Understanding the building blocks of dynamic systems

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Abstract

We report three empirical studies intended to clarify why individuals misperceive the relationships between stocks and flows. We tested whether familiarity with the problem type, motivation to solve the problem, or the graphical presentation of the problem affected participants' understanding of stock and flow relationships. We conclude that the misperceptions of stocks and flows are a pervasive and important problem in human reasoning. Neither the domain familiarity nor increased motivation helped individuals improve their perception of stock and flow relationships; but it seems that the graphical representation directs attention to flows and not stocks, setting the stage for subsequent mistakes. Individuals attend to the most salient points of a graph rather than comprehending the overall accumulation over time. Future research needs to investigate several aspects of the problem representations, such as the use of physical or textual rather than graphical representations. Copyright © 2007 John Wiley & Sons, Ltd.

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Introduction

Accurate perception of system dynamics is important for understanding problems that concern all of us, such as global warming (Sterman and Booth Sweeney, 2002) and overexploitation or extinction of natural resources (Moxnes, 2003). Unfortunately, there is rather pessimistic evidence regarding people's ability to perceive system dynamics correctly, which implies that the actions and policies created to deal with dynamic systems (for example, the level of pollution in the atmosphere) may be misguided.

According to Sterman and colleagues (Sterman, 2002; Booth Sweeney and Sterman, 2000) our problems with the perception of system dynamics come down to a poor understanding of the most basic principles or building blocks of dynamic systems, including stocks and flows as well as time delays. Booth Sweeney and Sterman (2000) investigated individuals' understanding of the relationships between stocks and flows by asking them to draw the quantity in the stock and how it varies over time given the rates of flow into and out of the stock. The authors presented MIT graduate students with a bathtub and asked them to sketch the path for the quantity of water in the bathtub over time, given

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the patterns for the inflow and outflow of water. Despite the apparent simplicity of this task the authors found that only 36% of the students answered correctly.

In follow-up research Sterman (2002) developed another task (see Figure 1). This task presented individuals with a graph showing the rate at which people enter and leave a department store. Individuals were asked four questions. The first two questions tested whether individuals could determine the difference between lines indicating the number entering and leaving the store (whether they could read the graph). The last two questions tested their understanding of the stock level given the flows. To determine when there is the most and the least people in the store students need to understand that the number of people in the store accumulates with the flow of people entering minus the flow of people leaving the store. In Figure 1, the most people are in the store at the point where the two curves cross. Although 94% of students answered the first two questions correctly, only 42% answered the last two questions correctly. Again, this study involved highly educated MIT graduate students.

We were intrigued by the results in Sterman and colleagues' studies, and we embarked on a set of studies aimed at understanding why people misunderstand the relationship between stocks and flows. Our purpose was to look deeper into what cognitive functions explain the problems people have diagnosing stock and flow systems. We tested whether the familiarity of the dynamic system (Experiment 1), cognitive effort (Experiment 1), computational difficulty (Experiment 2), and graphical features (Experiment 3) were responsible for the difficulty people have interpreting dynamic systems. Each of these issues has been shown to affect the performance on problem-solving tasks. Familiarity with a domain tends to lead people to construct better mental models of that system (Charness, 1991; Chi *et al.*, 1981); inducing people to think hard about a problem has also been shown to increase the quality of thinking about the problem (Petty and Cacioppo, 1986); computational complexity may overwhelm limited cognitive capacity (Simon, 1979); and finally, people can be misled by the graphical representation of a problem (Budescu *et al.*, 1988; Paich and Sterman, 1993; Pala and Vennix, 2005).

While each of these explanations seems plausible, we found that it was the graphical representation that seemed to be the source of difficulty for participants. At the same time, the lack of effect of familiarity, effort, and computational difficulty also provides clues into how people understand the nature of dynamic systems, and the nature of the thinking errors that cause their misperception.

Experiment 1

One reason it may be difficult for people to properly analyze stock and flow systems is that the cover story (people entering and leaving a store) suggests an incorrect mental model of the system, and this leads people to incorrect

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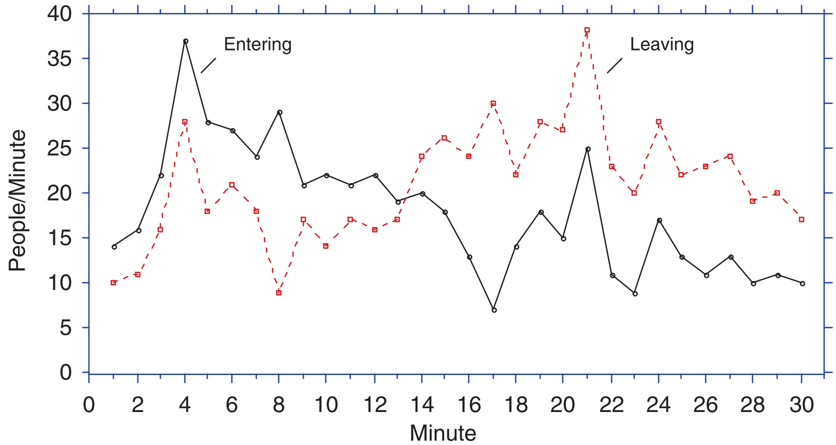
The graph below shows the number of people **entering** and **leaving** a department store over a 30 minute period.



Please answer the following questions.

Check the box if the answer cannot be determined from the information provided.

1. During which minute did the most people enter the store?

Minute ________ ☐ Can't be determined

2. During which minute did the most people leave the store?

Minute ________ ☐ Can't be determined

3. During which minute were the most people in the store?

Minute ________ ☐ Can't be determined

4. During which minute were the fewest people in the store?

Minute ________ ☐ Can't be determined

Fig. 1. Original graph found in Sterman (2002)

conclusions. One of the first steps in solving a problem is creating a *problem representation*. The representation is "a cognitive structure that corresponds to a given problem . . . constructed by the solver on the basis of domain-related knowledge and its organization" (Chi *et al.*, 1981, p. 131). The representation one creates is based on the initial perception of what the problem is. Rettinger and Hastie (2001) asked participants to decide in essentially the same probabilistic outcomes, but under a different cover story, including a straight gamble, a stock picking task, a grade, or a parking ticket. In these experiments,

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the alternate cover stories elicited distinct representations, in turn leading people to perceive the nature of the probabilistic outcome differently, and also changing the decision rules that were used. The cover story can also make certain relationships among parts of the problem easier to perceive. Kotovsky *et al.* (1985) showed how isomorphs of the Tower of Hanoi problem (i.e., problems with identical move and goal structures) were easier or harder to solve based on the attributes of the cover story. Some versions of the problem were easier for participants to keep track of and manipulate because the mental representation of the moves was consistent with people's intuitive knowledge; hence these were easier to solve.

It is possible that Sterman's (2002) task (Figure 1) suggested a representation that did not contain all the components of the system. That is, the rise and fall of people in a store is generally of small concern to people as they visit stores, and so we argue that this representation was not conducive to highlighting the stock part of that system. We therefore conceived a representation where the stock part of the dynamic system was more salient: a bank account. Note that Sterman and Booth Sweeney (2000) used a company's cash flow in one of their experiments, but we wanted to use a simpler version of this problem in an even more familiar and personally relevant context. A bank account is something that everyone will have experience with, because management of one's money is a critical function in people's lives. By giving people a dynamic system where the cover story is both intuitively familiar and where the stock was as salient as the flow, we expected people to be better able to answer questions about the behavior of the dynamic system because the mental representation created should include the stock and its relation to the flows (money going into and out of the account).

Hypothesis 1: People will be better at interpreting graphs of dynamic systems when the system represented is commonly understood in terms of stocks and flows.

Even with the right mental model of the problem, people can make errors if they put little effort into their thinking. Much work has been done on the effect of effort on information processing (Cacioppo and Petty, 1989; Chaiken *et al.*, 1989). The primary finding in this work is that the effort that goes into thinking can actually change the character of thought (Epstien *et al.*, 1996). In the stock and flow task, effort is needed because in order to deduce the level of the stock people must apply rules and knowledge to the graph. It would take effort to use "brute force" to calculate the net flow at each minute and then sum across minutes. Yet even discerning the net flow pattern may take time for people to either search their memory for the appropriate rules of calculus, or to explore the relationships between the flow lines and area between them long enough to see the pattern. At the same time, the graph has enough salient features (the flow peaks and the large net flow differences) so that using superficial cues may seem to provide answers, and if people were not thinking much

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about the problem these would seem to suffice. The conclusion is that if one does not think very hard about stock and flow problems, it is easy to get the wrong answer.

It is possible that participants in previous studies used little effort to think about the problem because the problem lacked any personal relevance or they were not prompted to think hard about it. In most persuasion research, telling a participant that their answers will be scrutinized for some self-relevant purpose induces effortful processing (Petty *et al.*, 2001). We therefore wondered if it would be possible to improve people's performance by increasing the effort they spent thinking about the problem. By doing this, we expect people to be less drawn to particular obvious features of the graph, and to spend more time discerning the relationship between the lines (and hence uncovering the stock).

> Hypothesis 2: Increased thinking effort will improve performance in understanding dynamic systems.

Methods

Eighty-one students from a private North American university were recruited via advertisements to participate in an experiment for $5. Participants ranged in age from 18 to 35 years old, were predominantly undergraduates, and approximately half were female. People were randomly assigned to one condition in a 2 (cover story: familiar, unfamiliar) $\times$ 2 (thinking effort: low and high) experimental design. All participants were able to complete the task in less than 10 minutes.

Materials and procedure

In all cases, participants were given a graph with instructions describing the graph and asked to answer four questions (the four questions presented in Figure 1). Students were given either a familiar (checking account) or an unfamiliar (store) cover story.

The description of the graph and the wording of the questions varied depending on the cover story, but the graph was identical to the original Sterman graph (Figure 1). The familiar cover story described money being put into and taken out of a checking account over 30 days; the unfamiliar cover story described people going in and out of a store over 30 minutes. Along with the graph, participants were given the four questions to answer (counterbalanced in their order of presentation). These asked: (1) when the most people [dollars] were in the store [bank account]; (2) when the fewest people [dollars] were in the store [bank account]; (3) when the most people [dollars] went into the store [bank account]; and (4) when the most people [dollars] came out of the store [bank account]. For each question, participants could answer either with the particular minute or "cannot be determined".

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In the high-effort condition students were told that their answers would be personally inspected by the researchers and used to gauge the university students' performance to those of other highly ranked schools. Conveying that participant's answers will be examined and used is a common technique in the literature on persuasion to induce effortful processing (for a review see Petty and Wegener, 1998). Individuals in the low-effort condition were not given this information.

Results and discussion

Responses to each of the questions were coded as right or wrong. Table 1(a) shows the percentage of correct responses for each of the conditions. To compare the effect of cover story and effort level on each response (when did most enter (*enter*), when did most leave (*leave*), when was most full (*full*), when was most empty (*empty*), we used a model-building approach with contrast-coded logistic regressions (Judd and McClelland, 1989) . Two tests were performed, one with and one without an interaction term. Table 1(b) displays these equations. Neither the main effects nor interaction affected the rate of success on any question.

Table 1(a). Percentage responding correctly to each question between conditions in Experiment 1

Cover	Motivation	Questions			
		Enter	Leave	Full	Empty
Store	Low	93%	93%	41%	33%
	High	89%	89%	33%	33%
Bank	Low	100%	100%	32%	29%
	High	93%	100%	43%	43%

Table 1(b). Logistic regressions for cover story and motivation predicting success on each question

	Enter		Leave		Full		Empty	
	Main effect	Interaction	Main effect	Interaction	Main effect	Interaction	Main effect	Interaction
Cover	–1.48	–0.48	–18.83	–19.12	0.15	–0.40	0.02	–0.40
Motivation	1.11	18.63	0.44	0.00	–0.13	–0.45	–0.35	–0.60
C × M		–18.19		0.44		0.77		0.60
χ^2	2.705	4.122	5.125	5.125	0.166	0.720	0.481	0.814
d.f.	2	3	2	3	2	3	2	3
p	0.259	0.249	0.077	0.163	0.920	0.869	0.786	0.846

Note: Standardized betas are given. None of the effects for cover, motivation, or their interaction are ever significant at $p < 0.05$.

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Similar to Sterman's (2002) findings, in this experiment neither effort nor the representation suggested by the cover story had any effect on the correct perception of stocks and flows. The fact that putting more effort into thinking had no effect made us wonder about the effectiveness of this manipulation. However, this manipulation has been widely (and effectively) used in persuasion research (Cacioppo and Petty, 1989; Cacioppo *et al.*, 1985; Petty and Cacioppo, 1996), so there is no *a priori* reason to assume that it would have failed in our experiment. As for the cover story, it appeared to have no effect whatsoever.

The results of the first experiment did not support our second hypothesis but did suggest a refinement of our first hypothesis—that people make mistakes because they construct an inappropriate representation of the problem. We initially thought unfamiliarity with the domain was the explanation, but it may be the visual depiction that contributes to the inappropriate representation of the problem. In the next experiment, we tested whether the visual form of the graph would affect the answers people gave.

Experiment 2

In the previous experiment, we conjectured that the story was what caused people to misinterpret the problem, and that this was the primary source of difficulty for interpreting the stock questions. In this experiment, we examined the effect of the graphical representation of the problem. In particular, we test whether the salient features of the graph, as well as the complexity of the graph, affect how people interpret the stock and flow system.

A common explanation for the difficulty with stock and flow problems is cognitive capacity: the more calculations one has to hold in working memory, the higher the likelihood of error. If this is true, then simplifying the graph should improve participant performance. In the previous experiment, the graph had 30 time periods with noisy flows, so there are many ways to simplify the graph. The first is to reduce the variation in the inflow and outflow. By making the rate of accumulation/depletion constant, it may make it easier for participants to discover the pattern of accumulation/depletion. On the other hand, in the previous experiment, figuring out the answer by mathematical calculation is tedious given that it would involve 30 arithmetical problems. Thus if one made the number of people entering/leaving smaller, and had fewer time periods, "doing the math" would be easier. This could lead to less error for those who chose to do the math in their head, and may make participants more willing to do the manual calculations to get the correct answers to the stock questions.

> Hypothesis 3: Participants will be more likely to discover the correct answers when there are fewer points on the graph.

While the numerical complexity of the graph may overtax working memory, it may also be that the look of the graph can be misleading. Here, the mistakes do not come from capacity but from answers that seem correct but are not. In looking at the actual answers given in the prior experiment, almost all of the wrong answers for when the store was most full/empty were either the peaks in the individual lines (points 4 and 21 in the original graph, see Figure 1) or the largest differences between flow lines (points 8 and 17 in the original graphs). Visually, these points are the most distinctive and seem to be plausible answers to the questions about the stock (e.g., to think the most people are in the store when there is the greatest difference between those who have entered and those who have left is correct for that point in time). Therefore, we thought removing the easy but wrong answers in a graph may spur people to be more reflective about their answers. Thus we gave individuals either a graph with a distractor point (a peak) or without one. Without a salient highest point, we expect people will not have an easy answer to mindlessly write down for the question about the fullness of the stock.

Hypothesis 4: Participants will be less successful interpreting the graph if it includes a distractor point.

Methods

Seventy-one students from a private North American university were recruited via advertisements to participate in an experiment for $5. Participant age, level of education, and gender were similar to those in Experiment 1, as they were drawn using the same method from the same university. People who had already participated in Experiment 1 were not allowed to participate in the present one. People were randomly assigned two graphs to analyze. Each graph came from a cell in a 2 (easy/hard) × 2 (no distractor/distractor) condition.

Materials and procedure

Participants were given two graphs of a dynamic system with instructions describing the graph, and asked to answer the four questions in Figure 1. The questions were identical to those in Experiment 1, but we always used the store as the cover story. The graphs were presented serially, and the order of presentation was counterbalanced. All participants were able to complete the task in less than 10 minutes.

The simple graphs had five points and represented a 5-minute time period. The complex graphs had 21 points and represented a 21-minute time period. Despite the difference in scale, the shape of the graphs was identical between the complex and simple conditions. We used two simple graph shapes (see Figure 2): two parallel lines that increased monotonically over the time period;

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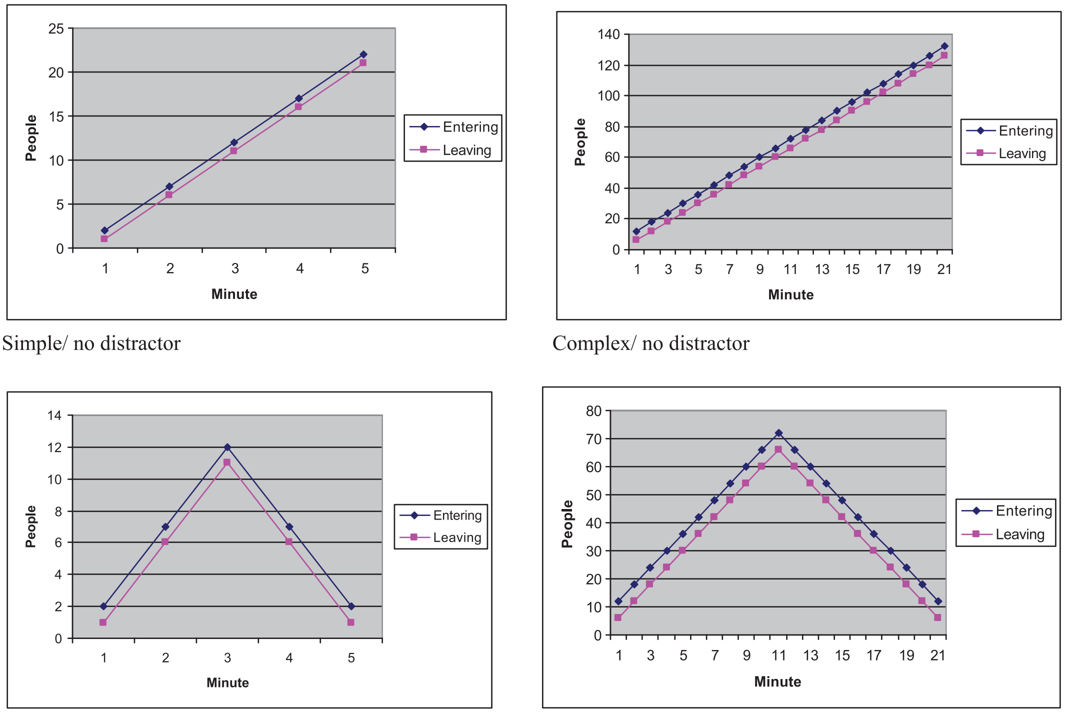

Simple/ no distractor

Complex/ no distractor

Simple/ distractor

Complex/ distractor

Fig. 2. Graphs used in each of the four conditions

and two parallel lines that increased in the first half and then decreased in the second half.

Results and discussion

The success rates for each condition are summarized in Table 2(a). To compare the effect of simplicity and having a distractor point on each response, we

Table 2(a). Percentage responding correctly to each question between conditions of Experiment 2

Shape	Complexity	Questions			
		Enter	Leave	Full	Empty
Line	Easy	97%	97%	37%	37%
	Hard	89%	89%	36%	42%
Triangle	Easy	89%	86%	36%	36%
	Hard	97%	100%	23%	31%

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Table 2(b). Logistic regressions for shape and complexity predicting success on each question

	Enter		Leave		Full		Empty	
	Main effect	Interaction	Main effect	Interaction	Main effect	Interaction	Main effect	Interaction
Shape	0.00	−1.44	−0.43	−19.37	0.32	0.64	0.00	0.21
Complexity	0.00	−1.44	−0.00	−19.12	0.32	0.64	0.24	0.44
S × C		2.89		20.82		−0.60		−0.39
χ^2	0.000	3.948	0.433	9.134	1.620	2.313	0.486	0.812
d.f.	2	3	2	3	2	3	2	3
p	1.000	0.260	0.805	0.028[1]	0.445	0.510	0.784	0.847

Note: Standardized betas are given. None of the effects for shape, complexity, and their interaction are ever significant at $p < 0.05$.
[1] The equation is significant due to the constant (not shown) which is significant a $p = .006$.

again used a model-building approach with contrast-coded logistic regressions (Judd and McClelland, 1989). Table 2(b) displays these equations. Neither the main effects nor interaction affected the rate of success on any question.

Once again, the rates of success are similar to the original Sterman task, and for the most part no differences were found among conditions. However, an interesting finding is that in Experiment 1 about 11% of the participants answered "cannot be determined" on the "stock" questions (questions 3 and 4). In this experiment, the rate jumped to 56% when the lines were parallel. We think this is the most significant finding of the present experiment.

This experiment showed that the look of the graphs has an effect on how people answer the questions, but it was not in the way hypothesized. What we failed to anticipate was that the highest point for the inflow or outflow (minute 3/11 in the apex condition or minute 5/21 in the line condition—see Figure 2) meant choosing the same point for when the stock was most empty and most full. This means that participants would have been logically inconsistent to answer the questions as we thought they would. This is also different from the Experiment 1 graph, where two *different* time points gave themselves as likely answers to the questions about the stock (i.e., points 4 or 8 for most full, points 21 or 17 for most empty).

The logical inconsistency resulting from having the same point as the time when the stock is most and least full, we believe, is what led people to answer "cannot be determined" at almost five times the normal rate. What was also surprising was that even with five points and even with two parallel lines, people did not correctly comprehend what was happening to the stock. Both of these findings led us to conclude that the graphical representation of the stock and flow is a strongly dominant effect on the interpretation of the dynamic system. In the final experiment, we try to corroborate this theory by predicting the kinds of mistakes people will make when answering questions about the

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stock in both the original Sterman (2000) graph as well as a simple graph modified from Experiment 2.

Experiment 3

The results of the first two experiments suggest the visual depiction is a key factor in the answers given. In addition to the effect on "cannot be determined" answers described above, it seems that people also have other systematic aspects of their mistakes. Anecdotally, when people analyze the Sterman graph incorrectly, they seem to choose one of three alternate points for when the stock is most full/empty: the peak for the inflow (most full) or outflow (most empty), the place with the biggest momentary net flow difference (the gap), or "cannot be determined". This pattern is somewhat consistent with the "pattern-matching" explanation given in Booth Sweeney and Sterman (2007). Choosing "cannot be determined" is not really matching the pattern, while choosing the peak would imply "highest point = most full", and choosing the gap is a bit more sophisticated because it implies some attention to inflow vs. outflow at a moment of time.

We argue that pattern matching is a too general explanation for how people answer these questions. People make some calculations about the stock, but these are often incorrectly constructed. Also, we believe that people ignore the accumulation of the stock from previous time periods. We suggest that people's tendency to ignore information not explicitly given (Fischhoff and Downs, 1997; Ross and Creyer, 1992) is responsible for this mistake. Therefore, people will look at the difference between the inflow and outflow when thinking about the stock (that information is given in the graph), but they will ignore current accumulation in the stock. This implies people will answer in a way that is consistent with the instantaneous relationship between the flows and the stock.

Hypothesis 5: Participants who incorrectly answer the questions about the level of the stock are likely to pick the point based on the momentary difference in net flow.

We also argue that although people's understanding of the stock is diminished as they ignore the accumulation/depletion of the stock, people are nonetheless aware that a stock cannot be most full and most empty at the same time. We therefore suggest that when a graph does not have unique points for the maximum and minimum net flow, it will prompt people to increase the amount of "cannot be determined" answers. This should also corroborate that people are focusing on the momentary net flow, as one must ignore accumulation/depletion to compare across points with equal net flow.

Hypothesis 6: When there are more than two points where the maximum/minimum net flow are different, the amount of "cannot be determined" answers will be increased.

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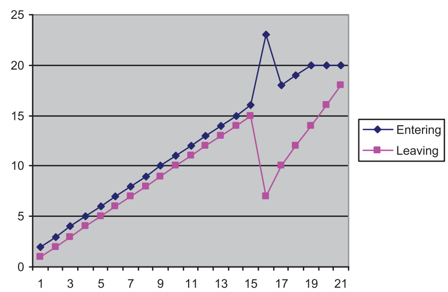
Methods

Thirty-six undergraduate students from a large North American public university participated as part of a class exercise in a senior-level management course. Students ranged in age from 21 to 45 years old; approximately one half were female.

Materials and procedure

Participants received two graphs about which they answered the same questions as in Experiments 1 and 2. The first graph was the original graph (Figure 1). Participants then received the *gap* graph (see Figure 3), where there is a single point where the gap between inflow and outflow is largest, and multiple points where the net flow was smallest.

Fig. 3. Gap graph



Results and discussion

In Hypothesis 5 we predicted that participants who incorrectly answered questions about the level of the stock would be systematic in their mistakes. That is, they would pick the point in time based on the *momentary* difference between inflow and outflow. To test this, we looked at how participants answered each Q3 and Q4. We coded their answers based on the visual description of the point chosen.

We looked at the subset of participants who did not correctly answer the stock-related questions (Q3 and Q4). We coded their answers on Q3/Q4 dichotomously: 1 if they picked the point(s) of greatest/least net difference, and 0 if they picked anything else (which was either "cannot be determined" or the peak for the corresponding flow line). In this coding scheme a success (i.e., 1) indicated consistency with our Hypothesis 5.

We compared whether the rate for picking this point was higher than 33% using a binomial test. This is the odds of picking the "net difference" point randomly from among the three choices. When answering when the most people were in the store, participants selected the time showing the

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largest positive net flow 25 out of the 30 times, and this was significant ($p < 0.001$). For the question asking when the fewest people were in the store, 16 of 31 people picked the time showing the largest negative net flow, and this was significant also ($p = 0.04$).

To test whether multiple points of equal net flow led to an increase in "cannot be determined" (CBD) answers (Hypothesis 6), we compared Q4 to Q3 on the single gap graph. There were multiple points of minimum net flow, but only one point of maximum net flow. Interestingly, the rates of CBD answers were not significantly different between Q3 and Q4 (12/23 vs. 13/23, respectively, $p = 1$ using Fisher's exact test).

Curiously, the overall rate of CBD answers for the gap graph was high (12 of 23 people put CBD for both Q3 and Q4), so we compared this rate to the rates of CBD answers found in Experiments 1 and 2 using a binomial test with the expected rates of CBD answers from each prior study (11% and 56%, respectively). We found that the CBD rate for the gap graph was significantly different from the rate in Experiment 1 with the Sterman graph ($p < 0.001$) but not from the rate in Experiment 2 with the parallel line graphs ($p = 0.87$).

The results of Experiment 3 support our hypothesis that people focus on the differences between the flows at a single point in time (Hypothesis 5). We believe that it is the preference for given information (Fischhoff *et al.*, 1978; Klein, 1999) which is at the heart of this matter. Yet the results for Hypothesis 6 merit further attention. More than one point where the net flow is maximum/minimum appears to make people more likely to erroneously assume that the stock's most/least full point cannot be determined (Hypothesis 6). But answering CBD when there were multiple points of smallest net difference between inflow and outflow tended to increase the "cannot be determined" answers for questions about when the stock is most full (which was a single point). Logically, people should perceive this difference as indicating the point where the stock is most full (as they did in the original Sterman graph), and only put CBD for when the stock is most empty. These inconsistencies may suggest that information on outflows is somehow harder to integrate than information on inflows. It may also suggest that people want to answer questions about the stock as a pair (e.g., CBD for one means CBD for the other), so that the answers are not independent.

General discussion and future research

In summary, we believe that our results suggest some ways in which graphs of dynamic systems are understood and what this implies for teaching system dynamics. The clearest finding is that the visual representation of the dynamic system is the critical source of difficulty for understanding the relationship between flows and the stock. In particular, the graphical depiction used as the baseline for this research seems to direct attention to some things (e.g., flows)

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and not others (e.g., stocks) in a particular way, and these problems set the stage for subsequent mistakes.

Our findings also suggest that people do have some understanding about the dynamics of a stock. The pattern of mistakes suggests people understand a stock is related to net flow, as Booth Sweeney and Sterman (2000, 2007) found, but also that they understand it cannot be most full and empty at the same time. It would appear that the trouble comes from how people adapt their understanding to the given graph—namely, that they look for single points where net flow is maximum or minimum, and they forget about any accumulation or depletion from before that point.

Others (Moxnes, 1998; Sterman, 1989) have explained people's pattern of response to stock and flow systems as the result of using a pattern-matching heuristic. We wonder if this is the only explanation. Looking at the actual answers given for the stock question, they were usually salient points on the graph (e.g., the smallest or biggest gap, the highest or lowest point). Yet these points are not considered in isolation. Our results suggest that people are doing some calculations about the net flow, as evidenced by people's answers in Experiment 3. If people were only matching patterns, we would expect to see a less consistent distribution of answers to the stock questions.

Our results also qualify the notion of the "static" mental models Moxnes (1998) theorized as responsible for people's errors on stock and flow problems. Moxnes argued that people have mental models where the relationship between the components in a dynamic system are seen as fixed; in other words, people think "more X = less Y" (static) rather than "the relationship of X to Y depends on the level of X" (dynamic). In our results, we observed a different kind of "static" mental model, in particular one that does not include change over time (i.e., Stock = In − Out, rather than New Stock = In − Out + Current stock). Future research should seek to determine if people really think of the relationships in their mental model as constant or simply that they have incorrectly specified a rule for how the systems interrelate (i.e., they are aware that components are dependent on each other, but have failed to correctly "write the equation").

We also think that it is important to reinforce that our experiments found no indication that the graphs were too complicated, or that numerical difficulty was the source of the problem. First, two straight parallel lines with five data points each, which could have been solved mechanically by doing second-grade level subtraction and addition, still showed a very low (37%) success rate for questions on the level of the stock. Second, the simplest graph (two parallel lines with five points) showed a statistically equal rate of success on the questions as the original Sterman graph, which had peaks, troughs, cross-overs, and 30 points. If capacity played a role, these rates should have been different. This is important because cognitive capacity is often one of the first alternative explanations people have upon reading this research.

Taken together we would suggest that poor understanding of dynamic systems evidenced by people predicting the behavior of a stock is in part a function of

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mental encoding of the problem. In these cases, the visual stimulus seemed to have the most salience in term of the (mis)encoding of the dynamic system. While we believe domain familiarity, cognitive effort, and computational complexity can safely be ruled out, there are many other potential mechanisms that we think deserve explanation based on our results.

The first would be to discover how people are actually encoding stock and flow problems. A more detailed analysis of people's thinking patterns, potentially using protocol analysis (Ericsson and Simon, 1993), may be helpful. Alternately, one could use different kinds of physical materials and allow people to explore the stock and flow relationships using these (see Zuckerman and Resnick, 2003). One would need to focus on the initial construction of the mental representation (Hayes and Simon, 1974) to see which relations between problem components were correct or incorrect. At the same time, people may hold incorrect beliefs about the relationship of stocks to flows, as was found using the systems thinking inventory (Booth Sweeney and Sterman, 2000). Again, these prior beliefs could be tested to see if they interfere with subsequent problem encoding and solving.

The idea that people have incorrect beliefs about the relationship between stocks and flows may explain why people are not able to overcome their initial misperceptions. Alternatively, research on insight (Sternberg and Davidson, 1995) has shown how people can get stuck in their original (incorrect) problem representations. Thus, people's continued misperception may be less a matter of incorrect knowledge and more a matter of incorrect problem representation.

Finally, it may just be that the time-dependent nature of these problems is what causes the difficulty—a common theme in much system dynamics research (Sterman, 2002). Yet *how* time dependency creates difficulty in these problems is still a question with at least two possible answers. One is that most people have difficulty thinking forward more than one move or cycle. Ho *et al.* (1998) showed this using problems where the more "turns ahead" one can think through, the better a person's answer is and the more they get rewarded. They find that the modal response is for people to think ahead one move. Alternately, people also have a hard time reconciling flows over time. A common classroom problem is the "horse trading problem", which says: "Bill buys a horse from you at $100 then sells it back to you at $110, then Bill buys the same horse back from you at $120 and sells it back to you at $130. How much money did Bill make or lose?" People often get this problem wrong because they miscalculate the flow, despite it being a simple problem. Breaking down what it is about time dependency that causes people difficulty assessing flows may help in system dynamics education.

Speaking to the larger problem of how to teach system dynamics, it may be that correcting people's encoding of stock and flow problems, readjusting their current beliefs about these problems, and overcoming the inherent difficulties in understanding the nature of stocks and flows all require different methods. Only more research will tell. In the meantime, our results suggest that in all

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research it will be important to partial out the perceptual difficulties related to the interpretation of graphs from the inherent difficulties in understanding stocks, flows, and time delays. Our results say that in understanding system dynamics a picture may not be worth 1000 words.

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