks. The researcher told them what each block did in a technical sense and demonstrated how to connect the blocks. The students were given a limited set of blocks to start with, and new blocks were added in parallel with the students' progress. The interviewer handed the blocks to the students and said, "Let's see what you can do with the blocks." The interviewer was careful not to use terms such as "build" that would imply one type of focus (structural, for example) over others (behavioral or functional, for example). After a few minutes, the interviewer added, "Try to explore different configurations. Let me know when you are done exploring this set and ready to move on." When students said they were ready to move on, the researcher added two more blocks. The additional blocks enabled the completion of a closed shape (see Figure 1.).

Figure 1.
"Rectangle" Loop

Figure 2.
"Square" Loop

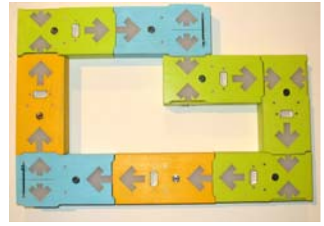

Figure 3.
"Non-Symmetric" Loop

The limitation in the blocks' design is intended to guide the students toward cyclic structures and the investigation of the behavior of circular causality. The researcher used simple, non-leading probes such as "Can you tell me about what you are doing?" or "Can you tell me about what you made?"

In the second part of the interview, the interviewer added two blue blocks, to enable the creation of more complex configuration, and said to the students, "Let's see what you can do with this set of blocks." After 10 minutes, if the students had not created the non-symmetric loop, the researcher presented a picture of one (see Figure 3), and said, "Another student made this and called it a 'circle', is this 'circle' similar or different than the previous ones you formed?" If the students only mentioned similarities, the interviewer probed for differences and vice versa.

Next, the interviewer introduced a set of analogies for the circular pattern in a given order for each set of students to see how well they could map the particular analogy. The analogies were asked in an order that started with simpler causal concepts becoming increasingly complex. For each one, the researcher asked: "Is this example similar or different to what is going on with the blocks"? The analogies were: (1) Dominoes falling over. (2) Toy train going around a track. (3) Bicycle chain. (4) Gerbil running on a wheel. (5) Water cycle. The first analogy, dominoes falling over, involves causality that is linear, sequential, and discrete. It is a type of chain reaction where there is causality local to each interaction point. The second analogy, a toy train going around a track, involves cyclic, sequential causality, where causality is local to each interaction point. The third analogy, the bicycle chain, involves cyclic simultaneous causality that is both local to the point where it is pedaled and distributed across the chain. The fourth analogy, the gerbil running on a wheel, is also cyclic simultaneous causality that is both local to the point where the gerbil is running. The final analogy, the water cycle, involves cyclic causality that is sequential in the specific example but simultaneous in a global sense, with local causality driving the pattern. We were interested in whether students would be able to map the relationship between the components of the blocks to the components of each example and what aspects of the causal relationship they picked up on.

Coding and Analysis. The videotaped sessions were transcribed, and coders worked from the transcriptions and the videotape. They were coded independently by two researchers for statements that indicated a focus on structure and on behavior of a system. The researchers coded for statements that suggested whether students were focusing on structural, behavioral, or analogical relationships and/or features of the blocks. Examples of behaviors and comments with a structural focus include:

- …building a physical structure where the lights don't work.
- …paying more attention to the notch in the block than the arrows.
- …building complex loops without testing them in terms of the light.
- …making bigger loops (but not additional loops for different behaviors).
- …"I can use it to make the letter "T."

Examples of behaviors and comments with a behavioral focus include:

- …talking about the behavior of the light. “It goes round and round.”
- …referring to the square shape as a circle or a loop (which emphasizes the behavior of the light over the physical geometric shape.
- …explicit distinctions between its geometry (“it is in the shape of a square”) and its behavior (“but it goes around in a circle.”)
- …“they are passing light to each other.”

Examples of behaviors and comments with an analogical focus include:

- …“it is kind of like a merry-go-round.”
- …”it works like a spinner board.”

The researchers also noted whether students mapped the relationship between the components of the blocks to the components of each analogy example and which aspects of causality students picked up on in their comments about the analogies.

One researcher coded 100% of the protocols. A second researcher coded a randomly selected 25% of the protocols. The scoring system was refined until initial agreement of at least 85% was reached. A second round of scoring was conducted with clarifications to the scoring rules resulting in agreement of 93%. Remaining cases were discussed until there was 100% agreement.

Findings And Discussion

Most students began by forming configurations with the blocks. Their comments suggested a clear focus on the physical, structural aspects of the blocks. In the following excerpts from the interviews transcripts, the letter ‘I’ represents the interviewer.

K: You could build a city.
T: Yeah. With the longest….the sens….
K: A giant road.
T: San Francis… Oh man, I can’t say this.
K: What?
T: San Francisco Bridge or something.
I: San Francisco?
T: Yeah, bridge.
K: Oh, the San Francisco bridge.
I: The Golden Gate.
T: Bridge.
K: Yeah, the red one?
T: And that’s the way to go.

I: What are you trying to make?
K: A square.
T: It looks kinda like a snake.
I: Like a snake?
T: A sneaky snake.
I: Ok.
T: And that’s the head.
I: Ok. It looks like a snake.
T: And those are the eyes and that’s the nose.
I: Ok.
T: And that’s the mark on it.

Interestingly, all of the student pairs did start with linear patterns. It was interesting that even though one team of girls wanted to make a circle right away, the physical creation of it was tricky for them.

As the students gained more ‘play time’ with the FlowBlocks, more students started to differentiate between the physical configuration and the behavior of the blocks. There was clear evidence that the students distinguish between the physical structure of the blocks and the patterns of the light. They were quite articulate about the difference between geometrical shapes and patterns of behavior. Some of the students also show a clear focus on the relationship between pattern and behavior. There were great terms here for distinguishing pattern from physical structure (“repeatedly”, “circulating” “self-contained”).

I: Ok. And what do you think about this shape? What would you call this one?
C: Um, a square.
I: A square?
A: A circle.
I: Circle?
C: Square or circle.
A: Well, for this it would be like a circle because…
C: Yeah, um, geometrically it’s like a square.
A: A square.
C: But if, like, we’re using circuits and stuff you would refer to it as a circle.
A: It depends on what kind of shape, because this is, like, a rectangle, and you couldn’t make a circle out of it, so it would be a circle sort of.
I: So what’s circle about it? Is it like, geometrically it’s a square, right?
C: Yeah.
I: So, but circle is still a good name for it?
C: Yeah, well if you’re only, if you’re able to talk about, like, um, how you, I don’t know how to explain it exactly. Say you wanna talk about how you’re using, um, like, circuits and batteries, you would, um….I, like… Ok, so this would be, you would say it’s a circle if you’re only talking about using a circuit or a battery or something, but… if you’re, like, if you want, if you wanna talk about, like, geometrically what shape it is you would say it was a square.
I: Ok. So if you talk about the circuit it’s a circle and if you talk about the geometrical shape it’s a square?
C: Yeah.
I: What do you think A?
A: I think it would be a circle, sort of, because you can’t really make a circle out of this shape. Geometry, like… it would be considered a square.
I: Um hmm.
A: But it’s really it would be sorta like a circle, for this matter.
I: For this matter it’s a circle?
A: Yeah.
I: Why?
A: Because it travels like that. And so, like, a circle kind of pattern.
I: Pattern? What do you mean when you say pattern?
A: Well, I mean, like, if you draw a circle it would sorta seem like you were drawing this.

K: I’m trying to make it go, make it so it can go around in a circle either way, but I could just change this completely.
S: […inaudible…]
I: Go around in a circle, you said?
K: Yeah.
S: Yeah, go around in a circle either way.
I: What do you mean, circle?
S: Well, a square actually, I think.

K: Yeah. Well, like, so it keeps going on and on and on.
S: Like we had before, but she wants it to go on so if it's…so if it goes this way it'll go around. It won't go around okay?
K: Yeah.
S: But if it goes this way it'll go around.
I: You know that when I play with people with this, some kids say circle and some kids say square. What do you think it is?
K: Well, the shape is a square or a rectangle.
S: Yeah but technically it's going around in a circle.
K: But like, a circle you think it, like, keeps going around and around forever.
S: Yeah, so…
I: So what word do you think is better to use, or what is the difference between using them?
S: Well, a square has corners and is actually going around
K: The actual shape is this.
I: Um hmm.
K: Is a square, but, um, the concept of what you wanna do is different.
S: Than what it actually is.
I: So the circle is more of the concept?
K: Yeah.
I: Like if the rectangle is a shape, so what is a circle?
S: A circle is a shape, but it's going around in a pattern that much like a circle.

Some of the students had already studied a unit on electrical circuits. Those students had a hard time seeing beyond that and were most likely to focus on the underlying mechanism of what made the blocks light, than on the actual behavior of the lights themselves. This mechanistic approach seemed to make it hard for students to use the blocks as an analogy to new situations and likewise transfer information from the blocks.

Once students began to focus on the behavior of the lights, they seldom reverted back to discussing physical structure except in contrast with behavior or in discussing the mechanics of sticking the blocks together. The point of transition for most students was the point at which they constructed a loop and the pattern in the blocks departed from a domino causality to a cyclic sequential pattern. It took students a varying amount of time to get to this point, with some of the teams making a number of configurations (all flat on the table) as with building blocks before switching to a focus on the behavioral aspects of the blocks. But once students made this switch, they pretty quickly started to explore various possibilities for creating loops.

Interestingly, there was little spontaneous generation of analogy, but students were able to analyze the analogies given with some success by noting aspects of the underlying causal forms, and were able to generate analogies when prompted. For instance, the following examples reveal some ability to map the components of the domino and cyclic relationships:

K: And, um, the light is, um… the light is like the, the… well the arrow is like the thing that hits it and the light makes it fall cause the next one…
M: Like the arrow is the domino and the light is the domino that started it.
K: That's hitting it.
M: So it keeps going. So it's like they're pushing the other one down so that if it's like in a line, if you push that one down… um, it will hit that one. So that's kind of like what the light is doing. Except it's the same thing.

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K: So it's like the train is going on the track.
M: And the green one is probably the, uh, the tracks that curve.
K: ….the light is the train that goes round and round on the tracks.

M: And the blocks are the tracks.
K: There's no end for it…. It would just keep on going round and round cause this is there and there's arrows there.

It is possible that students focused first on observing the behavioral aspects of the blocks and would only begin to make spontaneous analogies later given sufficient time to explore the behavioral aspects. An interesting extension to this study would be to give the blocks to students to play with for extended periods of time and videotape their actions to see if they move through different phases in how they play with them (beyond what was noted here with the move from physical structure to behavioral aspects). With the educational scaffolding built into the block design, the students were able to move beyond the structural level and focus on behavioral aspects of the causality within the system. This is promising given earlier research that suggests that students have difficulty moving beyond the structural features of a system. For example, using an aquarium as an ecosystem, Hmelo-Silver, Pfeffer, and Malhotra (2003) found that children and novices assumed that the role of plants in an aquarium is decorative only, that the plants are there to please the viewer--exemplifying how novices focus on the physical, visible parts of a system, or the structural level. People with greater expertise in the subject matter (such as teachers, aquarium enthusiastic, or academic experts) were able to separate between the structure and behavior levels, reasoning about the role of the plant in the aquarium and its interaction with other components.

An important extension of this work would be to consider whether the blocks could be used as scaffolds for deeper understanding of systems such as an aquarium or other ecosystems studied in school. So while the design of the blocks did help students notice behavioral aspects of the blocks themselves, the broader question of their ability to function analogically remains to be explored in greater depth and with more complex analogies and subject matter.

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