Developing understanding of the carbon cycle through play with physical analogues

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Structured abstract

BACKGROUND
The issue of anthropogenic greenhouse gas emissions has been of serious concern for decades, yet little action on the issue has been taken over this period. Sterman and Booth Sweeney (2002, 2007) conducted a number of experiments designed to assess the educated public's understanding of the stock-and-flow aspects of climate change and found that there was widespread misunderstanding. We developed a series of hands-on tasks designed to address this misunderstanding. We have found that participants' graphical literacy is low, but that practical and written understanding of the problem is high, which raises many questions about experiential-task design in engineering education.

PURPOSE
The motivation of the study was to assess the value of using a physical analogue to help participants understand a simplified carbon cycle.

DESIGN/METHOD
Participants watched a short video explaining concepts related to systems principles using the carbon cycle as the case study. Participants then completed a self-guided, hands-on activity that involved building a physical system composed of tubs and pumps where the movement of water represented a simplified version of the carbon cycle. They then completed a written and graphical task related to the activity. Approximately 500 responses were collated and analysed to assess participants' understanding of the problem space.

RESULTS
We observed that the majority of participants were able to provide a reasonable practical and written response to the problem, but a large portion of participants had difficulty providing a correct graphical response. In many cases the verbal and graphical responses were inconsistent. This brings into question the validity of asserting that understanding of a problem can be accurately measured using graphical methods alone, even when the audience could be reasonably presumed to be graphically literate.

CONCLUSIONS
Based on our observations, we challenge the reliance on graphs as a method of understanding participant's mental models of simplified systems, given that our key finding is that a large portion of participants could not provide a graphical response that matched their written response. We plan to conduct another round of the hands-on activity using qualitative methods to probe participant understanding. We conclude that careful attention needs to be given to task design when attempting to assess student's mental models of causality.

KEYWORDS
Sustainability education, public perceptions, shared understanding, carbon cycle

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Introduction

The issue of anthropogenic greenhouse gas emissions has been of serious concern for decades, yet little action on the issue has been taken over this period. The risk of pushing the Earth system out of a stable state is real (Rockstrom et al 2009). This problem cuts through all disciplines, and future engineers will necessarily be involved in any solutions.

Building an Understanding of Climate Change

Sterman and Booth Sweeney (2002, 2007) conducted a number of tasks assessing the educated public's understanding of the stock-and-flow aspects of atmospheric carbon concentrations and found that there was widespread misunderstanding of the interactions involved.

We developed a simple hands-on workshop (see Figure 1) to improve participant's understanding of the carbon cycle using tubs (representing the 'stock' or 'accumulation' of carbon), pumps and pipes (representing the processes involved in the additions and removal of carbon) and water (representing the carbon). Participants were asked to model an increasing level of carbon in the atmosphere (due to increased anthropogenic additions) using the tubs-and-pumps physical analogue. Participants were then asked to complete a written and graphical task to assess their understanding of the problem.

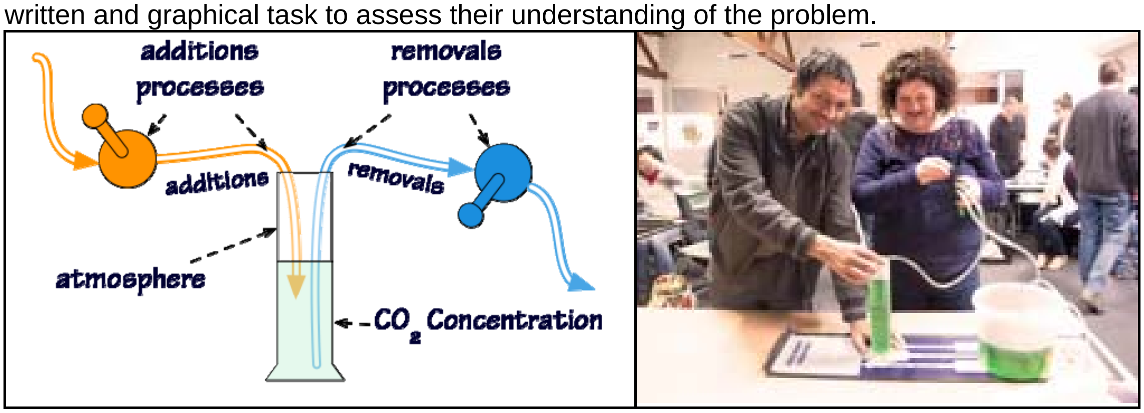


Figure 1: Left: Simplified 'Carbon' cycle constructed of tubs (stocks of carbon), pipes and pumps (carbon-flow processes) and water (carbon). Right: Participants in the Tubs & Pumps exercise (Photo courtesy of Dhitri Putri)

The model was deliberately simple, and did not incorporate causal structures such as feedback nor numerical control of flows. These factors, however, were implicit in many participant's thinking of the activity, as came out in discussions and interactions throughout the activity.

Dynamical models and STEM education

Dynamic behaviour over time and 'systems thinking' are not a significant part of STEM education in Australia, both in the K-12 and undergraduate systems. Systems thinking is an important tool in understanding complex problems, particularly problems that have dynamic complexity and changing behaviour over time. Although numerical and analytical in nature, there are no formal undergraduate or graduate degree programs in system dynamics or systems thinking in Australia.

System dynamics is based on feedback and accumulation processes . Forrester (2009) argues that "any child who can fill a water glass or take toys from a playmate knows what accumulation means", demonstrating that everyone is capable of understanding dynamical behaviour in cause-and-effect structures. There are fantastic opportunities to enrich educational programs in STEM subjects by taking a dynamical approach.

Metaphorical Understanding of Systems

Metaphors are a powerful basis for understanding in any situation (Lakoff and Johnson 1980). *Up is good, down is bad. Thumbs up, thumbs down. I'm on a high, I'm feeling down.*

Metaphors become a lot more powerful when they become the basis for understanding cause-and-effect. The *bathtub metaphor* provides a clear understanding of accumulations and processes (Sterman, 2000 and Meadows, 2009). Newell (2012) demonstrates this metaphorical mapping for understanding from the conceptual source domain (for example, water in the tub) to the conceptual target domain (an accumulation or stock) as a method of constructing powerful ideas.

The *chemical metaphor* (Lakoff and Johnson 1980: 143) brings a powerful understanding to the nature of complex problems, where elements in a problem are never 'solved' but may disappear (dissolve) from view under changed conditions. Papert (1980) describes how gears provided him with a conceptual source domain that helped him to understand abstract ideas, such as multiplication and simultaneous equations. Papert, of course, goes on to use the *turtle metaphor* as a conceptual framework for understanding geometry, physics and computer programming.

There is no coincidence that these effective metaphors have a grounding in easily understood physical experience. This is what makes them effective frameworks for building understanding. This is the basis for the use of concrete materials in early childhood education (Newell 2012).

Building Physical Analogues

The *bathtub metaphor* serves as an extremely relevant framework for thinking about stock-and-flow problems. However, the experiential nature of having a bath limits the effectiveness of the metaphor. For example, in ordinary use, the bathtub fills up once and drains once, perhaps with some intermittent flows to achieve temperature adjustment. The user would rarely conduct a dynamical experiment where the tap was on, and changing, and the drain open, and changing, whilst constantly observing the level of water in the bath.
Martinez and Stager (2013) demonstrate that hands-on learning is an effective way to construct knowledge, and they are at the forefront of a growing movement that takes Piaget's (1976) ideas on 'understanding through invention' as the basis for an approach to building understanding through hands-on making and tinkering.

Approach

Following these ideas, we have developed a manipulable physical analogue of the *bathtub metaphor*. We have dubbed this analogue 'tubs-and-pumps'. The tubs-and-pumps analogue is intended to be the conceptual source domain for understanding stocks and flows in general (the target domain). We are using it to investigate a particular research question, namely, can play with tubs and pumps help people to build a clear understanding of the effect of anthropogenic CO_2 emissions (additions) on the Earth's carbon cycle?

An initial hands-on workshop, involving experience with tubs and pumps, was designed and trialled during 2012. The workshop was run with students in four courses at the Australian National University over a 5-week period. The research had human ethics approval, and participants were briefed on ethical issues particular to the activity, particularly the anonymous collection of data. Participation was not compulsory, and did not influence participant's grades in their respective course. The workshop was designed to be completed in 45 minutes, and was conducted in tutorials in all courses. The activity required no pre-workshop instruction.

Workshop Design

When designing this experiment, a lot of care was taken to balance our need to obtain useful research results with our desire that the students gain new educational insights by completing the activity. Each workshop followed a similar format, outlined in Table 1.

Table 1: Workshop Plan

Time allocation	Activity	Prompt	Who

5 min	Introduction and discussion of ethics approval	Information sheet	Class
10 min	A simplified view of the carbon cycle	Video	Class
20 min	Selection of groups and hands-on activity	Instruction sheet, activity	Group
10 min	Questionnaire and submission	Questionnaire	Individual
Remaining time	Short presentation and open discussion	Prepared slides	Class

The key activities in the workshop were as follows:

Introduction to a simplified view of the carbon cycle

A 7-minute video describing key aspects of the carbon cycle was played at the beginning of each session (selected slides shown in Figure 2). The video described a simplified carbon cycle, and introduced participants to the activity. The video had open captions to aid comprehension.

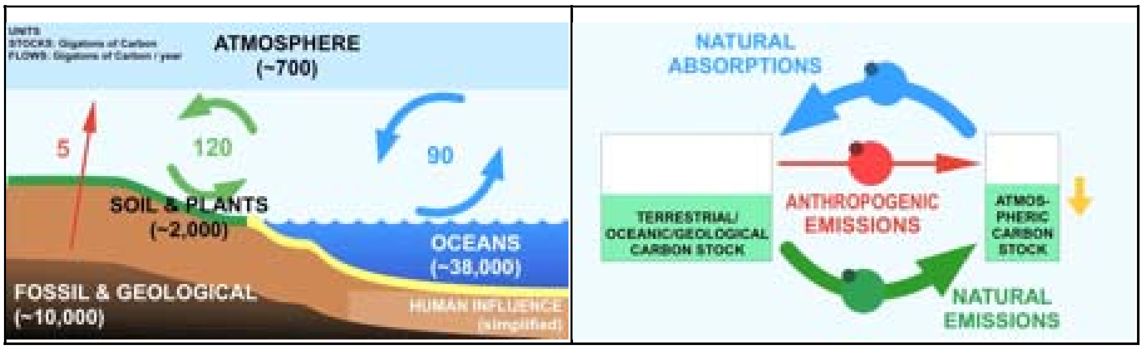


Figure 2: Frames from carbon cycle video. Left: key stocks and flows of carbon in the environment. Right: mapping of the activity to the carbon cycle

This simplified carbon cycle was mapped on to the physical analogue using tubs to represent stocks and pumps connected by pipes to represent flows. Participants were asked to operate the pumps according to protocols outlines in an instruction sheet.

Selection of groups and hands-on activity

Groups were self-selected, typically formed from participants in their immediate proximity. Roles were allocated within these groups. Roles included controlling three pumps (Natural emissions, Natural absorptions and Anthropogenic emissions) an instructor and, in groups that required a fifth person because of class numbers, an observer.

Once roles had been allocated, the facilitator ensured that each member of each group could identify their role before they began the task. Participants followed an instruction sheet, and little guidance was offered by the facilitator. Groups worked through the instruction sheet at their own pace. Groups were encouraged to explore further if they finished early, and encouraged to hurry up if they were working through the activities at to slow a pace. A questionnaire was distributed after the groups had considered their response to the problem posed in Step 7 and the individuals had returned to their tables.

Questionnaire and submission

Participants completed a one-page, double-sided questionnaire. One side asked for personal information, including: age category; gender; field/s of study; degree progress; language most comfortable communicating in; tubs-and-pumps activity group; role in the group, and; whether the participant had done the activity before. Participants were encouraged to complete this profile before completing the content questionnaire.

Participants were asked to provide a written solution to Question 1, which was a similar to scenario described above in *Step 7*:

> *Question 1: In the year 2000, the atmospheric carbon concentration was approximately 370 parts per million (ppm). Consider a situation where the Natural Emissions and Natural*

Absorptions are in dynamic equilibrium. What needs to happen to the Anthropogenic Emissions to ensure that the atmospheric GHG concentration stabilises at — and does not exceed — 400ppm by the year 2100?

Question 2 asked participants to sketch their response to Question 1 using a graph that was partially complete, shown in Figures 3-7. The graphical response derived from Sterman and Booth Sweeney (2002, 2007). Unlike Sterman and Booth Sweeney's activity, however, students undertaking the tubs-and-pumps exercise were able to draw on their hands-on experience to guide their responses.

Once participants had completed their questionnaire, responses were put into an envelope and analysed after the workshop. At this point in the workshop, a quick summary of typical responses were shown and used to motivate an open-ended discussion of the tubs-and-pumps experience.

Evaluation

Thirty-one workshops were conducted with students in a range of courses. Summary data, grouped by course, are shown in Table 2. Tutorials numbers were typically between 16 and 25 students, and the activity was conducted in groups. In total 485 responses were collected.

Table 2: Students involved in the study

Course	**Number of participants**	**Number of workshops included in the study**	**Number of groups**
Environment and Society: Geography of Sustainability	135	8	36
Systems Engineering for Software Engineers	33	2	8
Discovering Engineering	162	8	39
Systems Engineering Design	155	8	39
Total	**485**	**26**	**122**

Profile Questionnaire

The profile questionnaire was used to establish the demographics of the participants. These data are shown in Table 3.

Table 3: Participant Demographics

	Category	Count
Age	< 18	18
	18-21	391
	22-25	61
	26-30	8
	> 30	7
Gender	Male	335
	Female	144
	NA	6
Preferred Language	English	387
	Chinese	65
	Other	33

	Category	Count
Degree Progress	First Year	267
	Second Year	97
	Later Years	107
	Other	14
Degree Program	Comp Science	71
	Economics	13
	Engineering	264
	Env Science	44
	Humanities	30
	Mathematics	4
	Science	56
	Not Available	3

Note: Category counts total 485

Results

Written responses were categorised according to key words participants used to describe the task of stabilising atmospheric carbon according to their flow type (natural/anthropogenic emissions/absorptions) and the change in behaviour (increase/stabilise/decrease/decrease to zero/other). Possible responses were tabulated as shown in Table 4.

Table 4: Categorisation table of possible responses, used for each response.

	Increase	Stabilise	Decrease	Decrease to zero	Other
Natural Emissions					
Natural Absorptions					
Anthropogenic Emissions					
Anthropogenic Absorptions					

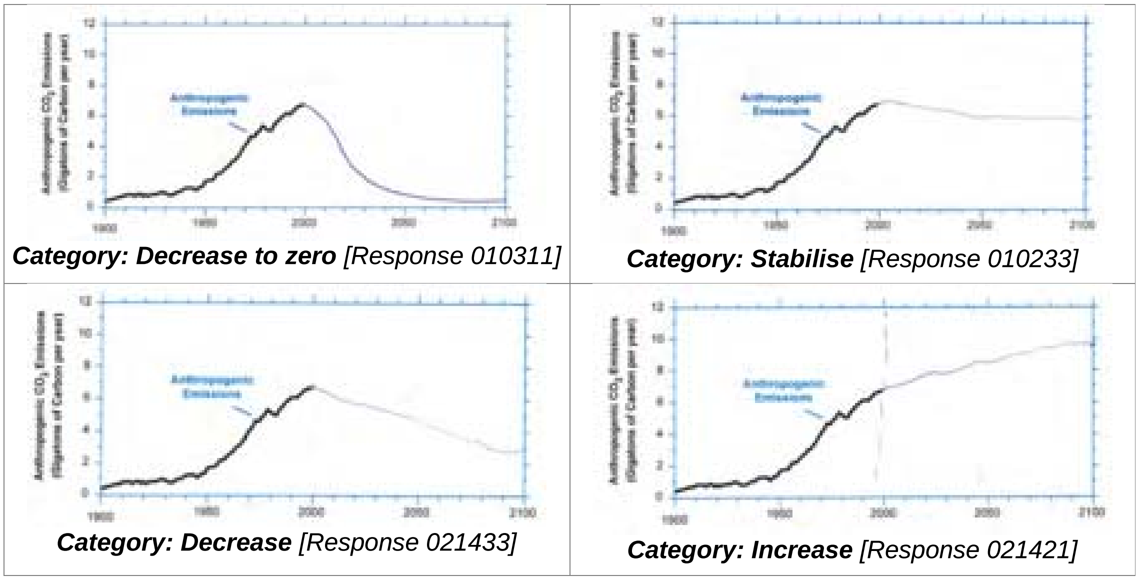
A ‘correct’ response to the scenario in Question 1, where anthropogenic emissions decreasing to zero is the primary intervention, was:

> *Keeping in mind the green water model that we used, the only action that would make the GHG concentration stabilise is the complete stop of anthropogenic emissions. [categorised as: anthropogenic emissions - decrease to zero; Response 020842]*

An ‘incorrect’ response to the scenario in Question 1 was:

Natural absorption needs to absorb at a rate equal to anthropogenic/natural emissions [categorised as anthropogenic emissions, natural absorptions, natural emissions - stabilise; Response 010312]

Graphical responses for the anthropogenic emissions task were assigned to the same five change-in-behaviour categories as the written response. Typical answers for the categories ('other' omitted) are shown in Figure 3.



Category: Decrease to zero *[Response 010311]*

Category: Stabilise *[Response 010233]*

Category: Decrease *[Response 021433]*

Category: Increase *[Response 021421]*

Figure 3: Typical graphical response categories. The 'Other' category is not represented.

In the analysis of the results, it became apparent that there were often mismatches between the written response and the graphical response. The relationship between the written response and the graphical response was categorised as: 'Matched' or 'Mismatched', and compared to the categories of graphical responses. The results are shown in Table 5, and descriptions of typical responses are provided in the Discussion.

Table 5: Categorisation of results.

	Correct Graph AE to zero	**Incorrect Graph**		**TOTAL**
		decrease	stabilise/increase	
Description Matched	**18.6%**	**29.1%**	7.1%	54.8%
Description Mismatched	0.0%	9.6%	**35.5%**	45.2%
TOTAL	18.6%	38.8%	42.6%	N=467

Note: Results that were categorised as 'Other' (18) responses are not included.

Discussion

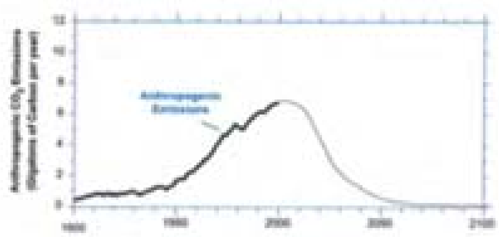
In summary the data show:.

- 83.2% of written responses were correct or partially correct (bolded in Table 5).
- 42.6% of participants drew a graph that did not show any decline in CO_2 emissions; however, a high proportion of these student's written responses were correct or partially correct.

- All students who drew a ‘correct’ graph, showing Anthropogenic Emissions reducing to zero could describe this well, suggesting that when the participant has a good understanding of the system, they can respond correctly.
- 45.2% of students could not adequately graph what they described, suggesting that either there is an issue with graphical literacy amongst the respondents, or that there was a misunderstanding of the dynamics illustrated by the task.
- 7.1% of students drew an incorrect graph, and their written responses suggest that this was intentional, suggesting that their mental model of the tubs-and-pumps system was inadequate, or incorporated additional, unarticulated considerations.
- 9.6% of students graphed a decrease in anthropogenic emissions, but provided a written response that did not match, suggesting that their mental model of the system was inadequate. It is possible that they felt that the time series should be as shown by their graph but they were not sure why.

Below is a discussion of the three categories of response that demonstrated a correct or partially correct understanding of the dynamical system.

Correct graphical response, described well (18.6% of responses)
Correct graphical responses were always described well. There were no correct graphical responses supported by mismatched descriptions. This group likely represents participants with a good mental model of the problem space. A typical response for this category is shown in Figure 4.



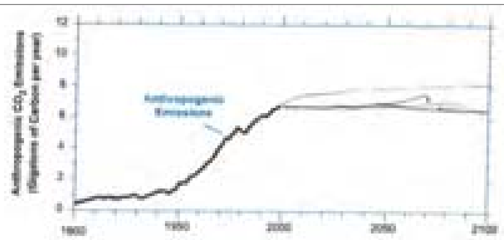
Anthropogenic Emissions to zero

Anthropogenic Emissions need to be zero in order to maintain equilibrium as stated in the short video or negative (absorption) to restore original atmospheric carbon stock.

[Response 021441]

Figure 4: Typical ‘correct’ response showing a graph tending towards zero

Incorrect graph, matching description (29.1% of responses)
This category of responses indicate a group that typically provided a response that was not graphically correct, but the description was consistent with the graph. This could indicate that participants had an inadequate mental model of the system, but either brought preconceptions to the solution (for example, “It could never reach zero”) or considered other factors in their solution, such as the possibility of a net increase in Absorption. It could also mean that the participant believed that a reduction to zero was not required. A typical response for this category is shown in Figure 5.



Anthropogenic emissions stabilising

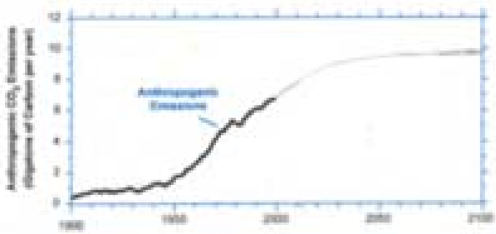
Anthropogenic Emissions needs to stop increasing each year and remain roughly the same from year to year i.e. gradient of 0

[Response 021542]

Figure 5: Typical 'incorrect' graph showing stabilisation, with a matched description

Incorrect graph, mismatched description (35.5% of responses)

This category overall represents a group of people who produced an adequate written response (for example, describing a decrease) but provided a graph where the Anthropogenic Emissions had increased. As the written response does not match the graph, it appears that this group either mistook the graph as a representation of the Atmospheric Concentration (a graphing error), or mistook a decrease in the rate of growth as reduction of atmospheric carbon levels (a mental model error). A typical response for this category is shown in Figure 6.



Anthropogenic emissions increasing

Decreasing and ultimately getting rid of anthropogenic emissions

[Response 010622]

Figure 6: Typical mismatched response showing a increase in anthropogenic emissions with a description stating that anthropogenic emissions should decrease.

Graphical literacy

One unexpected result of this study was the low level of graphical literacy evidenced. Given that the vast majority of participants could reasonably be expected to have an understanding of STEM basics, the observation that 45.2% of participants produced a 'mismatched' graph/description is surprising. The assumption that participants completing degrees in STEM topics should also be able to graph competently may be invalid. It could also demonstrate that the task given is confusing, and that a significant effort should be made, in future work, to understand the relationship between graphing ability and mental models.

This is a significant concern for all STEM-related education, especially when graphing methods are used to gauge and test student understanding. It also raises interesting questions around the role of graphical and visual responses in understanding mental models of participants.

Future work

Discussions with participants after the workshops suggest that the activity is a useful tool in helping to build understanding of very basic relationships in the carbon cycle. Building on the above observations, further work is required to discover whether the percentage of correct responses can be improved through an alternative design of the experiment and, particularly, the testing mechanism.

The high percentage of mismatched responses could also indicate that a graphical response is not a reliable method for testing a participant's mental models. Ford and Sterman (1998) discuss further testing methods, including visual and verbal descriptions. An alternative method of testing could explore a series of "what-if" scenarios to further elicit the participant's understanding of the problem.

Conclusion

Based on our observations, we have concerns about the validity of a graphical approach to assessing participant's understanding of the dynamics of simplified systems, given that our key finding is that a large proportion of participants could not provide a graphical response that matched their written response. We suggest that the activity itself was useful in understanding simplified systems, with over 80% respondents providing a written description of a future scenario that improves the current situation. Further work is required to understand the role of graphs in testing mental models, and whether alternative testing methods can elicit better representations of participant's mental models.

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