The Use of Qualitative Principles to Promote Understanding of Systems

Linsey A. Smith   **Dedre Gentner**

Department of Psychology, Northwestern University
2029 Sheridan Road, Evanston, IL 60208 USA
linsey@u.northwestern.edu
gentner@northwestern.edu

Abstract

Prior work has demonstrated that individuals have poor intuitive understanding of the principles governing the dynamics of systems, including an understanding of stocks and flows. We present pilot data that suggests that providing individuals with the qualitative principles that govern stock and flow dynamics facilitates performance in systems thinking tasks. We also discuss follow-up studies we are currently running and propose future directions for this work.

Introduction

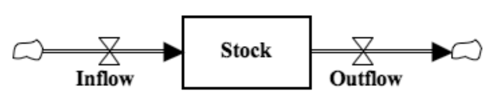
It has been argued that a prerequisite for achieving competence in a physical domain is a grasp of the qualitative principles – the laws, mechanisms, and causal relationships – that govern the domain (de Kleer and Brown 1984; Forbus 1984, 1996; Kuipers, 1994). It is this set of principles that enables one to engage in highly sophisticated reasoning about the domain. These principles need not be domain-specific, but may in fact be associated with several domains; one such set of principles are those that describe the dynamics of systems. This collection of principles, which includes concepts like stock-and-flow relationships, time delays, and simple feedback effects, is important in predicting the dynamic behavior of very disparate systems, from water flow to social dynamics.

Several experiments have assessed individuals' intuitive systems thinking skills. The results are not encouraging: highly educated subjects with extensive technical training demonstrate poor understanding of the basic principles governing systems, including the concept of *accumulation,* or the relationship between the net flow into a stock and the quantity of the stock (Booth Sweeney & Sterman, 2000; Cronin, Gonzalez and Sterman, 2009; Cronin & Gonzalez, 2007; Sterman & Booth Sweeney, 2002, 2007; Pala & Vennix, 2005). These results have been replicated with a variety of other populations (e.g., Pala and Vennix 2005). Recent work shows that performance remains poor in even simpler tasks and across a wide range of data display and response modes (Cronin, Gonzalez and Sterman, 2009).

Stock and Flow Dynamics in Systems

Stocks and flows are fundamental to the dynamics of systems (Forrester, 1961). Stock-and-flow relationships are pervasive across systems of all types, from predator/prey interactions to cash flow to greenhouse gas levels; understanding these systems – even at the most rudimentary level – requires mastering the relationship between stocks and flows. The dynamics of stock-and-flow relationships can be well approximated by a qualitative model, as shown in Figure 1. We can use the notation of Qualitative Process theory (QPT; Forbus, 1984) to describe this model (Figure 1b).

(a)



(b)
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I+(stock-amount,inflow)
I-(stock-amount,outflow)
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Figure 1. A simple stock and flow model. 1(a) depicts a stock-and-flow diagram. 1(b) expresses stock-and-flow processes in Qualitative Process theory notation.

In QPT direct influences are modeled using I+ (*Increases*) and I- *(Decreases),* which indicate a direct connection between two variables, e.g. inflow positively influences stock amount. In Figure 1(b), we use QPT notation to describe two direct influences on stock amount: the amount of stock is positively influenced by the input flow rate and negatively influenced by the output flow rate**.** Additionally, QPT notation can be used to describe the crucial relations between stock amount, inflow, and outflow: as long as the inflow exceeds the outflow, the amount of stock will increase; when inflow exceeds outflow, the amount of stock will decrease; when the inflow is equal to the outflow, the amount of stock stabilizes. These relations are translated into QPT notation in Table 1(b).

Sterman and Booth Sweeney (2002, 2007; Booth Sweeney & Sterman, 2000) tested subjects' understanding of stock-and-flow relationships by asking them to determine how the quantity in a stock varies over time given the rates of flow into and out of the stock. These studies reveal robust and highly systematic errors in reasoning: when people are given graphs indicating the inputs and outputs to a system, they often ignore accumulation and sketch the stock level as if it were simply a function of the input. Specifically, people seem to employ a *correlation heuristic* – they assume that the shape of the stock level should look like the shape of its input (Cronin, Gonzalez and Sterman, 2009). Cronin et al. (2009) demonstrate that this could not solely be explained by problems in interpreting graphs, lack of motivation or lack of cognitive capacity, and that instead, it is quite simply a failure to take into account the relationship between inflows, outflows, and stock amounts.

Mastery of stock-and-flow relationships requires a basic understanding of the principles underlying accumulation (which are briefly described above). The principles governing a domain—that is, the laws, mechanisms, and causal relationships—need to be mastered at the qualitative level to provide the foundation for deep, robust understanding. Additionally, a mastery of qualitative principles provides the necessary grounding and framework for quantitative proficiency in the same domain. The current research aims to identify strategies that may improve understanding of basic principles in system dynamics, such as accumulation. One strategy, which is our focus here, is to teach qualitative principles directly. Will explicitly providing learners with the basic relationships that govern stock-and-flow systems enable them to perform better on systems thinking tasks?

Articulating Systems Knowledge Through Graphs

In the current research, we adapt the *graphical integration* task from Booth Sweeney and Sterman (2000), which requires participants to sketch a stock amount over time given inputs and outputs to a system. Our choice to use a graph construction task was motivated by several factors. First, most advocates of systems thinking agree that much of the art of systems thinking involves the ability to represent and assess dynamic systems graphically (Booth Sweeney & Sterman, 2000), thus our graphical integration task has ecological validity. Second, graphical constructions can reveal a great deal about implicit aspects of individuals' representations of dynamic systems that may not be accessible through other means of communication like speech. Both the comprehension and construction of graphical displays and other types of diagrams requires a consistent mapping between conceptual relationships and visual features of the graph (e.g., a downwardly sloping line indicates a decreasing quantity), and a correspondence between these conceptual relationships and the referents of the graphs (e.g., a downwardly sloping line represents a decrease in the value of some stock) (e.g., Bertin, 1983; Carpenter & Shah, 1998; Gattis, 2002; Gattis & Holyoak, 1996; Hegarty, 2004; Pinker, 1990; Tversky, 2002; Tversky, Kugelmass & Winter, 1991; Zacks & Tversky, 1999). Thus, one assumption we can make is that the graphs participants draw will reasonably reflect their conceptual understanding of the relationships they are graphing.

The Current Experiment

In our initial experiment, for which we are still collecting data, we asked participants to complete several graphical integration tasks that assessed understanding of stock-and-flow relations.

Method

Participants. Nine participants from Northwestern University took part in the study individually or in groups of two. Participants completed the task in 10-15 minutes and for their time they received credit towards a course requirement.

Materials and Procedure. The experimenter gave one task booklet to the participant, and upon completion they returned the booklet to the experimenter. The booklet included five problems. Each problem consisted of a few sentences and a graph describing the behavior over time of particular variables in a stock-and-flow scenario. Participants were asked to respond by sketching a graph of the expected behavior over time of another variable in the system. Half of the participants received the list of qualitative principles shown in Table 1, the other half did not receive principles of any kind.

Table 1: Qualitative principles that describe stock-and-flow relationships (i.e., accumulation). 1(a) shows the format of the qualitative principles given to participants, 1(b) represents the same principles in QPT notation.

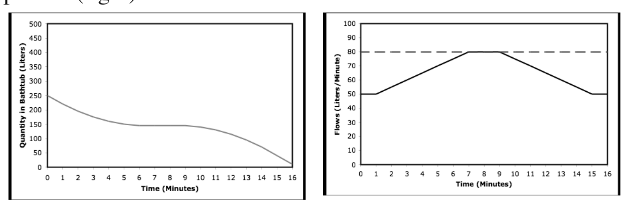
(a)	1. When the inflow exceeds the outflow, the stock is rising. 2. When the outflow exceeds the inflow, the stock is falling. 3. When the inflow is equal to the outflow, the stock is neither rising nor falling – it could be at a plateau, a peak, or a trough.
(b)	If inflow > outflow, D_s[amount(STOCK)] = 1 If outflow > inflow, D_s[amount(STOCK)] = -1 If inflow = outflow, D_s[amount(STOCK)] = 0

To make the task concrete, we introduced stocks and flows in the context of a bathtub. The task described a bathtub with water flowing in and draining out. Participants were then given three graphical integration tasks in which they had to draw the time path for the quantity in the stock (the water level in the bathtub), given the rates of inflow and outflow. They were then given two more difficult graphical integration tasks in which they were given the time path for the stock quantity and the outflow, and were asked to draw the inflow.

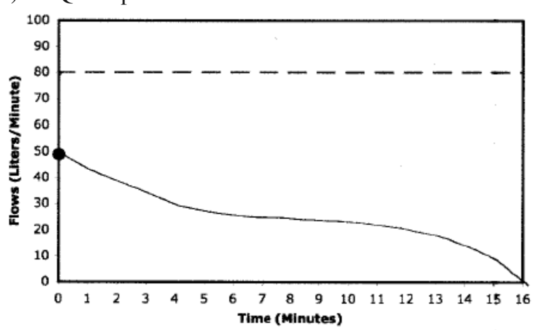
Preliminary Results

Figure 2 illustrates representative responses on the more difficult problems (i.e., drawing inflow when given outflow and stock level) from subjects who received qualitative principles (QP; Figure 2(c)) or didn't receive the principles (No-QP; Figure 2(b)), along with the correct responses (Figure 2(a)).

(a) Stock level given to participants (left) and correct inflow pattern (right).



(b) no-QP response



(c) QP response

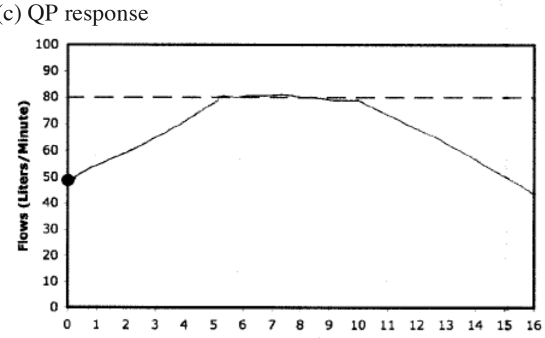


Figure 2. Responses for the difficult task. 2(a) shows the stock amount given to participants, and the correct inflow/outflow patterns. 2(b) shows a representative No-QP response; the inflow is correlated with the stock level. 2(c) shows a representative QP response; the inflow pattern is largely correct.

These sketches already reveal noticeable differences in how participants in the two conditions completed the graphical integration task. In Figure 2(b) the participant drew an inflow whose shape closely tracked the shape of the stock trajectory. This behavior suggests that the participant was basing his or her responses on a correlation heuristic, indicating a failure to take into account the contribution of outflow to the stock level. Figure 2(b) shows a typical response from a participant who received the qualitative principles. The participant draws an inflow pattern that is largely correct, suggesting that he or she understands the relationship between input, output, and stock level.

Participants in the No-QP condition did not utilize a correlation heuristic on all the problems; in fact, several of their sketches were on the whole accurate. However, examination of even their correct sketches suggests they used a very different construction process than those who received the qualitative principles. All five of the participants we thus far have run in the No-QP condition employed a point-by-point strategy (Figure 3), in which they appear to plot individual points on the graph, then connect them with a line. The margins of the pages in their booklets were also littered with equations, further supporting the idea that these participants were computing each point individually, then connecting them. Overall, it appears that No-QP participants employed a piecemeal strategy to arrive at a solution. Of course, using a pen-and-paper approach doesn't really let us identify the time course of sketch construction, so these claims are mere speculation, in the next section we propose a method that will allow us to conduct a more fine-grained analysis of participants' graph production.

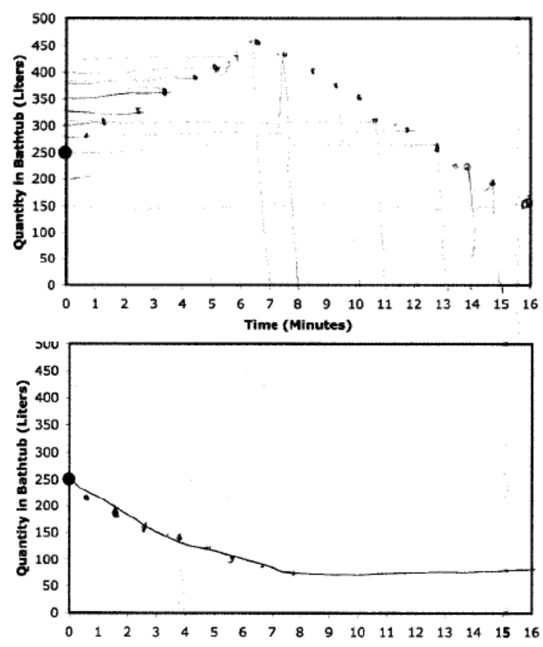


Figure 3. Sketches from two No-QP participants. Both demonstrate a point-by-point approach to constructing the graphs.

Future Work

These preliminary findings are promising. They offer encouragement for the idea that providing qualitative principles can improve individuals' representation of stocks-and-flows. However there are several limitations to analyzing sketches drawn on paper; importantly, this assessment technique only permits coarse coding of the sketches. Looking at a pen-and-paper sketch cannot reveal the time course of the sketch, e.g., which elements were drawn first, or the amount of time that elapsed between the production of different elements. We may be missing a valuable opportunity here, as some of the representational differences in individuals may be evident during the construction process in the graphical integration task. To address this issue, we are currently adapting our experiment so that sketching behavior can be captured by *CogSketch* (Forbus et al., 2008), a new sketching system. CogSketch is an open-domain, general-purpose sketch understanding system. Importantly, CogSketch records a timestamp along with every point and keeps track of erasures. This allows experimenters to examine the time sequence of events in sketching at a much finer grain than traditional methods of sketch analysis (e.g., videos) allow. By utilizing CogSketch, we can observe potential differences in the process of graphical construction that may reveal differences in representation.

Additionally, the graphical integration task is rather limited in scope. It could be the case that providing qualitative principles simply facilitates performance on our graphing task. Does this fully demonstrate understanding? In order to test whether participants who received qualitative principles indeed have a more accurate representation of stocks-and-flows, we are designing several transfer tasks. The prediction is that if participants who were given the principles posses a deeper understanding of stock-and-flow dynamics, they will demonstrate better performance on transfer tasks. We are designing both *close transfer* and *far transfer* tasks. The close transfer task is a multiple choice task that involves a textual rather than graphical response in which participants select which of several stock trajectories they believe to be most consistent with a particular inflow-outflow scenario. A far transfer task requires participants to transfer their understanding of stocks-and-flows to other domains: instead of having participants only solve problems involving water levels in bathtubs, they will be given one of two kinds of tasks: (1) graphical integration tasks or multiple choice questions assessing stock-and-flow relationships in other domains, such as cash flow or predator-prey relations or greenhouse gas emissions; or (2) analogy task where participants must identify analogous stock-and-flow relationships in other domains. Both of these tasks would enable us to identify broader learning outcomes of providing qualitative principles.

Conclusion

Prior work has demonstrated that individuals possess poor intuitive understanding of the principles governing the dynamics of systems, including an understanding of stocks and flows. We are currently investigating whether providing people with the qualitative principles that govern stock and flow dynamics facilitates performance in systems thinking tasks. Preliminary results are promising: individuals given qualitative principles demonstrated higher proficiency in a graphical integration task, whereas participants who were given the principles tended to employ a correlation heuristic (Cronin, et al. 2009), in which the pattern of inflow and stock level were closely matched, and outflow was ignored. Additionally, individuals not given the principles appeared to utilize a very different process of graph construction, which may reveal differences in representation. To more rigorously test this possibility, we are beginning to collect sketch data with CogSketch, a sketch understanding system, which will enable us to dissect the time course of participants' graph construction. Additionally, we are designing transfer tasks to identify whether providing qualitative principles leads to more robust learning.

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References

Bertin, J. 1983. *Semiology of graphics*. Madison, WI: University of Wisconsin Press.

Booth Sweeney, L. & Sterman, J.D. 2000. Bathtub Dynamics: Initial Results of a Systems Thinking Inventory. *System Dynamics Review, 16*: 249-294.

Carpenter, P.A. & Shah, P. 1998. A model of the perceptual and conceptual processes in graph comprehension. *Journal of Experimental Psychology*: *Applied, 4*: 75-100.

Cronin, M., & Gonzalez, C. 2007. Understanding the building blocks of system Dynamics. *System Dynamics Review, 23*1: 1–17.

Cronin, M., Gonzalez, C. & Sterman, J.D. 2009. Why Don't Well-Educated Adults Understand Accumulation? A Challenge to Researchers, Educators, and Citizens.

Organizational Behavior and Human Decision Processes, 1081: 116-130.

de Kleer, J. and Brown, J.S. 1984. A qualitative physics based on confluences. *Artificial Intelligence* 24(1-3): 7-83

Forbus, K. 1984. Qualitative Process Theory. *Artificial Intelligence, 24*: 85-168.

Forbus, K. 1996. Qualitative reasoning. *CRC Handbook of Computer Science and Engineering*. CRC Press.

Forbus, K., Usher, J., Lovett, A., Lockwood, K., & Wetzel, J. 2008. CogSketch: Open-domain sketch understanding for cognitive science research and for education. *Proceedings of the Fifth Eurographics Workshop on Sketch-Based Interfaces and Modeling*. Annecy, France.

Forrester, J. W. 1961. *Industrial Dynamics*. Cambridge: MIT Press; Currently available from Pegasus Communications: Waltham, MA.

Gattis, M. 2002. Structure mapping in spatial reasoning. *Cognitive Development*, *17*: 1157–1183.

Gattis, M., & Holyoak, K. J. 1996. Mapping conceptual to spatial relations in visual reasoning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*: 231–239.

Hegarty, M. 2004. Diagrams in the mind and in the world: Relations between internal and external visualizations. In A. Blackwell, K. Mariott, & A. Shimojima Eds., *Diagrammatic representation and inference*, pp.1-13. Berlin: Springer-Verlag.

Kuipers, B. 1994. *Qualitative Reasoning: Modeling and Simulation with Incomplete Knowledge*. Cambridge, Massachusetts: The MIT Press.

Pala, O., & Vennix, J. A. M. 2005. Effect of system dynamics education on systems thinking inventory task performance. *System Dynamics Review,* 212: 147-172.

Pinker, S. 1990. A theory of graph comprehension. In R. Freedle Ed., *Artificial intelligence and the future of testing*, pp. 73–126. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Sterman, J. D., & Booth Sweeney, L. 2002. Cloudy skies: Assessing public understanding of global warming. *System Dynamics Review,* 182: 207-240.

Sterman, J. D., & Booth Sweeney, L. 2007. Understanding public complacency about climate change: Adults' mental models of climate change violate conservation of matter. *Climatic Change, 80*(3-4): 213-238.

Tversky, B. 2001. Spatial Schemas in Depictions. In M. Gattis ed.: *Spatial Schemas and Abstract Thought*. The MIT Press, Cambridge: 79-112.

Tversky, B., Kugelmass, S., & Winter, A. 1991. Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology, 23*: 515–557.

Zacks, J. and Tversky, B. 1999. Bars and lines: A study of graphic communication. *Memory and Cognition, 27*6: 1073-1079.