

Using a water tank analogy to transform students' intuitive knowledge of dynamic systems

A qualitative study of the case of motion

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*My main hope for this dissertation is
to inspire*

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Abstract

This dissertation is a study of the effects of a water tank analogy on students' intuitive knowledge of basic dynamic systems of motion. Prior research from science education shows that student understandings of science concepts and phenomena are frequently at odds with scientific laws and principles. Students bring to formal instruction a repertoire of intuitive knowledge of the physical world that they develop through their interpretation and assimilation of daily life experiences. These intuitive understandings are robust and appear to be strongly resistant to instruction. As a consequence, finding pedagogical tools and strategies that help students change their intuitive understandings of physics systems is currently a great concern in education research. Because it is hard to predict how teaching-tools and methods work in light of students' repertoire of intuitive knowledge, it is important to thoroughly test new teaching interventions.

Dynamic systems consist of stocks and flows. *Stocks* represent things that can be accumulated over time, and *flows* are the rates at which stocks change. In the field of System Dynamics, the stock and flow (SF) model is usually introduced through a *water tank or bathtub analogy*, and *stock and flow diagrams* (SFDs) are used as a tool for conceptualizing and representing dynamic systems. This thesis explores how students develop a scientific understanding of Newton's First and Second Law as they use the water tank analogy to make sense of motion phenomena.

The thesis takes the *Knowledge in Pieces* (KiP) approach to conceptual change as a starting point. From the KiP approach, learning for scientific understanding does not occur as the *replacement* of existing intuitive knowledge with scientific knowledge. Instead, the development of scientific understanding occurs as an *incremental transformation* of intuitive knowledge into one that is more and more consistent with scientific interpretations. Hence, a primary concern in this thesis is to understand how students' intuitive knowledge of basic dynamics of motion is transformed as students attempt to transfer the water tank analogy to motion systems. To explore this

question, we track incremental changes in students' intuitive knowledge during episodes of transfer when using the water tank analogy. To do so, we characterize intuitive knowledge in terms of small bits of knowledge called *phenomenological primitives* (p-prims), which have been previously described in the KiP literature. The purpose of this research endeavor is exploratory in nature. Our focus is not on testing binary hypothesis about whether students learn or not with the SF water tank analogy. Instead, the aim is to begin identifying and understanding the range of factors that characterizes *how* and *what* students learn with this analogy.

Tracking knowledge change as it occurs during a learning episode requires detailed data. Two sets of qualitative data were collected through individual clinical interviewing. One data set is from interviews before and after a six-weeks teaching intervention using the water tank analogy with 12 seventh graders in Colombia. The second data set is from interviews with university students during a one-hour exposure to the water tank analogy.

From these studies we find that successful transformation of intuitive knowledge does occur. We observe several learning episodes in which the water tank analogy helps students transform their knowledge of basic dynamics of motion into one that is more congruent with scientific knowledge. Students' explanations show that the tank analogy helped students find plausibility in causality and dynamic behavior of motion systems that they saw implausible before the intervention.

However, we also find that learning with the water tank analogy is complex; successful transformation of knowledge can be compromised in several ways. Our findings can be grouped into three *challenges* involved in learning with the tank analogy. First, students may attribute meanings to the analogy that differ from those intended and seen by the expert (teacher or researcher). These meanings may lead students to reject the analogy, in which case further transformation of knowledge is unlikely to occur- unless meanings are corrected somehow. Second, learning with the tank analogy occurs through a process of conflict "resolution" between competing knowledge associated with the analogy and with the motion system. The outcome of

this competition can be successful or unsuccessful transformation of intuitive knowledge. Regardless of the outcome, competition of knowledge implies that it takes time for possible learning to occur. And third, we find that in cases of competition, students can also modify their own representation of the water tank analogy to make it consistent with their existing intuitive knowledge of the motion system. In this case, transformation is unsuccessful; the analogy is modified but students' existing knowledge remains unchanged.

These findings have implications for both teaching and research. Nevertheless, the exploratory nature of the study makes the findings particular relevant for further, narrower research. In general, the aim of this dissertation is to provide a framework for future cycles of formulation and testing of teaching strategies and theories of learning with the tank analogy and other SF systems. Specifically, we provide a model for characterizing and tracking students understanding of SF systems. For teaching, we propose a step-wise program for using the SFD not only to refine students' *problematic* intuitions, but also to provoke and engage *useful* intuitions that may help learners see plausibility in SF explanations. We also identify particular generalizations made by learners of the water tank analogy. These generalizations determine what systems students perceive as analogous to the water tank. Hence, generalizations may inform the selection of SF examples that have meanings to the learners and that are congruent with what the SFD is indeed intended to represent. Moreover, our findings should help teachers identify possible pitfalls during students' interactions with SF systems, which could otherwise remain invisible.

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Introduction

“Researcher (R): What if when people are born, people are added to the tank, and when people die, people are removed from the tank? Does it work for you?

Student (S): It sounds strange. How are people going to get out of the tank? How can people go out through pipes?”

“R: What about sand?

S: No, the sand is different. The sand wouldn’t have the same ease to flow out and so the tank could never get completely empty.”

“R: What about a piggy bank?

S: No, a piggy bank only has a way in. Otherwise, it wouldn’t make sense to have your money in it.”

*Interview episodes with 7th grade students
from Medellín, Colombia.*

1. Overview

There is now a vast literature describing the difficulties students have in understanding causality and behavior of dynamic systems. In turn, this has led to an interest in methods to teach more effectively. Of key interest in this dissertation is a water tank system, which seems to be the most common *analogy* used to teach basic dynamics and to introduce *stock and flow diagrams* (SFDs). The *tank analogy* is supposed to help students transform their *intuitive knowledge* of science phenomena into one that is more consistent with science theories and principles. My focus is on transforming students’ intuitive knowledge of causality and basic dynamic behavior of *motion*. In addition to exploring the learning outcomes of using the tank analogy, I examine a range of *complexities* involved in the process of learning. I study students’

acceptance of the *plausibility* of applying the tank analogy to different systems and how they resolve *conflicts* between their understanding of the tank analogy and their existing knowledge of motion systems.

The dissertation consists of four papers:

1. Intuitive knowledge of dynamic systems: educational theory benefiting System Dynamics teaching
2. Learning with a water tank analogy: how students' intuitive knowledge of basic dynamics of motion changes during transfer
3. A case study on “reverse transfer”: when learners modify a water tank analogy to fit physics intuitive knowledge
4. Students' generalizations of a stock and flow analogy; support and hinders for transfer

In this introductory chapter I show how these papers contribute to a particular research aim. The chapter is divided into three main sections. First, I describe the general background that motivated and framed the research program. Next, I state my research questions, describe the four papers, and indicate how each of them contributes to my research aim. Finally, I discuss general issues associated with the qualitative research methods used in this study, the characteristics and validity of the data they generate, and the kind of research questions they are suitable for.

2. Background and motivation

The following is a brief account of the evolution of the rationale that motivated and framed this research project.

This research program began back in 2006 when I decided to write a Master Thesis on the learning effects of using SFDs for teaching basic dynamics in physics. Pursuing this line of research seemed as a useful contribution to two fields: Science Education and System Dynamics. In science education there is an extensive body of literature describing a multitude of intuitive and very resistant conceptual understandings of basic dynamics that students bring to school (e.g., (Clement, 1982; Clough & Driver, 1985; Johnstone, Macdonald & Webb, 1977; McCloskey, 1983; McDermott, 1984). Science education literature has also started exploring teaching methods (e.g., (Brown & Clement, 1989; diSessa, 1982; Parnafes, 2005; Roschelle, 1991)). A parallel development can be observed in System Dynamics where misperceptions of dynamics systems have been reported for different domains (Moxnes, 1998; Sterman, 1989a; Sterman, 1989b; Sterman & Sweeney, 2002; Sweeney & Sterman, 2000; Sweeney & Sterman, 2007). This led to interest in teaching methods. Also, Doyle (1997) pointed to the need of providing more rigorous scientific evidence of the effects of system dynamics tools. Later several papers have addressed the learning problem and have tested teaching interventions (e.g., (Doyle, Radzicki & Trees, 1998; Kainz & Ossimitz, 2002; Moxnes & Jensen, 2009; Moxnes & Saysel, 2009; Pala & Vennix, 2005; Phuah, 2010; Steed, 1994; Sweeney & Sterman, 2000). Building on the teaching literature and trying to contribute to the teaching of System Dynamics, the title of my Master Thesis was “*Measuring the effect of using SFDs on students’ understanding of basic dynamics of motion.*”

The choice to concentrate on *motion* phenomena was motivated by two factors. First, there is the richness of intuitive understandings of dynamic systems identified by the literature in this domain. Second, motion phenomena are described by well-established scientific theories and principles – given by Newton’s Laws. Hence, in this field there is no doubt about the underlying theory, and there are fairly well

agreed upon ideas about what knowledge students should ideally develop.

To address the research aim of the master thesis project, I designed a teaching intervention that emphasized those aspects of motion dynamics that the literature finds to be problematic for students. I exposed a group of school students to this intervention, and measured students' understanding using a standardized test on conceptual dynamics¹ before and after the intervention. The statistical results showed some improvement in students' performance. However, by the end of the study I did not understand *what* knowledge students had really acquired, or *how* the improvement in performance occurred, or even *why* the improvement was not greater. As a consequence, I was rather unable to provide insights that could be significantly useful for designing future interventions with SFDs. The results from that initial study made me realize that if I wanted to begin understanding what really happened between the pre and post tests, I had to find ways to measure *knowledge change* at a more detailed level.

When starting the PhD project, a search into learning literature in science education made me aware of work in conceptual change: the *knowledge in pieces (KiP)* approach to intuitive physics knowledge (diSessa, 1993; diSessa, Forman, Pufall & Et, 1988; Hunt & Minstrell, 1994). Among the existing approaches to conceptual change², the KiP approach seemed particularly appropriate for my purpose of *identifying and tracking specific changes in knowledge throughout a learning episode with SFDs*.

According to KiP, learners' intuitive understandings of physics systems consists of fairly diverse and basic *bits of knowledge* that learners assimilate through common experience with the physical world. These knowledge bits appear useful to the learner but they become challenging for advancing learning because they are strongly engrained and resistant to change. diSessa (1993) called these knowledge bits *phenomenological primitives (p-prims)*.

To understand better what a p-prim is, consider the following example. When a ball is kicked on the ground or a cup is pushed on a table, both objects respond in the same way: they move for a while until they finally stop. Having been exposed frequently to these familiar situations, learners establish associations between observations such as the “initial kick or push,” the “subsequent motion,” and the “final gradual stop.” Consequentially, students will often assimilate from these experiences ideas such as: “force is required for motion to persist” (*force sustains motion p-prim*), and “objects stop because velocity *simply* dies away” (*dying away p-prim*).

In addition to characterize students’ existing knowledge of basic dynamics of motion, p-prims have particular properties that reinforced my interest on SFDs as a teaching tool for knowledge change:

- (1) P-prims are triggered or cued by the learner’s perceived features of a situation, which are mostly at the level of observable behavior or physical configurations. Hence, p-prims may appear useful to predict behavior but they usually miss the explanatory structure causing such behavior.
- (2) P-prims are not necessarily correct or incorrect in themselves. Rather, incorrect understandings associated with p-prims relate to the activation and use of particular p-prims in inappropriate situations.
- (3) P-prims are not complete model descriptions; they are minimum representations of a given situation. P-prims are useful in the sense that they enable learners to explain and make predictions. However, they are so obvious to the learner that they remain rather unconscious and unproblematic, and therefore, their appropriateness is rarely put at question.

¹ Force Concept Inventory by Hestenes, Wells and Swackhamer, (1992)

As a consequence of these three properties, diSessa and other researchers argue that learning for scientific understanding consists of a gradual transformation of intuitive knowledge (Clement, Brown & Zietsman, 1989; diSessa, 1993; Osborne & Wittrock, 1985). Particularly, diSessa specifies:

- “...Understanding should evolve toward *compactness*, involving few principles that are as general as possible...adapted to do the work of interpreting diverse situations in common terms.” (diSessa, 1993, p. 190).
- Learning should provide that p-prims are subordinated to formal principles, and organized according to cuing priorities that allow them to be recalled in a *coordinated way*.” (diSessa, 1993, p. 143) – rather than being dependent on observable behavior or physical configurations cues.

These arguments inspired me to study how SFDs could support learning by constituting a compact set of scientific knowledge toward which intuitive knowledge could evolve, and how SFDs could provide a structure where useful intuitive knowledge could be placed and activated in a coordinated way. I further assumed that by characterizing the knowledge associated with SFDs into small bits of knowledge, I could track stock and flow (SF) knowledge and p-prims throughout learning episodes during a teaching intervention. In this way, rather than measuring learning based on pre- and post-test results, I could describe *what knowledge was involved and how it was changing*. The expectation being that as students learned with SFDs, their knowledge would become less and less similar to the p-prims and closer and closer to the SF knowledge bits.

Finally, since I was using a tank analogy, it was also natural to consult literature on the role of *analogies* in knowledge change (e.g., (Brown & Clement, 1989; Clement, 1993; Clement et al., 1989). Introducing SFDs through a water tank analogy, I had to

² See Vosniadou (2008) for a review of conceptual change literature.

consider that analogical reasoning involves another particular phenomenon of learning: *knowledge transfer*. Would transformation of intuitive knowledge of motion occur as students attempted to transfer SF knowledge from the water tank analogy to the context of motion? Hence, the water tank came to occupy a central role in my study of knowledge change with SFDs.

In addition to the explicit results that I was seeking in this project, I have also contributed to establish a common theoretical framework for System Dynamics and learning sciences. That has been the most challenging aspect of the project. It may also be the most important contribution of my dissertation.

3. Research questions

The following are the general research questions addressed in this dissertation. The questions explore two dimensions associated with learning with the tank analogy:

- (1) Seeing and accepting the tank analogy as a plausible representation of other dynamic systems, and
- (2) Using the tank analogy to reason about basic dynamics in the context of motion.

1. Seeing and accepting the analogy as a plausible representation of other dynamic systems:

What generalizations do students make of the water tank analogy? And *how* do these generalizations affect students' acceptance or rejection of the analogy as a plausible representation of other systems?

2. Using the tank analogy to reason about basic dynamics in the context of motion:

What are the effects of using the tank analogy on students' intuitive knowledge of basic dynamic systems of motion? In other words, what do students learn and how do they learn when they are instructed to transfer the tank analogy to the context of motion? Addressing these general questions requires answering the following specific questions:

- i. *What* do students already know about basic dynamics of motion? In other words, what is the existing intuitive knowledge that students bring with them to formal instruction?
- ii. *How* does students' existing knowledge change during transfer? In other words, what learning mechanisms produce these changes?
- iii. *What* does students' knowledge look like after transfer? – learning outcomes.

Figure 1 below shows the main two dimensions of learning with the tank analogy explored in this dissertation, the general research questions associated with each dimension and the corresponding papers addressing each question. In the next sections I describe the data sets used and each of the papers in detail.

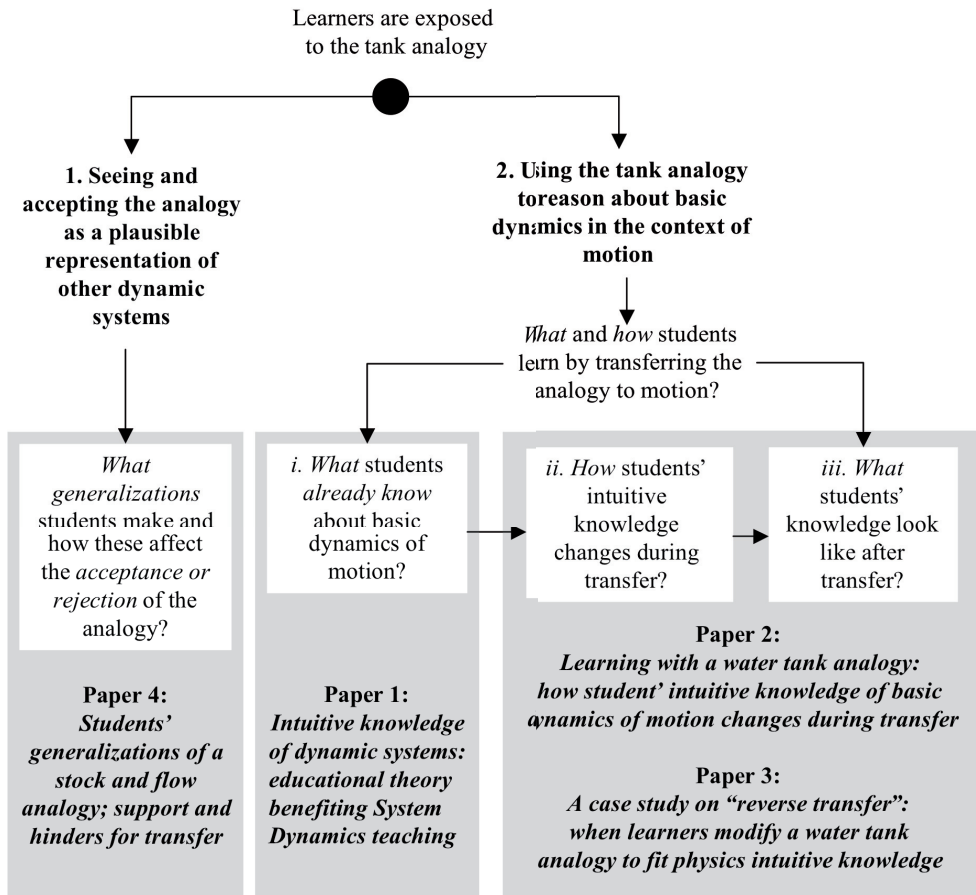


Figure 1. Papers and the corresponding research questions they address

4. Data Sets

Two data sets constitute the empirical basis of this dissertation.

Paper 1 and 2 build on data collected through individual clinical interviews with twelve seventh grade students from three public schools in Medellin, Colombia. Interviews were conducted before and after a six week's teaching intervention on basic dynamics of motion using a water tank analogy. Paper 1 uses data from the pre-interviews and Paper 2 from the post-interviews.

Paper 4 builds on data collected through individual clinical interviews with 8 undergraduate students from the University of Bergen, Norway. The duration of each interview was of around 45 minutes.

Paper 3 builds on data from both data sets. This paper presents 2 case study episodes from undergraduate students, and 3 case study episodes from seventh graders.

5. Paper overviews

Figure 1 shows the general research question addressed by every paper. In what follows I present each paper in detail.

Paper 1: Intuitive knowledge of dynamic systems: educational theory benefiting System Dynamics teaching

Paper 1 explores what students already know about basic dynamics of motion before they take part in my six week teaching intervention. It analyses students' existing knowledge to identify intuitions that are inconsistent with a SF understanding of motion. These intuitions constitute the knowledge that needs to be refined during teaching. Beyond problematic intuitions, my analysis also identifies *useful* intuitions in students' existing knowledge. These intuitions constitute potential stepping stones for advancing SF understanding. The motivation here is the premise that useful intuitions can help learners find plausibility in scientific explanations (Clement et al., 1989; diSessa, 1993; Osborne & Wittrock, 1985).

I use SFDs to characterize the intuitions exhibited by the students in my study, and compare these intuitions to those described in literature. Particularly, the aim is to investigate whether my particular sample of students indeed exhibit *p-prim*-like knowledge elements like the ones described in the knowledge in pieces approach (diSessa, 1993).

A methodological aim for the paper is to establish a common language between System Dynamics and intuitive knowledge theory. In so doing, I also delineate important assumptions that underlie my entire research program.

* *An early version of the paper was accepted and presented at the 7th Biennial Meeting of the European Association for Research on Learning and Instruction, Special Interest Group on Conceptual Change, Leuven, Belgium, 2010. A next version was accepted for the 2011 International Conference of the System Dynamics Society in Washington, DC.*

Paper 2: Learning with a water tank analogy: how students' intuitive knowledge of basic dynamics of motion changes during transfer

Paper 2 presents the *learning outcomes* of students' exposure to a six weeks teaching intervention (14 hours in total) using a water tank analogy to reason about basic motion dynamics. The paper answers questions about: what students' knowledge looks like after transfer and what learning mechanisms affect changes in students' knowledge. The results are presented in *episodes of knowledge change* exhibited by the students during individual interviews conducted in the last session of the intervention. The paper differs from previous research in that I analyze explicitly the use of a tank analogy.

The paper fulfills two purposes:

1. To provide evidence of successful knowledge change with the water tank analogy. I show several learning episodes in which the water tank analogy helps students transform their knowledge of basic dynamics of motion into one that is more congruent with scientific knowledge.
2. To investigate a complex phenomenon that conditions *whether* and *how* knowledge change occurs: *competition* between the SF knowledge being transferred from the analogy and students' existing intuitive knowledge of motion dynamics.

This phenomenon of knowledge competition implies that it is not sufficient that students *grasp* the knowledge being transferred. Transfer may require that this knowledge has to compete in *plausibility* with students' existing knowledge of the target context.

The paper presents 18 representative episodes of knowledge change. Three questions are addressed for each episode:

1. What knowledge students transfer from the tank analogy to the motion context.
2. What existing intuitive knowledge (p-prims) competes with the SF knowledge being transferred.
3. How students' understanding of the motion system changes during the transfer episode, i.e. what the outcome of competition is.

The paper presents multiple episodes of successful transformation of intuitive knowledge. The water tank analogy helps students transform their knowledge of basic dynamics of motion into one that is more congruent with scientific interpretations. Students' explanations show that the tank analogy helped students find plausibility in causality and dynamic behavior of motion systems that they saw implausible before the intervention.

Paper 3: A case study on “reverse transfer”: when learners modify a water tank analogy to fit physics intuitive knowledge

Recent research emphasizes that transfer is *complex* (Lobato, 2006). Paper 2 provides evidence of a complex phenomenon associated with transfer from the water tank analogy: *knowledge competition*. Paper 3 provides evidence of a complex phenomenon that may occur when students attempt to establish consistency between competing knowledge: *reverse transfer*.

Most views of transfer, are built on the assumption that what changes during transfer is *knowledge*, while students' representations of *transfer situations* (source/analogy

and target) remain unchanged. In contrast to this dominating assumption, some researchers propose a view of transfer as an ongoing transformation not only of the knowledge, but also of the representations of the situations involved (Beach, 1999). In this view, the source/analogy and the target are not taken as “givens.” It is assumed that learners can structure these situations until they become similar to something they know (Bransford & Schwartz, 2001; Carraher & Schliemann, 2002).

Paper 3 presents evidence from five case studies of the phenomenon I call *reverse transfer*. Reverse transfer occurs when students modify their representation of the water tank analogy to make it consistent with their intuitive knowledge of basic dynamics of motion. In these cases, knowledge change is unsuccessful, except that it resolves the student conflict. The students modify the source system (water tank analogy) but their knowledge of the target system (motion) remains unchanged. Hence, reverse transfer is a potential hindering mechanism for knowledge change.

Paper 4: Students’ generalizations of a stock and flow analogy; support and hinders for transfer

As a complement to Papers 2 and 3, Paper 4 explores a more fundamental dimension of learning with the water tank analogy: students’ perception of the appropriateness of the water tank analogy as representative of other SF systems – when students are first exposed to the analogy.

Paper 2 and previous studies of analogical reasoning and knowledge change (Kapon & diSessa, 2010) show that successful refinement of knowledge requires that learners see the knowledge associated with an analogy as more plausible than the learner’s existing knowledge of the phenomenon in question. Hence, in Paper 4 we set out to explore whether students find and accept as plausible the use of a tank analogy across dynamic systems from different domains.

Motivated by a pilot study in which a student had difficulties accepting the appropriateness of the tank analogy to represent some but not other systems, we

conducted a new study with 8 undergraduate students to explore *why* this occurred. We designed an interview during which students were first exposed to a water tank system and then asked to think of systems they thought were similar and to explain why. We also proposed to the students other particular pre-established systems.

Through analysis of the interviews, we identified *10 generalizations* that students make from the tank analogy which determine students' perceptions of the appropriateness of the water tank as an analogy to other systems. In other words, these generalizations play supportive and hindering roles in transfer from the water tank analogy. Hence, generalizations have implications for teaching. Supportive generalizations need to be pointed out and emphasized. Possible hindering generalizations need to be made explicit by inquiring learners to describe the associations they are making. Otherwise, the generalizations may easily remain "silent" and complicate further learning.

6. Papers summary

Together, the four papers in this dissertation show that the water tank analogy is an effective instructional tool for fostering knowledge change of dynamic systems. My work focused on the context of motion. However, intuitive knowledge such as the one successfully refined in my interventions, has been documented across several other contexts and domains in science (math, biology, electricity). Hence, I expect the water tank analogy and SFDs to be effective beyond the context of motion. My work provides a theoretical and methodological framework to investigate the effect of the SFD and its associated analogies across contexts in future research. Moreover, I hope that my descriptions of the complexities involved in such a process of knowledge refinement will inspire teachers to formulate improved teaching strategies. The main take home message is perhaps that to stimulate transformation of intuitive knowledge with the tank analogy – or other SF analogies, we need to help students see that the analogy necessarily describes and explains the reality they experience.

7. Research methods

Qualitative research methods are commonly used in studies that attempt to track knowledge development throughout an intervention or learning episode. Even though quantitative studies can be more 'easily' replicated, the data obtained in these studies is usually insufficient to determine *how* students' knowledge evolves and *why* it does so. Qualitative studies on the other hand, can shed more light on specific features of a teaching intervention that foster or hinder particular changes in students' knowledge. However, the research field of knowledge change is still at a rather early stage of development and the techniques used are still being refined³. Therefore, issues of data quality and validity are commonly questioned.

Two qualitative research methods were used in this research for the collection and analysis of data: clinical interviewing and knowledge analysis. In this section, I discuss some relevant issues regarding the aim of these methods, the characteristics of the data they generate or treat, and the challenges they involve. I discuss these issues here because, for space reasons, they are not discussed in any of the papers at the level of detail that I believe is necessary.

Before I discuss these methods however, I present a concise description of the teaching tools used during my interventions: the Tank and Car Interfaces.

7.1. Teaching Interfaces

To teach students with the water tank analogy, I built two computer interfaces: the tank and car interfaces (see Figure 2 and 3 below). These interfaces were designed by the author based on existing research in intuitive physics. The main purpose of the interfaces was to stimulate the refinement of students' intuitive knowledge, first in the context of the tank, then in the context of motion. In the last case, the flows of

³ This issue was discussed at the 7th Biennial Meeting of the European Association for Research on Learning and Instruction, Special Interest Group on Conceptual Change, Leuven, Belgium, 2010.

velocity can be controlled by students, and the car's velocity develops in accordance with the level of water in the tank.

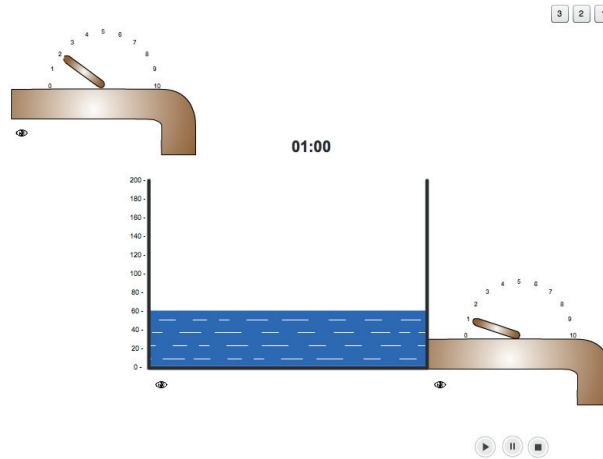


Figure 2. Tank interface

The properties and features of the interfaces and their accompanying teaching sequences are described in further detail in the appendix, while Paper 2 provides further description of their rationale.

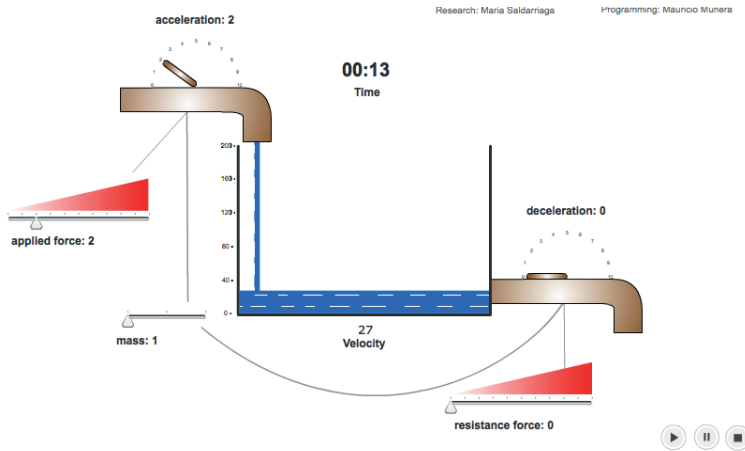


Figure 4. Car interface

7.2. Clinical Interviewing

An interview is a one-to-one conversation between an interviewer and a subject or a group of subjects. The aim of a clinical interview is to allow the subjects to expose their “natural” way of thinking about a particular situation or task (diSessa, 2007). Therefore, the role of the interviewer is to support inquiry avoiding exercising any judgment on the correctness or appropriateness of the subject’s thinking.

In our context the typical procedure of an interview consists of the interviewer posing a situation or task and encouraging the subjects to explore and express aloud their thinking about the situation. Interviews may involve the use of support tools such as pen and paper or computer interfaces designed to focus students’ attention and to provide a communication bridge between the subject and the interviewer. Most clinical interviews are semi-structured. The interviewer usually has a set of predetermined situations or tasks, but particular questions may emerge during the interview according to the flow of the subject’s reasoning and the interviewer’s understanding of this. For instance, noticing that a specific situation offers particular difficulties to the learner, the interviewer may decide to introduce variations of the situation to further expose the subject’s reasoning. Any variation in questioning will depend on the purpose of the interview.

The interviewer’s constant focus on clarifying and further explore students’ reasoning introduces an interpretative level in the interview itself. That is, during the interview, the interviewer is *already analyzing* the subject’s way of thinking and testing different hypothesis by asking clarification questions or slightly changing the situations of study. This differs from most common research methodologies in which performance is measured during an intervention and the resulting data is analyzed afterwards. Interviews are usually videotaped and later transcribed for further analysis or they are directly analyzed using qualitative software that allows video coding⁴.

⁴ See Ginsburg (1997) for a full description of clinical interviewing methodology.

Clinical interviewing is challenging; particular difficulties are associated to the role of the interviewer and the subject, and the nature of their relationship during the interview. For instance, the interviewer may fail to expose the subject's reasoning because of a lack of experience interviewing or because the subject is not articulated enough to describe her/his thinking. It may also happen that the lack of evaluation of wrong vs. correct answers by the interviewer creates a feeling of uncertainty in the interviewee who may then feel afraid of providing wrong explanations. Also, clinical interviews possess the challenge that questions proposed by the researcher must appear sensible to the subject (diSessa, 2007). If the task is too difficult or too simple, the subject may not know how to proceed or they may simply attempt to solve the task by guessing rather than reasoning thoroughly about it (Sherin, 2001).

Moreover, because of the pre-disposed nature of the settings in which clinical interviews are conducted, the method is considered by some as non-ecological –i.e., it is argued that the experimental settings of clinical interviewing do not approximate the real life situations to which subjects are exposed⁵. In response to these critiques, clinical interviews are usually compared to the natural inquiry activities that occur in everyday life and classroom settings where students engage in problem-solving situations. As defined by diSessa (2007) “clinical interviewing is a form of mutual inquiry [between the interviewer and the interviewee] that is a developmentally derivative of naturally occurring individual and mutual inquiry activities.” Hence, a goal for a well-conducted interview is that the subjects do not feel the interview as something out of the context of their schooling activities, but as a common activity of inquiry and sense making. This, according to diSessa (2007), establishes a partial warrant for ecological validity.

Finally, interview studies are challenged regarding the generalizability of the results they generate. Regarding this issue, Kvale and Brinkmann (2008) distinguish *analytical* from *statistical* generalization. Statistical generalization is tested the extend

⁵ diSessa (2007) provides a thorough discussion of the critics and challenges of clinical interviewing.

to which quantitative results apply across *populations*. In contrast, analytical generalization is used to determine the extent to which a phenomenon applies across *contexts*, which can be shown to share similarities by a reasoned judgment. The assumption here is that human activity is situated in local contexts of practice, and therefore, knowledge of these activities is necessarily context-dependant to a great extent. According to Kvale and Brinkmann (2008), well-known cases where knowledge has been generalized from interview case studies include Freud's theories on human behavior.

7.3. Knowledge analysis

Knowledge analysis is a methodology for studying learning in terms of cognitive structures or knowledge units. The purpose of knowledge analysis is to develop descriptive theories of the *content* and *change* of knowledge units during learning, based on external evidence exhibited by the learner such as actions and talk (Parnafes, 2005). Examples of research using knowledge analysis include: Parnafes' (2005; 2010) study of students' development of conceptual understanding of harmonic oscillation through computer simulations; Sherin's (1996; 2001) investigation of the intuitions used by students to make sense of algebraic equations in physics; and diSessa's (1993) identification of the basic intuitive knowledge units used by students to make sense of physics systems. diSessa's research is the most representative work in knowledge analysis and it has served as a main theoretical framework for subsequent research in the field.

To illustrate the focus of knowledge analysis studies, consider, for instance, that during an interview about motion a student predicts that "a toy car will always slow down after it has being pushed." The student's prediction is directly observable to the researcher; the knowledge that leads the student to make this prediction is not observable in most cases. The purpose of a knowledge analysis study will be then to identify plausible knowledge structures that can account for the student's prediction. In the case of our particular example, diSessa (1993) identified a knowledge element

called *dying away* that accounts for the students' prediction of the car slowing down. According to diSessa, *dying away* is the belief that most patterns of amplitude (sound, heat, motion) in the world simply have to end; nothing can stay hot or move forever. Hence, *dying away* is a piece of knowledge that can explain why the student predicts that the car will always slow down after being pushed.

There is nothing like a *unique* methodology of knowledge analysis. As with other research methods such as grounded theory, differences in procedure are rather prevalent. diSessa (1993) provides the most thorough description of the method in his monograph, however, Sherin's (1996; 2001) description is commonly used as a methodological reference by researchers in the field. In general, knowledge analysis consists of a systematic coding of students' utterances (explanations, and actions if relevant) during an episode of inquiry or learning. These utterances are generally registered during clinical interviewing. According to Parnafes (2005), two levels of analysis are involved in knowledge analysis: (1) a description of *what* happens during the episode, and (2) an explanation (e.g., explanatory theory) that accounts for *how* and *why* students act or reason during the episode.

During the descriptive stage of analysis the episodes are examined repeatedly to try to uncover the characteristics of the learning patterns that are followed by the students throughout the episode. At this stage there is no attempt to explain, but to understand what the episode is showing (e.g., is the student changing interpretations? Is the student holding one interpretation during the entire episode?). Once the researcher has an idea of the sequence of events occurring during the episode, the next stage consists of using all the observable information available in the episode (students' talk, actions, shifts in interpretations, etc.) as evidence of the student's internal process of learning that underlies the observable behavior (Sherin, 2001) (i.e., knowledge structures, and mechanisms of knowledge change).

Multiple theories may appear to explain aspects of an episode. It is at this stage where theories have to be reconsidered once and again in light of the whole episode and even across other episodes of the student during the whole interview (Parnafes, 2005).

Then the theory is extended to other students to check for generality and it is continuously adapted, if necessary, to the corpus of data (Sherin, 2001). The resulting theory describes a phenomenon of learning that extends across subjects given a particular context of learning. This theory emerges from the data and it should be able to capture the content and changes of the knowledge being used by the student during the episode. Knowledge analysis theories are comparable to those developed in grounded theory studies. “They are developed through the use of conceptualization to bind facts together, rather than through inferences and hypothesis testing.” (Kvale & Brinkmann, 2008, p. 325)

The focus on *underlying* knowledge structures makes knowledge analysis challenging and vulnerable to critics. Knowledge structures are not directly observable and the leap from behavior to hypothetical knowledge structures may be a large one (Sherin, 2001). Hence, on one hand, knowledge analysis is indeed highly interpretative and heuristic. On the other hand, a systematic and rigorous use of the available data during the theory building process should help increase the appropriateness of the theory. Moreover, theorizing about knowledge structures is the only way we have to talk about them because, as I mentioned before, we cannot yet directly observe knowledge in a laboratory. Some critics of knowledge analysis methods (Halldén, Haglund and Strömdahl, 2007) indicate that although ascribing meaning to observed behavior is challenging, it does not mean that nothing can be said about knowledge structures and their change during learning. Rather, they suggest that knowledge analysis methodologies should be reinforced to reduce the leap from utterances to the meanings of what is uttered. This can be done by moving from a view of meaning as residing in the learner’s mind to a view that is more holistic and considers the meaning making as the result of the interaction between the speaker, the listener, and the context of learning.

In the Experimental Design section of every paper, I describe how clinical interviews and knowledge analysis methods were used for the particular purposes of this study.

References

- Beach, K. (1999). Consequential transitions: A sociocultural expedition beyond transfer in education. *Review of Research in Education*, 24, 101–140.
- Bransford, J. D., & Schwartz, D. L. (2001). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education*, 24, 61-100.
- Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science*, 18(4), 237-261.
- Carraher, D., & Schliemann, A. D. (2002). The transfer dilemma. *The Journal of the Learning Sciences*, 11, 1-24.
- Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics*, 50(1), 66-71.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, 30(10), 1241-1257.
- Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education*, 11(5), 554 - 565.
- Clough, E. E., & Driver, R. (1985). Secondary students' conception of the conduction of heat: Bringing together scientific and personal views. *Physics Education*, 20, 176-182.
- diSessa, A. A. (1982). Unlearning aristotelian physics: A study of knowledge-based learning*. *Cognitive Science*, 6(1), 37-75.
- diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10(2/3), 105-225.
- diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction*, 25(4), 523 - 565.
- diSessa, A., Forman, G., Pufall, P., & Et (1988). Knowledge in pieces. *Constructivism in the Computer Age.*, 49-70.
- Doyle, J. K. (1997). The cognitive psychology of systems thinking. *System Dynamics Review*, 13, 253-265.
- Doyle, J. K., Radzicki, M. J., & Trees, W. S. (1998). *Measuring change in mental models of dynamic systems: An exploratory study.*

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- Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge University Press.
- Halldén, O., Haglund, L., & Strömdahl, H. (2007). Conceptions and contexts: On the interpretation of interview and observational data. *Educational Psychologist*, 42(1), 25–40.
- Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, 30, 141-158.
- Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. *Classroom Lessons: Integrating Cognitive Theory and Classroom Practice*, 51-54.
- Johnstone, A. H., Macdonald, J. J., & Webb, G. (1977). Misconceptions in school thermodynamics. *Physics Education*, 12, 248-251.
- Kainz, D., & Ossimitz, G. (2002). Can students learn stock-flow-thinking? An empirical investigation. In *System dynamics conference*. Palermo, Italy.
- Kapon, S., & diSessa, A. A. (2010). Instructional explanations as an interface---the role of explanatory primitives. *AIP Conference Proceedings*, 1289(1), 189-192.
- Kvale, S., & Brinkmann, S. (2008). *Interviews: Learning the craft of qualitative research interviewing*. Los Angeles: Sage Publications, Inc.
- Lobato, J. (2006). Alternative perspectives on the transfer of learning: History, issues, and challenges for future research. *Journal of the Learning Sciences*, 15(4), 431 - 449.
- McCloskey, M. (1983). Naive theories of motion. In *Mental models* (Dedre Gentner & Albert L. Stevens ed.). (pp. 299-322). New Jersey: Lawrence Erlbaum Associates.
- McDermott, L. C. (1984). Research on conceptual understanding in mechanics. *Physics Today*, 37(7), 24-32.
- Moxnes, E. (1998). Overexploitation of renewable resources: The role of misperceptions. *Journal of Economic Behavior and Organization*, 37, 107-127.
- Moxnes, E., & Jensen, L. C. (2009). Drunker than intended; misperceptions and information treatments. *Drug and Alcohol Dependence*, (105), 63-70.
- Moxnes, E., & Saysel, A. K. (2009). Misperceptions of global climate change: Information policies. *Climate Change*, 93, 15-37.
- Osborne, R., & Wittrock, M. (1985). The generative learning model and its implications for science education. *Studies in Science Education*, 12(1), 59 - 87.
- Pala, & Vennix, J. A. M. (2005). Effect of system dynamics education in systems thinking inventory task performance. *System Dynamics Review*, 21, 147-172.

- Parnafes, O. (2005). *The development of conceptual understanding through the use of computational representations. Phd thesis.* University of California, Berkeley.
- Parnafes, O. (2010). When simple harmonic motion is not that simple: Managing epistemological complexity by using computer-based representations. *Journal of Science Education and Technology*, 1-15.
- Phuah, T. (2010). *Can people learn behaviours of stock and flow using their ability to calculate running total? An experimental study.* Thesis, The University of Bergen.
- Roschelle, J. (1991). *Students' construction of qualitative physics knowledge: Learning about velocity and acceleration in a computer microworld. Unpublished doctoral dissertation, university of california, berkeley.*
- Sherin, B. L. (1996). *The symbolic basis of physical intuition A study of two symbol systems in physics instruction. Phd thesis.* University of California, Berkeley.
- Sherin, B. (2001). How students understand physics equations. *Cognition and Instruction*, 19(4), 479-541.
- Steed, M. (1994). *Effects of computer simulation construction on shifts in cognitive representation: A case study using STELLA.* Thesis,
- Sterman, J. D. (1989a). Misperceptions of feedback in dynamic decision making. *Organizational Behavior and Human Decision Processes*, 43(3), 301-335.
- Sterman, J. D. (1989b). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science* , 35(3), 321-339.
- Sterman, J. D., & Sweeney, L. B. (2002). Cloudy skies: Assessing public understanding of global warming. *Syst Dyn Rev*, 18(2), 207-240.
- Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, 16(4), 249-286.
- Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *Syst Dyn Rev*, 23, 285-311.
- Vosniadou, S. (2008). Conceptual change research: An introduction. In *International handbook of research on conceptual change.* (pp. xiii-xxviii). Routledge.

Paper 1:

*Intuitive knowledge of dynamic systems:
educational theory benefiting System Dynamics teaching*

Intuitive knowledge of dynamic systems: educational theory benefiting System Dynamics teaching

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Abstract

Over the last couple of decades, education research has studied learners' *intuitive understanding of causality and dynamic change* in science phenomena. An important finding is that these understandings are often at odds with scientific laws and principles, and that they persist even after formal education. Less research has gone into finding effective teaching strategies to correct intuitive understandings. In this paper, we take an initial step toward the formulation of teaching strategies of dynamic systems in physics using *stock and flow diagrams* (SFD). We examine the intuitive understandings of *motion* dynamics exhibited by twelve seventh grade students during clinical interviews. Focus is on four basic elements in dynamic systems: stocks, flows, net flows, and instantaneous cause and effect relationships. We identify *problematic* intuitions that teachers must be aware of and deal with in their teaching. Equally important, we identify *useful* intuitions of dynamic systems that teachers can actively engage to accelerate student learning. Finally, we propose a five step teaching strategy for dynamic systems and point out the need for testing and further research.

Keywords: dynamic systems, stock and flow diagram (SFD), phenomenological primitives (p-prims), anchor conceptions, analogy.

1. Introduction

We know from existing literature that people have *intuitive understandings of causality and dynamic change*. Furthermore we know that these intuitive understandings often differ from established scientific knowledge and that they may persist even after formal education. However, apart from the general acknowledgment that traditional teaching strategies are not adequate, we possess insufficient knowledge about how to formulate alternative strategies that support the refinement of these intuitive understandings. This paper is an initial contribution toward that goal, where the focus is on examining students' existing intuitive knowledge of dynamic systems to identify not only *problematic*, but also *useful* intuitions that can be used to support further learning of dynamic systems. The intent is not to present a model of the cognitive learning process involved. Rather we limit our aim to highlight those aspects of intuitive knowledge that approximate stock and flow (SF) interpretations of causality and dynamic change in motion phenomena, and to discuss how this knowledge can be used in teaching as stepping-stones to construct scientific understanding.

The focus in our study is on basic dynamics of *motion*. This focus is motivated not only by the richness of intuitive understandings of dynamic systems in this domain, but also by the existence of well-established scientific theories and principles—given by Newton's Laws, which define a reference for the set of knowledge that students should ideally develop.

Using clinical interviews with 12 seventh grade students from Colombia, we explore students' ways of reasoning about causality and dynamic behavior in the context of a simple motion situation in one dimension: a toy car being pushed along a flat surface. The purpose here is to examine what particular knowledge students use to explain and predict basic patterns of change over time for velocity (i.e., increase, decrease, equilibrium). The interviews were video recorded, coded, and analyzed using qualitative techniques for *knowledge analysis* (Sherin, 2001). Using knowledge analysis methods, we identified particular *intuitive knowledge elements* underlying

the students' reasoning during the interview. These knowledge elements represent the knowledge "possessed" by students that leads them to predict and explain phenomena in particular ways. We describe and further explore these knowledge elements in this paper.

Our investigation is organized around four basic elements in dynamic systems: stocks, flows, net flows, and instantaneous cause and effect relationships. For each of these elements our exploration consists of three steps. First, we examine knowledge elements to identify both *problematic* and *useful intuitions*. In contrast to the broad variety of intuitive knowledge described in existing literature, we limit ourselves to intuitive knowledge that contradicts or approximates the SF elements involved in Newton's First and Second Law.

Second, we compare the knowledge elements observed in our data to previous findings in intuitive knowledge in physics, particularly to literature on *phenomenological primitives (p-prims)* (diSessa, 1993). The purpose of this comparison is to validate our observations of intuitive knowledge.

Third, we illustrate how teachers awareness of students intuitions can guide the formulation of improved teaching strategies. To do so, we use Clement and Brown's (1989; Clement, 1993) work in connection with Newton's Third Law (for every action, there is an equal and opposite reaction). Clements and Brown's work shows how useful intuitions can be used in teaching with analogies to help students' refine their problematic intuitions. With this research in mind, we consider a program for teaching with stock and flow diagrams (SFD) using students' useful and problematic intuitions.

The results suggest that students do have intuitions that are both problematic and useful for reasoning about causality and dynamic change. Even though students tend to think of causality as instantaneous, it is also possible to identify elements of SF thinking in students' intuitive knowledge. Particularly, students have ideas of "storing" and "using-up" and they exhibit awareness about the need for time to pass for certain changes to occur. Moreover, we find that the knowledge elements we

observe in our study, both problematic and useful, correspond to several of the p-prims previously described by diSessa (1993).

Our work is useful for research-informed design of teaching strategies using SFDs. Our particular approach brings together two fields of research: system dynamics and education. From education, we bring in the use of in-depth qualitative research techniques and the highly detailed descriptions of the form and content of students' intuitive knowledge (i.e. p-prims descriptions). From system dynamics we bring in the conceptualization of what is necessary to interpret dynamic systems, expressed by SFDs and also by the *bathtub* or *water tank analogy* (Forrester, 1961; Forrester, 1968).

The paper is organized as follows. First, we review literature on students' intuitive understandings of motion using a basic SFD for illustration. We describe diSessa's p-prims approach and use Clement's work to exemplify how useful intuitions can be reused for teaching. We follow up with a description of the interviewing and data analysis methods used. Next, we present and discuss the intuitive knowledge elements we observe, organized in four different groups and according to whether they are problematic or useful intuitions. Finally, we discuss the implications of our work for teaching and present our step-wise teaching program for dynamic systems using SFDs.

2. Physics intuitive knowledge

In this section we use a SFD for motion to explain and characterize intuitive knowledge elements (phenomenological primitives or p-prims). Then we discuss the role of p-prims in teaching.

2.1. SFDs and intuitive knowledge of dynamics

Figure 1 is an SFD that illustrates the basic mechanisms of motion⁶. Net acceleration is an instantaneous function of net force divided by mass (Newton's Second Law) illustrated by a thin arrow. Velocity is a stock that accumulates net acceleration (Newton's First Law), acceleration is "flowing" through the pipe into the "container" with velocity. Since this is a very simple model, it may come as a surprise that it took a scientist of Sir Isaac Newton's caliber to devise this model of motion. The great thinker of Ancient Greece, Aristotle, postulated that velocity is an instantaneous function of force.

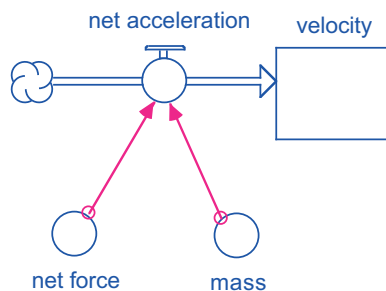


Figure 1. SFD for motion

⁶ The SFD notation used in this paper is a slightly modified version of the one originally developed by Forrester (1961; 1968). The diagrams here have been drawn using iThink software.

The challenge for Aristotle and those who followed over the next two thousand years probably was to realize that velocity is a stock. A likely reason for this is that velocity cannot be directly observed; it can only be estimated by observing change in distance over a given period of time. Newton realized that *velocity is a stock*: an object at rest tends to stay at rest and an object in motion tends to stay in motion with the same velocity unless acted upon by an unbalanced force. Newton's second law corrects Aristotle by saying that *it is acceleration that varies instantaneously with force, not velocity*. Therefore, Newton's great contribution here was a clear distinction between two types of causal relationships: instantaneous and integrating.

The distinction between instantaneous and integrating causality is crucial for the understanding of dynamic systems. Having instantaneous causality in mind, any change in velocity must be caused by a corresponding change in force. With integrating causality, there is no need for a change in force for velocity to change (force can be constant and different from zero) and there is no need for a continuous force for velocity to be different from zero. The system (stock) can have a 'life of its own', which may seem mysterious for those who have only instantaneous causality in mind.

Before we move on we need to complicate the model somewhat. Newton's laws concern net force and net acceleration. In the System Dynamics tradition, we distinguish explicitly between in- and outflows when the flows are influenced by different mechanisms. Figure 2 shows the SFD for motion when we disaggregate the flow of net acceleration. Here *acceleration* denotes positive change in velocity produced by forces in the direction of velocity, and *deceleration* denotes negative change in velocity produced by forces in the opposite direction of velocity. Normally the word acceleration is used to denote positive net acceleration while deceleration is used to denote negative net acceleration. Our use of words may cause some confusion, however, this is not an unknown challenge in stock and flow systems and we have found no better way to deal with this challenge.

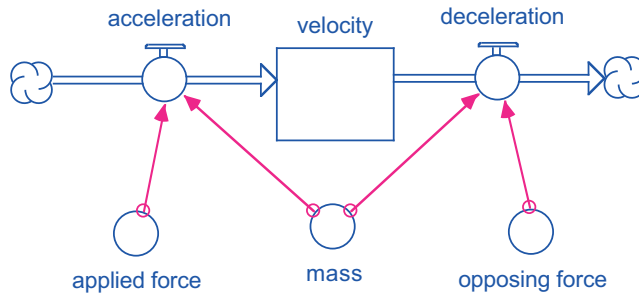


Figure 2. Disaggregated SFD for motion

In spite of apparent simplicity of the SFD in Figure 2, the educational literature finds that students do not have Newton's scientific model in mind when dealing with motion phenomena. Rather they operate with simplified heuristics to explain phenomena and to predict behavior. There is now considerable work describing a surprisingly large number of heuristics used to explain behaviors generated by the model in Figure 2. Of particular interest here is diSessa's (1993) work on phenomenological primitives (p-prims).

P-prims are small bits of knowledge that allow people to explain and predict behavior in the physical world. P-prims are assimilated from personal experience and they are activated and used at a rather unconscious level. They work more like obvious ideas that come to people's mind depending on what they perceive out of a situation, rather than like ideas that are deliberately worked out and used. Consider the example of the *dying away p-prim*. Certain phenomena in the world appear to exhibit decaying patterns (movements come to a halt, coffee cups cool down, the sound of a bell decays). For such phenomena, *dying away* becomes an obvious intuition to satisfactorily explain and predict behavior. People believe that an object slows down and comes to a stop because motion *simply has to end*. It is true that many people would use *dying away* as a short-cut to more advanced explanations or simply to describe observed behavior. A fundamental requisite of *dying away as a p-prim* however; is that it appears as self-explanatory (not requiring further explanation) to

the learner: it is simply the way things happen; things have to end. The following observations about p-prims are central:

1. *P-prims are triggered or cued by perceived features of a situation.* These features are mostly at the level of surface configurations rather than at the level of more abstract causal mechanisms. Some p-prims, for instance, are cued when a person holds a book in the hand, but not if the same book rests on a table. Both systems are physically equivalent, but they appear different to the learner. The person is perceived as an *active agent*, the table is not. In conclusion, two “equivalent” situations can activate very different intuitive knowledge in the learner.

2. *P-prims lead to correct or incorrect explanations and predictions* depending on whether they are triggered in situations where they happen to be appropriate or inappropriate. Therefore, it can occur that a student gives a correct explanation of a behavior simply because the behavior is a fitting context for a p-prim, and not because the student really understands the mechanism generating the behavior.

3. *P-prims are not complete model descriptions;* they are minimum representations of a given situation, but to the learner they hold sufficient explanatory power. P-prims are not theory-like knowledge, which works as a whole and is applied consistently across situations. Since p-prims are so dependent on perceived cues, it is not always the case that two situations, in which one and the same p-prim applies, are perceived as the same by the learner.

2.2. The role of intuitive knowledge in learning and teaching

Because intuitive knowledge is deeply engrained in learners' cognitive repertoire, its refinement is challenging, even during formal teaching. Hence, better teaching methods are needed. While this need is recognized⁷, much research has not been devoted to testing ways to use p-prim knowledge in teaching.

Here we propose a teaching strategy for dynamic systems where students' useful intuitions are activated to help them see plausibility in SF representations in SFDs. This proposal builds on research that aims at identifying useful intuitive knowledge and exploring the ways in which this knowledge can support learning – in contrast to assuming intuitive knowledge as only problematic (Brown & Clement, 1989; Clement, 1993; Clement, Brown & Zietsman, 1989; diSessa, 2009a; Minstrell, 1982; Parnafes, 2007).

To illustrate how useful intuitions can be used during teaching, we use Clement and Brown's work on *anchor analogies* (Brown & Clement, 1989; Clement, 1993). They formulate strategies where useful intuitions serve as analogies (anchors or sources) to situations that are not as intuitively plausible for the students (targets). They reason that if students can get to perceive the anchor and target as similar, they can realize how their useful intuitions of the anchor can also apply to the target situation.

For instance, according to existing literature, many students have difficulties with Newton's Third Law (for every action, there is an equal and opposite reaction). Students refuse to believe that "static" objects such as tables, can exert forces on other objects like coffee cups or books sitting on the table. However, it is usually not problematic for students to believe that a spring can exert a force on the hand when compressed, because they can observe the spring to deform (Clement, 1993). Thus, students' association of *deformation* with *reaction forces* constitutes an useful intuition for understanding Newton's Third Law. To engage this useful intuition,

⁷ This issue was discussed at the 7th Biennial Meeting of the European Association for Research on Learning and Instruction, Special Interest Group on Conceptual Change, Leuven, Belgium, 2010.

Clement and Brown (1989) designed a series of situations where the spring works as an anchor analogy to other objects whose deformation is progressively less observable. The sequence of situations is as follows: (1) the hand pressing the spring (anchor analogy), (2) the book resting on a piece of foam, (3) the book sitting on a piece of cardboard, (4) the book sitting on a table (target).

After using this sequence with students, Clement and Brown report significant gains in students' understanding of Newton's Third Law (Brown & Clement, 1989; Clement, 1998). Nevertheless, perhaps the most important conclusion from Clement and Brown's work is that being able to use knowledge across situations requires more than simply being shown how both situations correspond to each other. It also requires being able to see this correspondence as *plausible*. In Clement and Brown's example, it is not sufficient to *indicate* to students that "the table is like a spring at a microscopic level." It is necessary to use bridging situations, such as the foam and cardboard, for the students to come to see the table situation as compatible with their intuitions of deformation and reactions forces.

Motivated by Clement and Brown's research, we investigate problematic and useful intuitions concerning stocks and flows relationships of Newton's First and Second Laws. We also discuss possible ways in which the SFD and its water tank analogy could be used to bridge situations in which useful intuitions apply with more challenging situations.

3. Experimental Design

3.1. Participants and setting

The data presented in this paper was collected through clinical interviews with 12 seventh grade students from three public schools in Medellin, Colombia. All schools had similar curriculums and none of the students had received any formal teaching in physics. This is important, since the research focus is on intuitive knowledge developed through common experiences, rather than on conceptions developed

through formal education. The data presented here are part of a bigger corpus of data collected throughout six consecutive weeks of teaching (14 hours in total). By the time the clinical interviews were conducted, the students had been exposed to an interactive animation of a tank (a simple water tank analogy of the SFD) for a total of 4 hours. Thus, the students could have been biased towards correct dynamic interpretations compared to other students. To the extent that they still relied on p-prims in the interviews, our results are yet another finding that analogical transfer, as Clement and Brown's work suggest it, is neither unambiguous nor is it spontaneous.

The students were selected by the science teacher at each school; with no particular instruction for selecting the students. Since the selection was done at the beginning of the school year, the teachers did not have much previous knowledge of their students upon which to base their choices. Eight of the interviews were conducted in classrooms inside the students' respective schools, while the other four were conducted in a room at a teachers' training center in the city.

3.2. Interview Procedure and conceptual test

In general, the interviews followed interviewing methods from educational research as described by diSessa (2007) and in greater detail by Ginsburg (1997). The interview sessions were semi-structured. The structured portion consisted of a conceptual test (described below) given to the student immediately before the interview. The open part of the interview consisted of follow-up questions by the researcher about the student's answers. The aim of using both assessment techniques, the conceptual test and the follow up interview, was to focus students' reasoning around the dynamic dimensions of the phenomena under study, and at the same time, opening the opportunity for an in-depth exploration of the reasoning behind particular student explanations. In these interviews, the role of the researcher is not to influence students' knowledge. The researcher's role is limited to elicit students' reasoning by creating a physical and communication environment that allows for "natural" inquiry like the one that usually occurs in a real school classroom. Moreover, the researcher task is not to evaluate the correctness of students' explanations, but to try to

understand the reasoning underlying their explanations. To highlight this aim to students, the researcher usually emphasizes before the beginning of an interview, that what matters in what they personally believe is the way something works.

The conceptual test given to the students before the interviews involved questions about four situations associated with a basic motion phenomena: a car being pushed (Appendix 1). The style of the questions was based largely on the Force Concept Inventory (FCI) by Hestenes and others (1992). The FCI is a multiple choice test to evaluate students' conceptual understandings of Newtonian mechanics; it has been designed to include choices that range from the scientific to the most common intuitive understandings identified in the literature. We used the structure and wordings of the FCI to formulate questions that focused on dynamic change and causality in the situations associated with the car's motion. The selection of the car's motion as case study was motivated by the richness of intuitive understandings documented in the literature regarding impulses and continuous pushes. Well-explored phenomena offer a good starting point when attempting to link two fields of research. However, for future research, using phenomena that have not been previously explored would help further advance our understanding of intuitive knowledge of dynamic systems.

In contrast to the common research purpose of testing, we did not use the conceptual test to gather quantitative data about students' choices. Rather, the test was used as an elicitation guide for supporting the discussion during the interview. The test helps focus students' attention on certain aspects of the phenomenon in question, but it is not sufficient to gather information that helps understand *why* students' predict or explain a phenomenon in a particular way. Examining the *why* requires qualitative techniques like interviewing. Finally, the motivation for giving students specific options rather than asking them open questions was to explore students' sense of plausibility of *a particular set of explanations*. This purpose contrasts to research that aims at documenting *any explanation* that students exhibit of a given phenomena.

3.3. Data analysis

The interviews were video recorded and analyzed using software for live video coding. The interview fragments presented in this paper were transcribed verbatim and translated from Spanish to English. The analysis was informed by *knowledge analysis* methods. Knowledge analysis is a methodology aimed at the development of descriptive theories of knowledge structures and their change during learning. diSessa (1993) provides a thorough description and discussion of the methodology. Sherin (2001) provides a simplified and practical account which is commonly quoted by practitioners of the field. Here we describe the three stages of analysis that we followed. Examples from the data are used to illustrate.

Stage 1: Students' literal explanations as units of analysis

During the first stage, we categorized *students' explanations* for choosing a certain option in the test. To do so, we created categories that corresponded to *literal expressions* used by the students in their explanations. We call these categories *articulations*. Articulations are many and diverse because there are as many articulations as there are students' ways of expressing an idea. Examples of articulations are (in italics): "the car stops because...*there is nobody to move it*;" "the car moves because...*the girl keeps pushing it*;" "it will stay there because...*the girl doesn't keep pushing it*." Since articulations correspond to an early stage of analysis they are not presented in detail in this paper, however, examples of transcript fragments are provided for each element in the results section. The analysis conducted during this first stage follows a bottom-up style of coding such as the one used in grounded theory research. The purpose here is to let the categories emerge from the data.

Stage 2: Underlying knowledge elements as units of analysis

The second stage of analysis followed a more top-down style. Here the researcher searches for possible patterns across students' articulations with a focus on *underlying intuitive beliefs*. This characterization of the intuitive knowledge that underlies students' explanations is the main purpose of *knowledge analysis* methods. Since intuitive knowledge is rather unconscious, it is unlikely that students articulate an underlying belief in an explicit way. It is the work of the researcher to make sense of a student's explanation in light of the existing literature and of the whole of his/her reasoning across different phenomena. Identifying and characterize underlying knowledge consists of an iterative process of:

- (1) identifying a knowledge element "candidate,"
- (2) describing the new element according to the aspects of the constitutive articulations that it is presumed to capture,
- (3) revisiting all articulations to check for the applicability of the new element, and
- (4) testing the knowledge element with the available data to see if it is used in ways it would be expected to according to its properties,
- (5) review the existing literature to check if the element has being previously described.

It often happens that more suitable knowledge elements emerge during the process and all the existing ones need to be revised. The goal is to get to a set of knowledge elements that capture the properties of students' reasoning.

To illustrate these five steps, let's consider once more the examples of articulations in stage one: "the car stops because...*there is nobody to move it;*" "the car moves because...*the girl keeps pushing it;*" "it will stay there because...*the girl doesn't keep pushing it.*"

(1) The first step is to identify a knowledge element that possibly underlies these students' explanations. We could, for instance, hypothesize that students' articulations, suggest the belief that "an applied force (the girl pushing the car) is required to keep the object in motion." We call this piece of knowledge *force sustains motion*.

(2) We describe this knowledge element as the idea that "a continuous force is required for continuous motion."

(3) This step consists of revisiting all students' articulations to check for those that support the existence of *force sustains motion*. For instance, can the belief in *force sustains motion* explain a student's articulation such as "the car will stay there because she doesn't keep pushing it."? The more articulations support the existence of a knowledge element, the more confident we can have in its appropriateness.

(4) The next step is to test the knowledge element. A way to do this is to predict those situations in which it should not be used and then test this prediction. For instance, *force sustains motion* appears to be used only in situations where there is an observable agent (from the perspective of the student) exercising a continuous force on the moving object. Therefore, one would expect students not to use this element whenever there is *not* an observable agent sustaining the motion. This is indeed what the data shows. When the students are asked to explain the car's decreasing velocity after it has been given a sudden push, the explanation of the agent as responsible for sustaining the motion is replaced by other explanations. The new situation makes evident that the motion of the car could sustain itself – at least for a while, without the direct contact of the agent. *Force sustains motion* loses its explanatory power in this case.

(5) Finally, the last stage of the analysis consists of comparing the knowledge element to elements described in the existing literature, particularly to diSessa's p-prims. This contributes to *validity* (when other research has identified the same elements in the same or similar situations) and *generalizability* (when other research has identified the same elements in different situations and domains). In

our particular example, the *force sustains motion* element we observed, corresponds to a p-prim previously identified by diSessa (1993).

The above procedure may raise some questions. Given that intuitive knowledge has been described in detail in previous work, why search for knowledge elements from scratch? First, it was our purpose to *corroborate* the existence of p-prim, rather than risk to impose it on the data. Second, it was important to determine *which* particular knowledge elements our students used to reason about *patterns of change* of velocity. Third, to our knowledge, no similar studies have been conducted with students from Colombia, and it was possible that differences in culture and language could generate results that differed from previous findings in USA and Europe⁸.

One may also question our focus on knowledge elements. Why not focus on more comprehensive structures such as “mental models,” “schemes,” or “theories” since there is an ongoing debate about this issue? (Vosniadou (2008) and diSessa et al. (2004). During the analysis process, each interview was continuously analyzed as a whole looking for instances in which two or more elements were systematically used together. If several elements are found to be repeatedly used in conjunction, that should serve as an indication of the existence of a knowledge structure that is more comprehensive than the individual elements themselves. However, we found no single group of elements that was used by more than one student or across different situations. In contrast, the isolated knowledge elements could be tracked across students and situations, indicating that these elements are appropriate units to analyze and describe the form and content of the subjects’ knowledge.

Stage 3: Characterizing intuitions as useful or problematic

Our final stage of analysis consisted of examining and characterizing the observed knowledge elements as *problematic* or *useful* intuitions of dynamic change and causality.

⁸ Issues of language and culture in intuitive knowledge studies are discussed in Vosniadou (2008).

4. Results

This chapter has four sections focusing respectively on the SF elements *stocks*, *flows*, *net change*, and *instantaneous causality*. For each of the SF elements we identify knowledge elements and describe them by examples from the data. We use SFD symbols to characterize the knowledge element and to illustrate how they differ from scientific interpretations. Thus we can emphasize both the useful and inappropriate aspects of each knowledge element. Finally, we discuss whether the knowledge elements we have identified have been described in previous research, particularly in the p-prims literature.

Unless otherwise mentioned, at least 7 of the 12 students exhibited each of the knowledge elements listed below. Nevertheless, keep in mind that these numbers do not represent precise estimates of frequency of use. Most of the time students go back and forth between elements that may even contradict each other from a scientific perspective. This contradiction or inconsistency is a fundamental characteristic of intuitive knowledge. Implications for teaching are considered in the discussion section.

4.1. Intuitions of stocks

4.1.1. Useful intuitions

This group includes one knowledge element involving the idea of *storing*. This knowledge element should be useful to further develop the concept of stock, *particularly* in situations where stock nature is not intuitively plausible (or obvious) to students.

Force is given (to an object)

Force is given is the idea that an agent gives (transfers) force to an object – also articulated by students as the object *taking* force from the agent. In the case of the car, students use *force is given* to explain that *after* being pushed, the car moves with the

force that the agent gave to it (fragment 1). *Force is given* is also used to explain decreasing velocity as the result of a lack of “enough given force” (fragment 2). In all transcripts S refers to the student, R to the researcher, and the words in brackets are clarifying comments added by the researchers during the analysis:

1. S: If the girl pushes the car, the car will get the force that the girl gave to it so it could move.
2. R: And why does the velocity decrease?
S: I say that with the push. I mean, the floor was slippery so it should go on but with a single push it won't get too far, velocity decreases.

Force is given may be represented as a stock of stored force with a flow of applied force (Figure 3). *Force is given* involves the idea of an “instantaneous accumulation”, as in the case of a *pulse*: in the single instant the object is pushed, an amount of given force is “stored” in the object. Importantly, Figure 3 is in accordance with the laws of physics, when applied force is integrated over time, the stock is a measure of an object’s impetus, i.e. mass times velocity. If applied force is divided by mass to get acceleration, the stock will be a measure of velocity as in Figure 1. *Force as a given* however, does not imply that students’ possess a correct impetus theory.

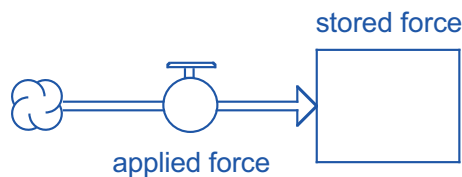


Figure 3. Stock and flow representation of force is given

The intuitive idea of a stored or given force has been widely described in the literature. McCloskey (1983) documents this idea in several physics situations

including objects being pushed and balls being thrown. McCloskey sustains that the idea of a “given force” is part of a bigger theory of intuitive motion that he calls “impetus theory.” Our results support the claim that students possess the idea of the given force, but it does not support the claim that students possess a coherent intuitive theory that they apply across all situations.

The idea of *force is given* is cued by an observable event caused by an agent, followed by a continuous pattern of behavior that prolongs in time. Cueing is important for teaching because it alerts teachers and researchers of potential intuitions (both useful and inappropriate) that students could bring into the interpretation of a particular situation. Also, cuing can be intentionally used by teachers and researchers to provoke and engage particular intuitions.

4.1.2. Problematic intuitions

While *force is given* involves a productive idea for reasoning about the storing property of stocks, the two knowledge elements below undermine this understanding. We name these knowledge elements: *force sustains motion*, and *velocity proportional to force*.

Force sustains motion

Force sustains motion is the idea that the presence of an agent exercising a continuous force on an object is needed to sustain the motion of the object. In the case of the car, for instance, it is the agent pushing the car that keeps the car moving. If the girl stops pushing, the car stops moving *instantaneously*. Students use *force sustains motion* to *explain* constant velocity as the result of the “girl pushing continuously.” The following articulations are common:

1. S: [The car moves at a constant velocity]...Because the girl is the one that applies the force so that the car moves. Unless the car is a remote controlled car. But here we are talking about us moving the car so the one that applies the force is the girl.

2. S: [The car moves at a constant velocity]...Because the girl is always moving the car.

Force sustains motion can be represented as in Figure 4. In contrast to *force is given*, *force sustains motion* does not involve an idea of “storing” that enables motion to sustain itself after the initial force has stopped acting. In this case, motion is only possible if there is a continuous force acting to sustain it.

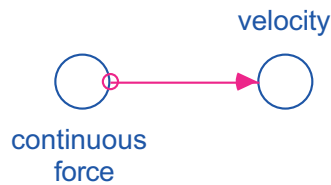


Figure 4. *Instantaneous cause and effect representation of force sustains motion*

Interpretations like *force sustains motion* have been identified by previous research in situations involving dynamics. The *force sustains motion* element corresponds to the *continuous force p-prim* (diSessa, 1993). This p-prim specifies a direct association of a “constant pattern of effort” and a change in velocity or position. Much like the *force sustains motion* that we have observed in our data, the *continuous force* p-prim explicitly ignores the pass of time in the process of gaining velocity.

Hammer calls this p-prim, *maintaining agency* (Hammer, 1996)⁹. Also, Brown and Hammer (2008) suggest that the *continuous force p-prim* “could be understood to schematize any causal agent maintaining an effect.” Examples of instances where *continuous force* applies appropriately are found in social relationships, where continuous encouragement may be necessary to sustain students’ motivation (Hammer, 1996). Similar interpretations have been documented in system dynamics

⁹ Although the original name for this p-prim is *continuous force/push*, we use the name *force sustains motion*. We consider this name to be more explanatory of the idea involved in the p-prim.

research. When reasoning about population change for instance, students focus on a rather salient cause (births) to predict changes in population (Sweeney & Sterman, 2007). This reasoning is similar to the interpretations involved in the *continuous force p-prim* in that they both specify an instantaneous relationship between a perceived salient cause and its effect. However, in contrast to the *continuous force p-prim*, it is not clear whether in the case of populations, students also believe that births are required to *sustain* any level of population (i.e., that population would be zero if births are zero).

In contrast to *force is given*, interpretations like *force sustains motion* are cued in situations where there is an observable agent acting to sustain a continuous behavior. Since, the agent is seen as continuously causing motion, it is not necessary to look for “stored forces” to explain behavior. Notice for instance that in the first example above, the student mentions the “remote control” as another possible agent to explain the constant motion of the car. This makes *force sustains motion* a very at-hand explanation cued by ongoing motion, where the active agent is observed or simply assumed.

Before we move on, it is important to provide some clarification. By now, the reader may have noticed a sort of interplay in the use of the terms “velocity” and “given force.” This may appear as an inconsistency in our descriptions; however, we use both terms to keep the descriptions of the elements as close as possible to the way students articulate them. In general, the distinction between force and velocity is problematic for students. While sometimes they refer to them as being different, sometimes they use the terms interchangeably. This does not imply however, that the students are conscious about the possibility of an impetus (see section 4.2.1.) vs. a velocity interpretation of motion.

Velocity proportional to force

Velocity proportional to force is the idea that velocity and force are proportional (or otherwise related) at any given instant of time. *Velocity proportional to force* (Figure 5) may seem the same as *force sustains motion* (Figure 4), however, these two

elements have different characteristics. While *force sustains motion* refers to the need of the presence of an active (observed or assumed) agent to sustain velocity, *velocity proportional to force* refers to the proportionalities between the magnitudes of velocity and force.

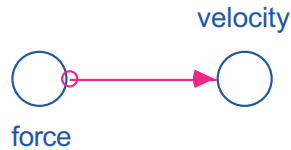


Figure 5. *Instantaneous cause and effect representation of velocity proportional to force*

Because of its simplicity, *velocity proportional to force* offers a very at-hand intuition for making inferences about the magnitude of velocity or force at a particular time. For instance, just by noticing that the object's velocity decreases over time, students can infer that the force decreases as well. And the other way around, if the force is said to double or triple, velocity will double or triple in the same way. The following articulations of *velocity proportional to force* are representative:

1. R: What would happen if the [applied] force triples?
S: The velocity is three times more than this [what it was before doubling the force].

2. R: So, for instance, how much is the applied force when the car is around here [after 2 sec of being pushed]? Is there still some of that applied force?
S: Yes, I mean I pushed the car very hard so it had 8 of velocity at the beginning but the velocity decreases 4, 2...like half until it gets to zero.
R: So that is the velocity, and what about the force? You said that the force of the girl also decreases.
S: Yes, it also decreases because the girl pushes the car and so the

velocity is very fast at the beginning but it decreases.

R: Is there still a force around here [after 2 sec of the push]?

S: Yes, very little.

The interpretation of *velocity proportional to force* is in part an instance of diSessa's *ohm's p-prim*. *Ohm's p-prim* is abstracted from situations where one has to make greater efforts and act against a resistance to accomplish greater results. For instance, pushing a cup (effort) to move it (result) across a rough table (resistance). The *ohm's p-prim* specifies a series of proportional relationships between these three variables—effort, resistance, and result: the greater the effort, the greater the result; the greater the resistance, the less the result (diSessa, 1993). Apart from pushing objects along a surface, *ohm's p-prim* is used by students to describe the relationship between mass and the velocity of objects falling to the ground (Masson & Legendre, 2008): the heavier the object, the faster it falls.

Similar interpretations have also been documented in system dynamics research in several fields like climate change and renewable resources management (Cronin, Gonzalez & Sterman, 2009; Moxnes, 1998; Moxnes & Saisel, 2009; Sterman & Sweeney, 2002). These researchers have observed, among graduate students, the assumption that “the output from its perceived input follows the pattern of change of the input.” Thus, for instance, CO₂ in the atmosphere (output) is assumed to follow the pattern of emissions (perceived as the input), or the number of people in a store (output) is assumed to follow the pattern of the people going in the store (perceived as the input). This reasoning has been described as *pattern matching*. Nevertheless, in the cases in which pattern matching has been observed, the input and output are not necessarily assumed to be proportional (as in the case of velocity and force), but in all cases the input and output are assumed to be correlated and to change instantaneously.

Inverse *pattern matching* or inverse proportionality, as predicted by *Ohm's p-prim* for a resistance, has also been observed in stock and flow systems. Moxnes (1998) found

that both lay and expert subjects predicted that reduced grazing would have an instantaneous positive effect on a food source (stock of perennial plants).

4.2. Intuitions of flows

4.2.1. Useful intuitions

The following element involves ideas of *losing* or *using up over time* what has been stored. Since “flowing out” is one of the main mechanisms of accumulation processes, the element in this group suggests that students possess useful intuitions that could be used to further construct the concept of accumulation. This knowledge element corresponds to diSessa’s *dying away p-prim*.

Before we present *dying away*, we would like to introduce another of diSessa’s elements called *change takes time p-prim*. Although we found no instances of the *change take time p-prim* in our data, this p-prim involves ideas of “building up” and therefore, it is worth to consider this p-prim as another potentially useful intuition of accumulation processes. The *change takes time p-prim*, also called *warming up p-prim* by diSessa, specifies that “...it takes time for any result quantity to reach its final value when a change in impetus takes place.” (diSessa, 1993). diSessa describes this p-prim as an abstraction of situations of “bringing up an object to a certain state” such as: accelerating a car up to speed, or heating up a soup. Probably we did not observe the *change takes time p-prim* because we did not produce or focus attention on situations that would cue this p-prim.

Dying away

Dying away is the idea that the force given to the object in the push or throw, is “used up”, “gets weaker”, or simply “ends” during motion. In the case of the car for instance, students use *dying away* to explain the car’s decreasing velocity after it has been given a sudden push:

1. S: [The car slows down]...Because when she pushes the car, the car will move with the force that she gave to it, but by the time that this force

gets weaker, the car will slow down and slow down, and then it will stay there without moving.

Another example shows the very dominant nature of *dying away*. When asked what would happen if the car is pushed along a surface without resistance, the student initially gives a prediction that appears normative (the car will go on and on). However, after being prompted, the student changes her prediction and uses *dying away* to justify it:

2. S: ...if the floor is very smooth, when the girl pushes the car it moves because the wheels go on and on. And at the end it depends on a wall or something to stops the car.

R: What if there is not a wall or something like it?

S: The car keeps going with the same velocity, but it decreases at some point because the car does not have more push.

Dying away may be represented as a stock of stored force with *using* as its outflow. In this case, however, the outflow is more like a “mysterious outflow” that simply “lets” the given force “escape” during motion (Figure 6). Choosing a flow symbol to represent *using* seems reasonable even though students would not express it this way. This symbol captures the idea that time needs to pass for velocity to decrease.

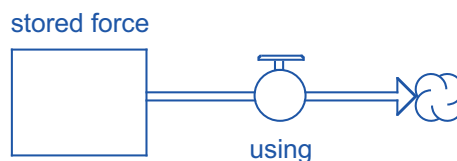


Figure 6. Stock and flow representation of *dying away*

The *dying away p-prim* has been documented and described in great detail by diSessa (1993). This p-prim serves to interpret situations in which the amplitude of an effect seems to gradually diminish until it dies, such as a soup getting colder, the sound of a

bell decaying after being struck, and the amplitude of a pendulum after releasing it (diSessa, 1993). Interpretations similar to *dying away* have also been identified in ecology where students use “disappearing”, “wearing out” or “eaten” (rather than turning into mineral matter) to explain what happens to organic matter during the decomposition process (Grotzer & Basca, 2003).

Most situations in which these interpretations (using up, dying away, wearing out) are cued, are characterized by an observable continuous decaying pattern of behavior and, importantly, a lack of an identifiable cause of that behavior.

4.2.2. Problematic intuitions

Those intuitions that complicate reasoning about stocks (*force sustains motion* and *velocity proportional to force*), also compromise students’ interpretations of flows. These intuitions (described in section 4.1.2) ignore the *pass of time* in the process of “building up” or “losing” velocity, which is the very property that characterizes a flow.

4.3. Intuitions of net-flow

The following element involves both useful and problematic intuitions about *multiple influences* and *net effects*. We describe these elements together since they have rather similar properties. These elements correspond to diSessa’s *canceling* and *overcoming p-prims*.

4.3.1. Useful intuitions

Canceling and overcoming

Canceling is the idea that no-change in the state of a system is the result of an ongoing equality between opposing influences. An example is when the car is continuously pushed and it moves at a constant velocity. In this case, students may

see the push as competing with the weight of the car to keep the car moving at a constant velocity or simply moving at all:

1. R: Why is the velocity constant?

S: Because the force of the girl is equal to the weight of the car.

R: Can you explain that?

S: Well, they [applied force and weight] go together. I mean she has to apply a force depending on the weight of the car.

2. R: What if the girl applies a force that is greater than the weight of the car?

S: The car will go faster and it wouldn't be constant. She has to apply the same weight so that the car doesn't move more.

Overcoming, on the other hand, is the idea that an ongoing difference between opposite influences is necessary for change (e.g., increasing velocity) or no-change (e.g., constant velocity). In the case of the car, for instance, overcoming is used to explain constant velocity as being the result of a continuous steady difference between the applied force and the weight of the car (or a resistance force) (fragment 3 below).

3. R: So why is the velocity constant?

S: Because she doesn't push it more or break less.

Both *canceling* and *overcoming* may be represented as in Figure 7. From this representation, it is possible to describe what is useful about these elements: they involve ideas of balance (an imbalance) that are useful to reason about equilibrium or change in stocks.

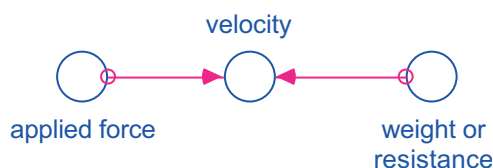


Figure 7. Stock and flow representation of canceling and overcoming

4.3.2. Problematic intuitions

Figure 7 also shows what is problematic about *canceling* and *overcoming*: here the net-effect causing the balance (or imbalance) is not dynamic (as in the case of the net-flow in Figure 2) but static (as in the case of force and mass ($a=F/m$) also in Figure 2). Therefore, these elements do not necessarily involve a normative idea of net-flow, but they could indeed be useful for constructing this concept.

Canceling and *overcoming* have been described by diSessa (1993). Students use *overcoming* and *canceling p-prims* to interpret the final condition (change or no-change) in situations of opposing influences (diSessa, 1993). A no-change in condition or ‘lack of result’ is explained by the *canceling p-prim* as one influence being undone by the other. Otherwise, the *overcoming p-prim* interprets the new condition as one influence winning over the other and achieving its “intended result” (diSessa, 1993). *Overcoming* is used to explain the decreasing velocity of an object thrown straight up as the result of the force of the hand winning over the force of gravity. Likewise, *canceling* of these two forces is used to explain what happens when the object is at the top: the force of the hand and gravity cancel each other out.

Research from system dynamics also documents students’ useful intuitions about net effects of multiple influences. Sweeney and Sterman (2007) observed that, when reasoning about populations, some students appropriately assume that an equality between births and deaths is required for the population to stay in equilibrium: “The population will stay the same because each day a baby is born and each day somebody dies.” (Sweeney & Sterman, 2007, p. 299). Also Cronin and Gonzalez (2007) observed that students appear to use the net effect between two influences (rather than focusing on a single salient cause) to estimate the changes in variables like the money in a bank account and the people on a building.

In general, intuitions of overcoming and canceling are cued in situations where multiple influences are perceived to compete or work together to sustain behavior.

4.4. Intuitions of instantaneous causality

4.4.1. Useful intuitions

The following element involves ideas of *direct effect*. As we saw in the section on intuitions of stocks, students already possess multiple ideas of instantaneous change. Hence, we may assume, that helping students reason about instantaneous causality does not impose a significant challenge for teaching. However, the challenge consists in helping students realize when their intuitions of instantaneous change apply and when they do not. The following element illustrates a case in which students' intuition of instantaneous change are appropriate. We name this element: *slipperiness reduces the decrease in velocity*.

Slipperiness reduces the decrease in velocity

This element involves the idea that slipperiness decreases the rate of decrease of velocity. In the case of the car, students use *slipperiness reduces the decrease in velocity* to explain that after giving a push to the car along a surface without resistance, the car will slow down more slowly than on the normal surface. The following fragment is representative:

1. R: What would be the difference between moving on a normal floor and on a very smooth floor?
S: I don't know.
R: Think about ice.
S: Oh yes, like on the skating place? It is different because it is more slippery obviously.
R: What would be the difference?
S: Uhm...i don't know...on the ice it moves faster.
R: Will they start slowing down at the same time on both floors?
S: No here, it decreases more slowly because it is more slippery.

Slipperiness reduces the decrease in velocity is an intuitive approximation to the concept of flow. Students have an idea that velocity may decrease slower or faster but

the mechanism through which this happens is still unclear. Therefore, we represent this element as a stock of velocity with *decreasing velocity* as its outflow, which is affected by *slipperiness* (Figure 8). Again, using a flow symbol to represent *decreasing* may still overestimate students' knowledge. Nevertheless, *slipperiness reduces the decrease in velocity* indeed involves an idea of the need for time to pass for velocity to decrease, and of the relative magnitude of the change (i.e., slower, faster).

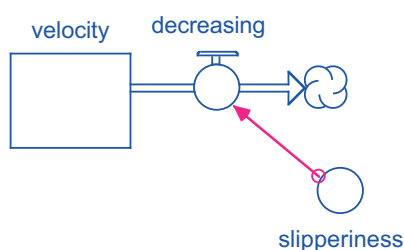


Figure 8. Stock and flow representation of *slipperiness reduces the decrease in velocity*

Slipperiness reduces the decrease in velocity could be seen as an instance of diSessa's *ohm's p-prim* as: the more slippery, the less the decrease in velocity; and the less slippery, the more the decrease in velocity. This however, would be a quite advance instance of *ohm's p-prim*, since it requires distinguishing the result (recall that *ohm's p-prim* has three elements: effort, resistance, and result) as the "decrease in velocity" rather than as velocity itself.

Nevertheless, we consider *slipperiness reduces the decrease in velocity* as a useful but still rather primitive knowledge element; students have an idea that slipperiness affect velocity, but they mix up "decreasing" with "increasing" effects. The following fragment (2) illustrates this. Fragment 2 also illustrates that *slipperiness reduces the decrease in velocity* may not always be expressed by students as clearly as in fragment 1.

2. R: So, what would be the difference between moving on a normal floor and on a very smooth floor?

S: That on the very smooth floor the car goes faster but the velocity will obviously decrease.

R: Will the velocity begin decreasing at the same time than on the normal floor?

S: No! I say it decreases more easily on the normal floor.

R: Why is it so?

S: Because it is not that smooth for the car to keep moving.

R: So what would the very smooth floor do?

S: It like increases the velocity.

Slipperiness reduces the decrease in velocity was displayed by only three of the students. Other three students exhibited a similar but simpler element that we call *slipperiness prolongs motion*. The students using *slipperiness prolong motion* articulate the idea that the slipperiness of the surface affects how far an object moves, but they are less specific about how this happens. In other words, students affirm that on a slippery surface objects will move further or longer, but they do not explain that this is because slipperiness makes velocity decrease more slowly. We do not present *slipperiness prolongs motion* as a separate element, because it is difficult to tell from the data whether the students actually possess the more advanced element of *slipperiness reduces the decrease in velocity*. They were not prompted by the researcher to provide further explanations of how slipperiness actually prolongs motion.

4.4.2. Problematic intuitions

Students tend to replace accumulations with instantaneous change. It seems quite obvious that this is because instantaneous cause and effect is an easier concept than accumulation. Consequently, it is not surprising that we have found no instances of storing ideas applied to instantaneous relationships. However, diSessa reports that some students use the *change takes time p-prim* to reason about the effect of an

applied force on an objects' acceleration, which is an instantaneous effect according to Newton's Laws: "Some students believe the acceleration that a force causes in an object, especially if [the force] is very rapid, continues for a time after the force ceases." (diSessa, 1993, p. 133)—because it may take time for the effect of a force to fully develop.

5. Discussion

We have shown that students' intuitive knowledge of causality and dynamic change is diverse but limited, and it requires significant restructuring. However, we also found that students have intuitions that are consistent with certain properties of stock and flow representations. In what follows, we first point out the teaching challenges posed by dynamic systems, based on own and previous research. Based on this research we propose a five step teaching strategy for dynamic systems. While these steps seem to follow logically from the research, we stress the need to test and refine in real teaching situations.

We also showed that the intuitions exhibited by the students in our study are similar to those observed in previous research. Uncovering and reporting students' intuitions, particularly those that are problematic, was a key focus of educational research for over two decades (see Confrey (1990) and McDermott (1984) for reviews). Now extensive literature documents these intuitions in great detail and current efforts are pointing to the need of defining frameworks for the formulation and analysis of particular instructional interventions and their effects on conceptual change (e.g., (Cobb, Confrey, diSessa, Lehrer & Schauble, 2003; diSessa & Cobb, 2004; Parnafes, 2005). This paper is a contribution in that direction. Departing from the assumption that students have not only problematic but also useful ideas that can be use for further learning (Brown & Clement, 1989; Clement, 1993; Clement et al., 1989; diSessa, 2009a; Minstrell, 1982; Parnafes, 2007), we propose a step-wise program for formulating teaching interventions using stock and flow diagrams (SFD). Based on our analysis of students' intuitions, we can identify as the main challenges for

teaching and learning: the dominance of instantaneous rather than accumulation thinking, and the pervasiveness of “spurious” influences or historical observations to explain behavior—i.e., lack of causal element in students intuitions. These results are in line with Moxnes (1998) and Sterman and Sweeney (2000; 2007).

5.1. Program for teaching using problematic and useful intuitions:

In what follow we present our five-step teaching program for intuitive knowledge refinement, then we provide an example using a water tank analogy of SFDs.

1. Know what problems to be aware of. Know which useful and problematic intuitions students may possess of the dynamic system under study.
2. Know what cues to use to provoke useful and problematic intuitions.
3. Know what questions to ask to increase awareness of both useful and problematic intuitions. Useful intuitions can be engaged and reinforced for advancing learning. Problematic intuitions can be confronted by helping students see those contexts in which their intuitions may or not apply. This will contribute to reduce over confidence in the intuition and to open the opportunity for further refinement.
4. Know how the SFD and particular SF analogies—such as the water tank, can be used for advancing steps 2 and 3. The SFD can provide opportunities for both provoking intuitions, and increasing students’ awareness of what is appropriate or not in a given context. Particularly, learning through SFDs involves transferring knowledge from a system source (such as the water tank) to other target systems. This offers opportunities for provoking useful intuitions in contexts that are well-known to students and re-engaging these intuitions in challenging contexts.
5. Know which contexts of application of SFDs can contribute to reinforce the useful and newly refined intuitions. Repetition may help stimulate students’

awareness of systematicity across systems by increasing the repertoire of context in which students can see the same intuition to apply.

As an example of application of our teaching program, consider diSessa's (1993) *dying away p-prim* (described in sections 2.1. and 4.2.1.). The *dying away p-prim* is useful in the sense that it involves an awareness of the past of time in the decrease in velocity; however, it is problematic in the sense that it misses the causal element (outflow) causing velocity to decrease. To refine this p-prim, in our interventions, we present students first with a water tank analogy of SFDs. We show students a computer interface with a tank full with water and ask them to empty the tank (while the outflow is hidden). This leads students to identify the *need* for a pipe through which the water can flow out the tank for the stock to decrease. Later on, we use the same analogy to reproduce a similar situation in the context of motion. We show students a stock of velocity decreasing and ask them to explain why it does so. We expect students to re-engage in the motion context the useful idea learned in the context of water –the need for an outflow for the stock to decrease. This teaching move opens the opportunity for further exploration of the flows as the cause of the change in velocity, and decreases student reliance on the “spurious” explanation given by *dying away*. In this case, the useful intuition about change over time given by the *dying away p-prim* is kept, but it is refined by the addition of a causal element explaining such change (see for Saldarriaga (2011c) for empirical evidence). Clement and Brown's (1989; Clement, 1993) example on bridging analogies presented in section 2, provides further evidence on how useful intuitions can help refine problematic ones.

Our step-wise program for teaching is not exhaustive, nor definitive; however, its main contribution is to emphasize a particular fundamental aspect involved in learning with the SFD or any instructional analogy: the role of students' prior knowledge of the target domain. By describing students' intuitions of the target domain, we are opening the exploration of a new avenue for teaching with SFD. In this view, the focus of a teaching intervention is not solely on the de-contextualized SF knowledge that we would like students to learn and transfer. Instead, we also take

into account what students already know of the target domain. If students' existing knowledge is problematic, it would require transformation. However, this transformation can get compromised if students do not see the plausibility of alternative SF explanations in the first place. In such a case, students' intuitions that are consistent with SF thinking can be engaged during teaching (used in turn as analogies) to help students see the applicability and build confidence on SF explanations.

In general, this paper constitutes a very initial step in the cycle of formulating and testing research-based teaching strategies using SFD. To the extent that dynamic systems are present in multiple contexts and domains, the SFD provides an important generic tool for knowledge transfer. Nevertheless, this paper offers an initial glance of the possible challenges—associated with students' existing knowledge, involved in learning and teaching with SFD. Other related challenges are presented and discussed in great detail in Saldarriaga (2011a; Saldarriaga, 2011c; Saldarriaga, Christensen & Moxnes, 2011). Awareness of these issues should not only contribute to improving teaching, but also to refine our assumptions of the nature of SF knowledge and what is involved in learning such a knowledge.

References

- Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science*, 18(4), 237-261.
- Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In *International handbook of research on conceptual change* (Stella Vosniadou ed.). (pp. 127-54). New York: Routledge.
- Clement, J. J. (1998). Expert novice similarities and instruction using analogies. *International Journal of Science Education*, 20(10), 1271-1286.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, 30(10), 1241-1257.
- Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education*, 11(5), 554 - 565.

- Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, 32(1), 9-13.
- Confrey, J. (1990). Chapter 1: A review of the research on student conceptions in mathematics, science, and programming. *Review of Research in Education*, 16(1), 3-56.
- Cronin, M. A., & Gonzalez, C. (2007). Understanding the building blocks of dynamic systems. *Syst Dyn Rev*, 23(1), 1-17.
- Cronin, M. A., 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*, 108(1), 116-130.
- diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10(2/3), 105-225.
- diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction*, 25(4), 523 - 565.
- diSessa, A. A. (2009). The construction of causal schemes: A cognitive analysis with a dialectical point. *AIP Conf Proc*, 1179(1), 11-14.
- diSessa, A. A., & Cobb, P. (2004). Ontological innovation and the role of theory in design experiments. *Journal of the Learning Sciences*, 13(1), 77 - 103.
- diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, 28, 843-900.
- Forrester, J. W. (1961). *Industrial dynamics*. Productivity Pr; Student Edition.
- Forrester, J. W. (1968). *Principles of systems*. Cambridge, EUA : Wright-Allen.
- Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge University Press.
- Grotzer, T. A., & Basca, B. B. (2003). How does grasping the underlying causal structures of ecosystems impact students' understanding?. *Journal of Biological Education*, 38(1).
- Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions?. *The Journal of the Learning Sciences*, 5(2), 97-127.
- Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, 30, 141-158.
- Masson, S., & Legendre, M. -F. (2008). Effects of using historical microworlds on conceptual change: A p-prim analysis. *International Journal of Environmental & Science Education*, 3(3), 115-130.
- McCloskey, M. (1983). Naive theories of motion. In *Mental models* (Dedre Gentner & Albert L. Stevens ed.). (pp. 299-322). New Jersey: Lawrence Erlbaum Associates.

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- McDermott, L. C. (1984). Research on conceptual understanding in mechanics. *Physics Today*, 37(7), 24-32.
- Minstrell, J. (1982). Explaining the "at rest" condition of an object. *Phys Teach*, 20(1), 10-14.
- Moxnes, E. (1998). Overexploitation of renewable resources: The role of misperceptions. *Journal of Economic Behavior and Organization*, 37, 107-127.
- Moxnes, E., & Saysel, A. K. (2009). Misperceptions of global climate change: Information policies. *Climate Change*, 93, 15-37.
- Parnafes, O. (2005). *The development of conceptual understanding through the use of computational representations*. Phd thesis. University of California, Berkeley.
- Parnafes, O. (2007). What does "fast" mean? Understanding the physical world through computational representations. *Journal of the Learning Sciences*, 16(3), 415-450.
- Saldarriaga, M. (2011). *A case study on "reverse transfer": When learners modify a water tank analogy to fit physics intuitive knowledge*.
- Saldarriaga, M. (2011). *Learning with water tank analogy: How students' intuitive knowledge of basic dynamics of motion changes during transfer*.
- Saldarriaga, M., Christensen, D. L., & Moxnes, E. (2011). *Students' generalizations of a stock and flow analogy and their supportive and hindering roles in transfer*.
- Sherin, B. (2001). How students understand physics equations. *Cognition and Instruction*, 19(4), 479-541.
- Sterman, J. D., & Sweeney, L. B. (2002). Cloudy skies: Assessing public understanding of global warming. *Syst Dyn Rev*, 18(2), 207-240.
- Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, 16(4), 249-286.
- Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *Syst Dyn Rev*, 23, 285-311.
- Vosniadou, S. (2008). Conceptual change research: An introduction. In *International handbook of research on conceptual change*. (pp. xiii-xxviii). Routledge.

Appendix

What do we know about why objects move?

Instructions

Circle the answer you personally think is the best.

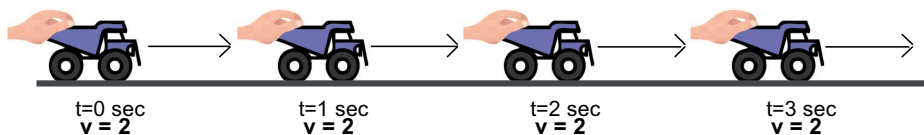
Do not skip any question and answer all of them.

For each question you can only circle ONE answer.

Remember that if something is constant it means that it is not changing.

Use the following description and the picture to answer questions 1 and 2.

A girl is pushing a toy car across the floor. As a result, the car moves at a constant velocity, as shown in the picture.

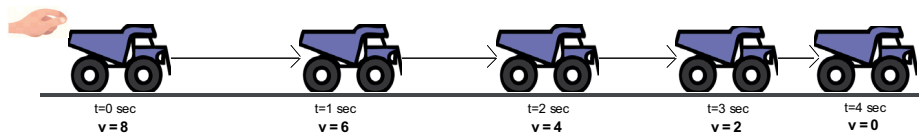


1. This happens because the force applied by the girl:
 - (A) is equal to the weight of the car
 - (B) is greater than the weight of the car
 - (C) is equal to the total force which resists the motion of the car
 - (D) is greater than the total force which resists the motion of the car
 - (E) is greater than both the weight of the car and the total force which resists the motion of the car.

2. If the girl in the previous question doubles the force that she is applying on the car, the car then moves:
 - (A) with a constant velocity that is double the velocity in the previous question
 - (B) with a constant velocity that is greater than the velocity in the previous question, but not necessarily twice as great
 - (C) for a while with a velocity that is greater than the velocity in the previous question, then with a velocity that increases thereafter
 - (D) for a while with an increasing velocity, then with a constant velocity thereafter
 - (E) with a continuous increasing velocity.

Use the following description and the picture to answer question 3.

Assume the toy car is not moving and then the girl gives it a short push. The car moves for some time with a steadily decreasing velocity until it stops again, as shown in the picture.



3. This happens because:

- (A) the force applied by the girl decreases until it becomes zero
- (B) there is a constant force resisting the motion of the car
- (C) there is an increasing force resisting the motion of the car
- (D) the constant force resisting the motion of the car wins over the force applied by the girl
- (E) velocity has a natural tendency to finish.

Use the following description to answer question 4.

The girl puts the car from question 3 on a completely smooth surface so that the surface does not create any resistance to the car's motion. Neither are there any other forces resisting the motion. The car is not moving and the girl gives it a short push.

4. After the short push, the velocity of the car:

- (A) stays constant and different from zero
- (B) stays constant and equal to zero
- (C) decreases steadily
- (D) increases for a while and decreases thereafter
- (E) stays constant and different from zero for a while and decreases thereafter.

Paper 2:

*Learning with a water tank analogy:
how students' intuitive knowledge of basic dynamics of
motion changes during transfer*

Learning with a water tank analogy: how students' intuitive knowledge of basic dynamics of motion changes during transfer

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Abstract

A current challenge in educational research is to find teaching tools and strategies that help students move from their *intuitive knowledge* of the physical world towards scientific theories and principles. This paper explores how students' intuitive knowledge of basic *dynamics* of motion changes when students are instructed to use a *water tank analogy* to make sense of motion phenomena. The water tank analogy illustrates a *stock and flow* (SF) conceptualization of dynamic systems. Stocks symbolize things that can be accumulated over time—as water in a tank. And flows are the rates at which stocks change—as the flows of water through the valves going in and out of a tank. During a six weeks period, 12 seventh grade students participated in a teaching intervention on motion. Individual interviews were conducted at the end of the intervention to explore students' learning with the tank analogy. Learning episodes were analyzed with a focus on: (1) what knowledge students attempt to transfer from the tank analogy (source) to motion (target); (2) what existing intuitive knowledge intervenes in this process of transfer; and (3) how students' understanding of the target context changes during transfer. We find that transfer *does* occur and students' intuitive knowledge *does* change in this process. The tank analogy helps students find plausibility in causality and dynamic behavior that they saw implausible before the intervention. The results provide empirical evidence of the complexities involved in transfer and our analysis contributes to the general understanding of how knowledge of *dynamic systems* develops during learning, particularly when using a SF analogy.

1. Introduction

The profuse literature on students' difficulties in understanding science concepts and phenomena emphasizes the need for teaching strategies to overcome these difficulties. A key challenge for such strategies is to bridge the gap between scientific theories and intuitive knowledge based on experience. Students must learn to move with ease between these two arenas for learning and also learn to apply acquired knowledge in contexts different from the ones in which initial learning occurred (Lobato, 2006). Such teaching requires tools. This paper explores the use of a *water tank analogy* to help students develop a scientific understanding of Newton's First and Second Laws. Newton's laws describe the *dynamics* of motion and are known to be the source of severe learning difficulties for students.

The water tank analogy consists of a water tank with pipes and valves for adding water to and removing water from the tank. The amount of water in the tank changes as water is added or removed over time. The water tank analogy represents a *Stock and Flow* (SF) conceptualization of dynamic systems. Stocks symbolize things that can be accumulated over time – as water in a tank (e.g, people, money in a bank account, velocity). And flows are the rates at which stocks change (e.g, births and deaths of people; saving and withdrawal of money, acceleration and deceleration of velocity).

All dynamics arise from the accumulation of flows into stocks over time, and therefore, the common assumption when using the water tank analogy in teaching is that experimenting with it should help students understand how *any* stock and flow relationship gives rise to behavior over time. In other words, the premise is that learning with the tank analogy enables students to *transfer* and use the SF knowledge gained through the tank analogy (source) to develop or *change* their existing understanding of dynamic systems in other contexts (targets). In this paper we

explore these phenomena of learning using motion as a target context. Specifically, our inquiry focuses on three questions:

(1) *What knowledge students transfer from the tank analogy to the context of motion?* To answer this question, we look at the knowledge associated with the tank analogy in terms of small bites of knowledge that we call *SF Insights (SFIs)*. We identify these SFIs in students' explanations and track them throughout episodes of transfer.

(2) *What existing intuitive knowledge intervenes in this process of transfer?* We identify and track intuitive knowledge elements in the same way as SFIs. The intuitive elements we identify correspond to *phenomenological primitives (p-prims)* that have been previously described in the literature.

(3) *How students' understanding of the target contexts changes during transfer?* By tracking SFIs and p-prims we can explore the learning outcome of teaching episodes. Focus is on how student explanations shift or do not shift from p-prims to SFIs; i.e. we describe the competition between SFIs and p-prims.

The empirical basis for our analysis comes from individual interviews with 12 seventh grade students from Colombia. The interviews were conducted at the end of a six-week (14 hours in total) teaching intervention during which students were instructed to use the tank analogy to make sense of basic motion phenomena. The three research questions above make our study exploratory and qualitative in nature. We do not attempt to *quantify* learning or to *test* the relative effects of different teaching interventions. Neither, do we aim at suggesting a *model* of learning. Rather, our aim is to establish an initial framework to advance understanding of *what* is learnt and *how* learning with the tank analogy occurs.

Our work builds on prior research on analogical reasoning and knowledge change by Kapon and diSessa (2010). Particularly, we use a simplified version of Kapon and diSessa's construct of *priority* to describe students' apparent perception of the plausibility of a competing knowledge element.

Our work differs from the existing literature in that we use a water tank as source analogy, and that we use SF diagrams (SFDs) as a transfer tool from the tank to the motion problem. The SFD is a generic transfer tool for dynamic systems originally developed by Forrester (1961; 1968). Moreover, our description of the knowledge associated with the tank analogy in terms of basic SFIs, constitutes a framework for “measuring” and tracking the development of conceptual understanding of dynamic systems from source to target.

Our findings suggest that students do transfer SF knowledge (SFIs) from the tank analogy to the context of motion, and the outcome of this transfer is, in many cases, a change in student’s understanding of motion. For instance, by realizing that velocity can be different from zero even if its “flows are closed” (no forces acting on the object), students come to see that velocity can be stored, and that therefore, a force is not necessary to *sustain* motion. This change in understanding implies that the SFI called *storing* comes to dominate the p-prim called *force sustains motion*. Also, by realizing that velocity will remain the same unless “one of its flows is changed” away from equilibrium, students come to attribute the cause of a decrease in velocity to the presence of an opposing force that “opens” the outflow of velocity. This change in understanding implies that a SFI called *flowing* (i.e., stocks change through flows), comes to dominate over a p-prim called *dying away*, according to which, velocity simply ends or dissipates as the object moves.

We also observe that for SFIs to dominate p-prims, it is not sufficient that students *grasp* a particular SFI and *notice* how this can be applied to the motion context. Instead, change in knowledge requires that the student be convinced that a particular SFI is a *more plausible* explanation than a competing p-prim. Hence, *competition of knowledge* is what characterizes the process of knowledge change when students attempt to transfer the tank analogy to the motion context. The student’s perception of plausibility determines the outcome of the competition. That is, successful transformations such as the ones illustrated with the *force sustains motion* and *dying away p-prims*, require that students perceive the SF explanation as necessarily more plausible than these competing p-prims.

As an example of competition, consider once more the *flowing SFI* and the *dying away p-prim*. One of the contexts explored during the interviews is that of a toy car that is pushed along a surface without resistance. When asked to predict what will happen with the car's velocity after the push, some of the students predict that the car will move for a while but it will *have to stop* at some point. When asked to explain this prediction, the students respond that the car will stop when moving on a normal surface because of the presence of a resistance force controlling the outflow of velocity (*flowing SFI*); however, they also respond that the car will stop when moving on a surface without resistance force because "the force given to the car in the push simply ends as the car moves" (*dying away p-prim*). In these cases, the students appear to indeed find plausibility in *flowing SFI*, but they struggle to give complete priority to this SFI over the *dying away p-prim*. Instead, the students are satisfied with allowing both explanations to coexist. In some of these cases, students come to successfully prioritize the SFI over the p-prim by realizing that *flowing SFI* is a plausible explanation for both contexts: in the presence of a resistance force, the outflow of velocity is opened; and in the absence of this force, the outflow of velocity is closed.

To the extent that successful transformation of intuitive knowledge occurs and that the water tank analogy helps students consider a range of possibilities for motion systems that they did not see to exist before, the water tank analogy constitutes an effective tool for knowledge change. Our results however, also show possible conflicts of knowledge that can occur during transfer. Teachers' awareness of these conflicts should in turn contribute to future formulations of improved teaching interventions to ensure that the water tank analogy has its intended effect. Such interventions seem equally important for other SF analogies and when using SFDs. Particular teaching efforts are needed to help students see an SF analogy as representing and explaining the *same* phenomenon that they experience in real life. In other words, we need to find teaching interventions that connect SF representations with world phenomena observed by learners.

The paper is organized as follows. First we present our framework: we describe the tank analogy, the stock and flow diagram (SFD) for motion, and we discuss briefly the transfer literature with a focus on Kapon and diSessa's (2010) work on knowledge competition. Next, we present the research design including descriptions of the teaching intervention and the interviewing methods. Finally we present our results organized in *episodes of knowledge change* taken from the interviews. These episodes take place as students attempt to transfer SF knowledge from the tank analogy to different motion contexts. For each episode we answer our three research questions: (1) what SFI is being transferred, (2) what p-prim is competing with the SFI, and (3) what is the outcome of the competition. We conclude with a discussion of results, methodology, and further research.

2. Framework

In this section we first look at the water tank system and demonstrate how it serves as an analogy to the basics of a stock and flow diagram (SFD), and in particular to the problem of motion. We describe the tank analogy not only in terms of its physical elements but also in terms of the knowledge associate with it – the knowledge that a learner must ideally posses to understand a dynamic system and to predict its behavior. We characterize this knowledge in terms of small bites of knowledge that we call *stock and flow insights (SFIs)*.

Then we use a SFD to characterize common *intuitive* knowledge associated with motion phenomena – the knowledge that students already posses of dynamic systems. This knowledge has been characterized in prior research in terms of pieces of knowledge called *phenomenological primitives* (p-prims). Finally, we look at the tank analogy and the SFD for motion in light of theoretical perspectives on transfer of learning with a particular focus on the role of prior knowledge in transfer.

2.1. The water tank analogy and the stock and flow diagram

Consider the water tank system in Figure 1. Here, the water accumulates in the tank as water flows in and out through the pipes, and the magnitude of the flows depends on the opening of the valves (flows are perfectly controlled by valves and do not depend on pipe pressures). The system is interactive; the valves can be opened or closed at different levels by dragging the handles, and students can observe that water accumulates in the tank. How much the water in the tank increases or decreases at any point in time, depends on the difference between in- and outflow.

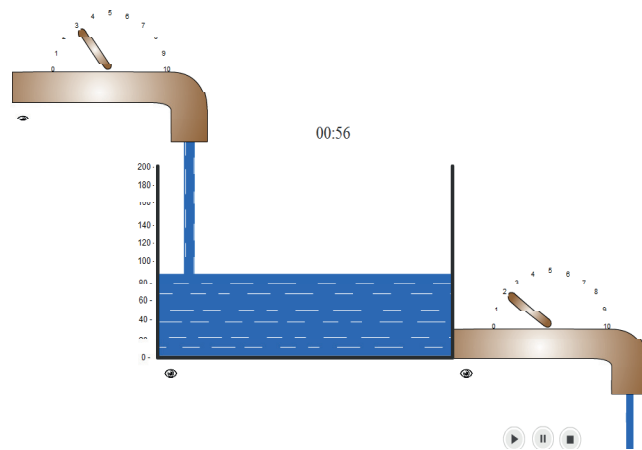


Figure 1. Water tank system representation

This water tank system is an *analogy* to the SFD¹ in Figure 2 and vice versa. An SFD consists of only *four* symbols. Rectangles represent *stocks*, and pipes with valves represent *flows*. Stocks are everything that is stored – as water in the tank (e.g, people, money in a bank account); and flows are the rates at which those stored things change – as the flows through the valves in the tank (e.g, births and deaths of people; saving and withdrawal of money). Thin arrows denote *instantaneous cause and effect relationships*; and circles denote *algebraic expressions* ranging from constants to

¹ The SFD notation used in this paper is a slightly modified version of the one originally developed by Forrester (1961; 1968). The diagrams here have been drawn using iThink software.

complex nonlinear functions. These four elements are in principle sufficient to represent any dynamic system².

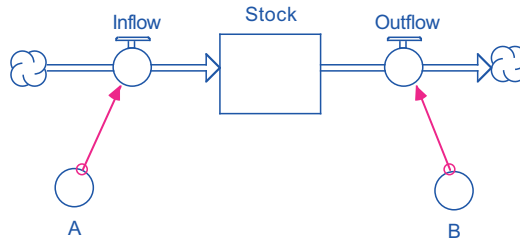


Figure 2. General stock and flow diagram with all four basic elements

2.2. Stock and flow insights

In what follows we use the SFD in Figure 2 to describe seven *SF insights* (SFIs). These SFIs denote *basic knowledge* that is *necessary* to understand the structure and behavior of linear dynamic systems with one stock. Hence, these six SFIs represent what students should take away from the water tank and transfer to the motion problem. Later in our analysis of learning episodes, we use the SFIs to characterize and track students' evolving knowledge of basic dynamics of motion.

1. Instant change SFI. This SFI involves the idea that “changes in one variable leads to an instantaneous change in an affected variable.” In a dynamic system flows are influenced instantaneously by actions; such as between A and Inflow in Figure 2. The essential characteristic of instantaneous causality is that integration over time is not part of its structure and therefore, change occurs instantaneously – in no time.

2. Storing SFI. The storing SFI involves the idea that “if something has the property of storing a quantity over time, it can be thought of as a stock.” A more refined idea

² Distributed systems, for instance a pendulum, where mass is distributed along the pendulum and not concentrated at its end point (as it always is in introductory physics), can be approximated but not perfectly described by a SFD.

involved in this SFI is that “a stock is necessarily influenced by its own past changes – it builds on what has been stored earlier.”

3. *Flowing SFI*. This SFI involves the idea that “stocks change and *only change* through flows.” A stock’s development can only be influenced by modifying its flows through actions, such as A and B in Figure 2.

4. *Accumulation SFI*. This SFI involves the idea that stocks accumulate their net flows over time, where the net flow is given by the difference between the sum of inflows and the sum of outflows. That is: what flows *in* minus what flows *out*. Mathematically, accumulation corresponds to integration:

$$Stock(t) = \int NetFlow dt + Stock(t_0)$$

In SFDs, the idea of accumulation is conceptually represented by symbols resembling a tank analogy where pipes with valves go in and out of the accumulating tank. In contrast to instantaneous causality, the accumulating tank carries the idea that accumulation takes time.

Accumulation can lead to a diversity of changes over time in the stock. Here, we characterize the *accumulation SFI* in terms of two separate SFIs corresponding to a net flow equal to zero and a net flow different from zero respectively: *equilibrium SFI*, and *change SFI*.

5. *Equilibrium SFI*. The *equilibrium SFI* involves the idea that the accumulation of a net flow equal to zero leads to equilibrium in the stock.

6. *Change SFI*. This SFI involves the idea that the accumulation of a net flow different from zero leads to ongoing change (increase or decrease) in the stock.

This distinction is meaningful in our study, since students appear to develop an understanding of *equilibrium* and *change SFIs* in separate ways. That is, a student that exhibits the *equilibrium SFI* may not necessarily exhibit the *change SFI*. Hence, tracking students’ understanding of the *accumulation SFI* as a whole, may underestimate students’ learning.

These six insights represent the key knowledge for interpreting linear dynamic systems with one stock. Other important SFIs that are beyond the purpose of this research relate to *feedback and nonlinearities*.

2.3. Stock and flow diagram for motion and students' intuitive knowledge

Newton's First and Second Laws describes motion dynamics. Figure 3 shows how these two laws can be portrayed in a SFD. Newton's First Law describes the cumulative nature of velocity: velocity integrates (accumulates) net acceleration (i.e., net change) over time. Newton's second law describes the instantaneous nature of acceleration: acceleration is directly proportional to the magnitude of the net force and inversely proportional to the mass of the object ($a=F/m$).

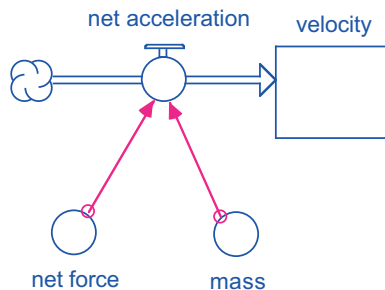


Figure 3. SFD for motion

This SFD for motion follows Newton's notation in which forces are aggregated into *net* forces and the changes in velocity are aggregated into *net* changes –*net* acceleration. However, in the system dynamics tradition, using stock and flow diagrams, we distinguish explicitly between in- and outflows when the flows are influenced by different mechanism. The reason for this can be illustrated by the tank analogy. If there are both in- and outflows, an analogy with a net inflow will deviate from the appearance of the real system and cause confusion. Figure 4 below, shows

the model of velocity when we disaggregate the flow of net acceleration. Here *acceleration* denotes positive change in velocity produced by forces in the direction of velocity, and *deceleration* denotes negative change in velocity produced by forces in the opposite direction of velocity. Normally the word acceleration is used to denote positive net acceleration while deceleration is used to denote negative net acceleration. Our use of words may cause some confusion, however, this is not an unknown challenge in stock and flow systems and we have found no better way to deal with this challenge.

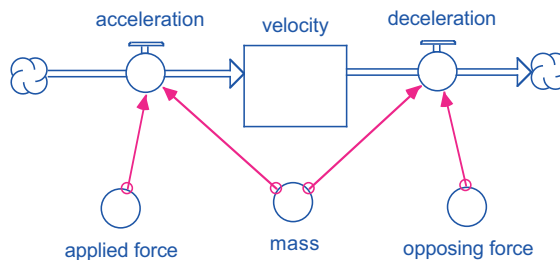


Figure 4. *Disaggregated SFD for motion*

Both SFDs represent correctly the structure of a Newtonian motion system, nevertheless, the disaggregated model is not only closer to the water tank analogy; it also allows us to distinguish the ways in which different forces affect velocity. For instance, “air resistance” involves a different causal structure than a “push” or the “force of gravity”.

The SFDs in Figure 4 is simple and captures an idealized system with only exogenous forces (not functions of velocity) and no other complicating factors. However, despite how basic this system is from an expert’s perspective, educational literature has found that students do not have Newton’s scientific model in mind when dealing with motion phenomena. Rather they operate with simplified heuristics to explain and predict behavior. There is now a considerable literature describing a surprisingly large number of intuitive understandings used to explain behaviors generated by the system

in Figure 4. Of particular interest here is diSessa's (1993) work on phenomenological primitives (p-prims).

P-prims are small bits of knowledge that allow people to predict and explain behavior in the physical world. P-prims are assimilated from personal experience and they are activated and used at a rather unconscious level. They work more like "obvious" ideas that come to people's mind depending on what they perceive out of a context, rather than like ideas that are deliberately worked out and used. Consider the example of the *dying away p-prim*. Certain phenomena in the world appear to exhibit decaying patterns (movements come to a halt, coffee cups cool down, the sound of a bell decays). For such phenomena, *dying away* becomes an obvious intuition to satisfactorily explain and predict behavior. People believe that an object slows down and comes to a stop because motion *simply has to end*. Because p-prims are applied rather unintentionally and are based on daily life experiences, they become challenging for education when they conflict with scientific theory.

2.4. Transfer and knowledge competition

If students are instructed to use the tank analogy to make sense of motion phenomena, can we expect students to transfer this knowledge? And if so, under which circumstances should we expect transfer to occur?

Before we explore the transfer literature in light of these questions, it is important to clarify our use of the terms *context* and *situation*. In transfer literature, the word *situation* is commonly used to refer to the source and target *contexts of study* in which knowledge is used. In system dynamics however, the word *situation* refers to the state of a system at a specific point in time. To avoid conflicts with these two terms, we use the more general term of *context* when possible.

The classical approach to transfer of learning has been that of *identical elements* initiated by Thorndike (Thorndike and Woodworth, 1901)³. From Thorndike's approach it is assumed that transfer would occur as far as the source and target contexts share identical elements such as physical features or common stimulus. In a series of experiments, Thorndike studied the accuracy of student quantity estimates in one context after learning to estimate the same quantity in another context. For instance, Thorndike and Woodworth studied students ability to estimate the area of circles and triangles after they had practiced estimating the area of rectangles (Thorndike and Woodworth, 1901). They observed that abilities to estimate areas did not generalize across contexts; transfer only occurred to the extent that the contexts shared identical elements. Hence, *shared identical elements* between contexts, was, according to Thorndike's approach, a good predictor of the likelihood of occurrence of transfer.

According to the identical elements approach, the question of whether SF knowledge is "transferable" or not would depend on how similar the water tank system is to the motion systems under study. Since our motivation to use the tank analogy in the first place is that these systems can be shown to share similar elements from a SF perspective, we would expect SF knowledge to be indeed "transferable". And we would expect students to transfer this knowledge once they recognize (or are made aware of) these similarities.

However, more recent research shows that there is more that influences transfer than the mere existence of shared similarities between source and target contexts (Brown & Clement, 1989; Carraher & Schliemann, 2002; Lobato & Siebert, 2002; Saxe, 1989). As a consequence, Lobato (2003) proposed to study transfer from the perspective of the learner rather than of the expert (i.e., teacher, researcher). According to Lobato, what counts as *transferable* needs to be defined according to what learners perceive as similar and generalizable, and not according to what is defined as generalizable from an expert's perspective.

³ See Lobato (2006) and Mestre (2005) for reviews on transfer theory.

A complex aspect of transfer of particular interest here is the *role of prior knowledge*. It can happen during transfer that even if the learner identifies generalizable aspects of an initial task or analogy, attempts to transfer to other target contexts can lead to conflict and competition between the *knowledge being transferred* and the learner's *existing knowledge* of the target. In these cases transfer requires the reconciliation between competing knowledge. Kapon and diSessa's (2010) work in analogical reasoning focuses on this complex aspect of transfer. Their approach is aimed at characterizing the intuitive prior knowledge involved in transfer and its role in students' resolution of conflicts between competing knowledge. Competition between SF knowledge and intuitive knowledge is characteristic of what we observe in the students' episodes of transfer in our study. Therefore, Kapon and diSessa's work is of particular interest here.

Kapon and diSessa's (2010) approach builds on Clement and Brown's (Brown & Clement, 1989; Clement, 2008; Clement, 1993) work on the use of analogies for knowledge change. According to Clement and Brown, the role of an analogy is to enrich the learner's representation of the target context. Specifically, an analogy is a good analogy if elements from the source context can be seen to account for elements in the target context that the learner did not "see" before being exposed to the analogy. In contrast, a bad analogy would be one that has particular elements that cannot be seen to exist in the target context. Hence, in this view good analogies are referred to as *candidates for reality*.

As an answer to the question of what counts as a candidate for reality, Kapon and diSessa (2010) proposed that judgments of the *plausibility* ("reality") of an explanation are a function of the learner's prior knowledge of the target context. That is, prior knowledge of the target determines students' assessments of the plausibility of competing explanations. This implies that students' existing knowledge of motion affects their preference for a SF explanation based on the water tank analogy over a competing explanation based on existing knowledge. Kapon and diSessa used their model to explain episodes of transfer from Clement and Brown's research (1989; Clement, 2008; Clement, 1993). In these episodes students were exposed to multiple

analogies aimed at transforming their initial intuitive ideas of Newton's Third Law (for every action, there is an equal and opposite reaction). Kapon and diSessa applied their model to explain the outcome of the transfer episodes in terms of the apparent *priorities* attributed by students to competing explanations. For instance, in some episodes, the high priority attributed by students to the idea of *rigidity* (the idea that solid objects are not deformable), led students to perceive *springiness* (the idea that solid objects are deformed even if at a macroscopic level) as invalid in the context of a book resting on a rigid table.

Our analysis is inspired by Kapon and diSessa's work, however we use a simpler framework for our analysis. We do not consider epistemological beliefs and we do not distinguish between different categories of *priorities*. We concentrate on p-prims and on the *apparent confidence* of the student in explanations as well as the *stability* of the explanation throughout the transfer episode.

With this view of transfer in mind, we address our three research questions: (1) what SFIs students transfer from the tank analogy to the motion context; (2) what existing p-prims intervenes in this process of transfer; and (3) how students' understanding of the target contexts changes as transfer occurs – i.e., what is the outcome of transfer.

3. Experimental Design

3.1. Participants and design

To explore the phenomenon of learning with the tank analogy, research was conducted in Colombia during the period January to April 2010 over six consecutive weeks, with a two hour long intervention once a week. Twelve students worked in pairs guided by a pre-designed teaching intervention. The students were seventh graders from three public schools in Medellín, Colombia and teaching was outside ordinary class hours. None of the students had received any formal teaching in physics previous to the intervention, and because all of the schools were public, their curriculums were similar. The students were selected by the science teacher at each

school; with no particular instruction for the selection. Since the selections were done at the beginning of the school year, the teachers did not have much previous knowledge of their students upon which to base their choices. The sessions were conducted some in the schools and some at a teachers training center in the city.

The intervention involved two general activities: teaching and interviewing. The teaching sessions allow for researcher-student interactions, which are close to the teacher-student interactions that occur in real school settings. The interviews provide opportunities for observing and describing students' knowledge in more detail than other data collection methods such as testing. In all teaching and interviewing activities, we combine interviewing methods from education (diSessa, 2007; Ginsburg, 1997) and design experiments (Lobato, 2003). From clinical interviewing in education we take the in-depth exploration of the content and form of students' knowledge. From design experiments we take the focus on the study of transfer of knowledge as it occurs under an instructional experience involving multiple variables (teacher role, teaching sequence and tools) rather than a systematic variation of single variables (Lobato, 2003). diSessa (2009b) reports the growing number of research in education that combines realistic learning conditions with rigorous analysis of the phenomenon of learning.

Table 1 below gives an overview of the general procedure followed during the six weeks of intervention. In what follows, we present the rationale for the different teaching and interviewing activities.

Table 1. Research design overview

Ses- sion	Activity	Activity Overview
1	Tank Teaching Sequence	(1) <i>Change takes time p-prim</i> : change <u>does not</u> take time for flows of water to change, but it <u>does</u> take time for water to accumulate in the tank. (3) <i>Not ohm's p-prim</i> : stock of water is not proportional to flows (4) <i>Not overcoming p-prim</i> : inflows higher to outflows, or viceversa, is only necessary to keep the stock of water changing. (5) <i>Not canceling p-prim</i> : equal inflows and outflows keep the stock of water without changing. In other words, a constant stock of water is the result of canceling of inflows with outflows. (6) <i>Not dying away p-prim</i> : stock of water can only change through flows. If the stock changes, there must be a flow acting to produce such change.
		Practice with Tank Interface Students are given tasks related to the tank teaching sequence. They work in pairs and use the tank interface to solve the tasks.
3	Test car motion	Students are given a conceptual test about the motion of a car. The test is given without any reference to the activities in session 1 and 2.
	Pre-interview about test answers	Interviews are conducted with each student individually with the aim of understanding students' reasoning for giving particular answers in the test. The data from these interviews is presented in Saldarriaga (2011b).
4	Car Teaching Sequence	(1) <i>Velocity as water in tank</i> : 1. Students explore three predetermined animations of a car moving at an increasing, a decreasing, and a constant velocity. There are indicators for time and velocity. 2. Students are asked how the tank could be applied in the case of the car; the idea of velocity corresponding to water in the tank is proposed and discussed. Three case studies from students' answer to this question are analyzed in Saldarriaga (2011a). (2) <i>Acceleration and deceleration as flows</i> : 1. Students are asked what they understand by acceleration and deceleration. 2. Students explore the car interface for the first time. 3. The idea of acceleration and deceleration as the flows of velocity is proposed and discussed. (3) <i>Applying the analogy</i> : 1. Students are presented with 5 scenarios in which the values for acceleration and deceleration are given, and students have to determine how the car's velocity will change over time (i.e., increase, decrease, stay constant). The students are asked about the values of acceleration and deceleration that produce every behavior with the researcher emphasizing what behaviors result from overcoming or canceling of flows. 2. The process is reverted. Students are presented with different patterns of change of velocity and they are asked to determine values for acceleration and deceleration that explain such a patten of change. Again, the researcher provides questions and guidance. (4) <i>Forces as the actions that control the flows</i> : 1. The researcher points to the fact that until now flows of acceleration and deceleration have been changed directly and then asks the students how objects are accelerated or decelerated in real life. The idea of forces as controlling the flows of acceleration and deceleration is proposed and discussed. 2. Two sets of tasks, now including the applied and resisting forces are given to the students. The procedure follows the ones for previous tasks.
		Test car motion Students are given once more the conceptual test about the motion of a car.
6	Post-interview about test answers	Interviews are conducted with each student individually with the aim of understanding students' reasoning for giving particular answers in the test. Also, in contrast to the pre-interview, in these interviews the researcher acts as a teacher trying to influence students' knowledge by encourage reflection and use of the tank.

3.2. Teaching

For the teaching activities, we developed two teaching guides: the Tank and the Car Teaching Sequences⁴. Two computer interfaces, the Tank and the Car Interface, were used to support the respective teaching sequences.

Tank and Car Interfaces

The interfaces are aimed at providing user-friendly, interactive representations of the tank analogy and its application to motion. A screen-shot of the Tank Interface was presented in Figure 1 in the Framework section. This interface involves the main three variables of the tank analogy: a stock of water, an inflow, and an outflow. Using this interface students can simulate different behaviors over time for the stock of water by adjusting the valves of the in and outflows. The interface also allows the researcher to create different scenarios by setting specific initial values and by hiding or making visible the different elements.

The Car Interface (Figure 5) represents the application of the tank analogy to the motion of a toy car in one dimension. Most of the visual elements and functions of the Tank Interface are kept as they were, except for the following changes: (1) names for the accumulation in the tank (“velocity”) and the inflow and outflow valves (“acceleration” and “deceleration”); (2) a toy car which moves according to the velocity accumulated in the tank; and (3) the additional variables of applied force, resisting force, and mass. Thus, the interface makes it possible to observe, at the same time, the object's motion and the underlying causal structure generating the motion.

⁴ Teaching sequences can be requested from the author.

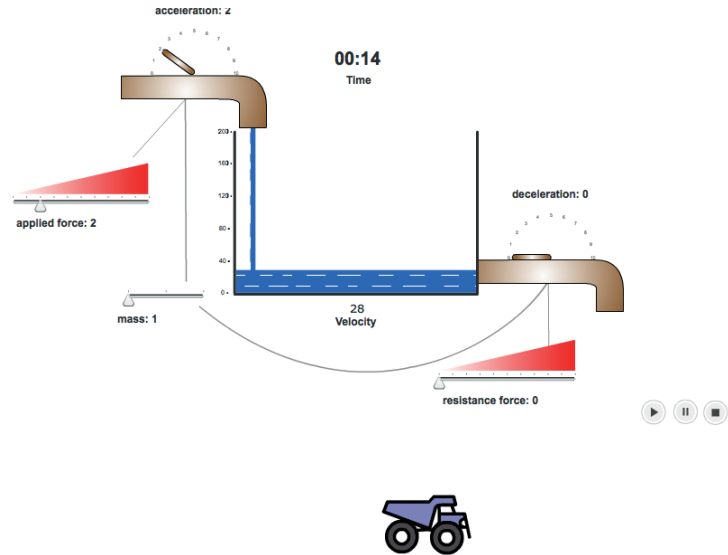


Figure 5. Screen-shot of car interface

Tank and Car Teaching Sequences

The Tank and Car Teaching Sequences were designed and used to guide students' interaction and exploration of the respective interfaces. The Tank Sequence (session 1) directs students' attention to key aspects of the structure and behavior of the tank. The choice of scaffolding was motivated by literature on students' intuitive knowledge of motion phenomena (p-prims). Table 1 shows how teaching is used to help the students learn where these p-prims can or cannot be correctly applied.

The Car Teaching Sequence (session 4) is similar to the Tank Sequence and it directs students' attention to the structure and behavior of the car system. The main purpose of this sequence is to activate their SF knowledge from the tank (source) when considering the car's motion (target). In general, both the Tank and the Car Sequence, are build on the idea that p-prims need to be re-organized (rather than replaced) by re-using them in the contexts where they correctly apply (diSessa, 1993).

3.3. Interviewing

Before we describe the interviewing, it is worth noting that the goal of our teaching intervention is not quantitative. We do not aim at instructing students in calculating exact values for some variable given information about others. Instead, we aim at helping students understand, as Legendre puts it, “the range of logical possibilities” of dynamic causality and behavior “before looking for a precise quantification of the results.” (Legendre, 1997, p. 267).

The interview sessions were semi-structured. The structured portion consisted of a conceptual test given to the students immediately before the interviews. The open part of the interview consisted of following up questions by the researcher about the student’s answers to the test. The aim of using the conceptual test before the interview was to focus students’ reasoning around the dynamic dimensions of the phenomena under study—rather than gathering quantitative data about students’ choices. During the interviews the researcher plays both the role of researcher and teacher; the aim is not only to understand students’ knowledge but also to try to influence that knowledge by encouraging reflection using the tank analogy.

The conceptual test given to the students before the interviews involved questions about the basic motion phenomena explored during the teaching interventions: a car being pushed. Four contexts for the car motion were explored in the test: *constant velocity*, *doubled applied force*, *push and slow down*, and *push under no-resistance* (See the Appendix for test). The style of the questions was based largely on the Force Concept Inventory (FCI) by Hestenes and colleagues (1992). We used the structure and wordings of the FCI to formulate questions that focused on change and causality. The test helps focus attention on certain aspects of the phenomenon in question, but it does not provide information on why students predict or explain a phenomenon in a particular way, which is what we study here. Examining *why* requires qualitative techniques like interviewing. Likewise, the motivation for giving the students specific options rather than open questions, was to explore how plausible students find *a particular set* of explanations for a given dynamic behavior or causality. This purpose

contrasts to wider scope research that aims at documenting the *full range* of explanations that students exhibit of a given phenomena.

3.4. Data analysis

The data presented in this paper come from the post-interviews in session 6 (see Table 1). The interviews were video recorded and analyzed using software for live video coding. The episodes presented in this paper were transcribed verbatim and translated from Spanish to English. The interview with student 11 was eliminated from the analysis. The day of the interview, the student was preoccupied by personal issues and could not concentrate on the interview. The interview was canceled after a few minutes.

The remaining individual 11 interviews were divided into learning episodes associated to the four contexts for the car motion explored in the test—i.e., constant velocity, doubled applied force, push and slow down, and push under no-resistance. Each of these set-ups was specifically designed to study the transfer of respectively SFIs for *equilibrium*, *change*, *flowing*, and *storing*. Next, each episode was analyzed and coded with a focus on characterizing each student's explanations of motion in terms of the SFI being transferred (research question 1) and competing intuitive knowledge elements (p-prims) (research question 2). Also, we characterized the learning outcome of each episode in terms of the explanation prioritized by the student by the end of the episode (research question 3). Here *priority* is judged based on the *apparent confidence* of the student in the explanation and on the *stability* of the explanation during the episode of knowledge change. This indicator should however, be interpreted cautiously. It is not necessarily a reliable measure of stable and lasting priorities. Instead, it should be interpreted as the student's apparent judgment of the plausibility of a certain explanation over another in the context of a particular episode of knowledge change. For the researcher, judging students' priorities is indeed a rather interpretative endeavor. However, in order to strive for robustness, we indicate clearly those cases in which *it is rather unclear to us* what interpretation the student prioritizes by the end of the episode.

4. Results: episodes of knowledge change

In Section 2.2 we listed six stock and flow insights (SFIs). Our results are limited to the SFIs of *equilibrium*, *change*, *flowing*, and *storing*. The two other SFIs are *accumulation* and *instant change*. The *accumulation SFI* is not left out of our analysis, it is simply characterized in terms of the *equilibrium* and *change SFIs*. The *instant change SFI* presents some empirical difficulties, which make this SFI rather “invisible” during coding. This issue is explored in detail in the discussion section⁵.

The episodes are presented in the order they developed during the interviews. This gives the reader an idea of the sequence in which changes may take place. We do not claim that this order represents a universal pattern of knowledge change. The order of the episodes is necessarily influenced by the structure of the interview itself.

4.1. Coming to see the *equilibrium SFI*

The first context explored during the interviews is that of a toy car being continuously pushed by a girl. Students were asked to explain the force applied to the car when the car was moving at a constant velocity.

The purpose of this context is to enable the transfer of the *equilibrium SFI*. Seeing *equilibrium* in the context of motion involves interpreting no change in velocity as the result of inflows and outflows of velocity being equal to each other. Table 2 summarizes our findings for the *context* and the *SFI* in this section. The third column shows p-prims that appear to compete with the *equilibrium SFI* including the possibility that No apparent p-prim is observed. The fourth column identifies, by numbers, the students that use each p-prim. Notice that a single student may use several p-prims and be registered more than once. The last two columns identify the students that, by the end of an episode, appear to prioritize the *equilibrium SFI* over

⁵ Despite the difficulties for observing the *instant change SFI* in our data, this SFI is not likely to be problematic since students’ p-prims repertoire is rich in intuitions of instantaneous causality.

the p-prim or vice versa. In the following we discuss each of the p-prims separately, starting with No apparent p-prim.

Table 2. *Coming to see the equilibrium SFI*

Context	SFI	P-prims involved	Students	Prioritizes:	
				SFI	P-prim
Constant velocity	<i>Equilibrium</i>	<i>No apparent p-prim</i>	1, 6	1, 6	
		<i>Force sustains motion</i>	8, 10	10	
		<i>Overcoming</i>	2, 3, 5, 9, 10, 12	2, 3, 5, 9, 10, 12	
		<i>Proportional to net flow</i>	4, 7		4

4.1.1. *No apparent p-prim*

This category corresponds to students that, when asked to explain the car's constant velocity, use the *equilibrium SFI* without any apparent conflict with competing p-prims. This does not necessarily mean that students 1 and 6 are natural talents that have assimilated the *equilibrium SFI* through own life experiences. Recall that data in Table 2 comes from interviews in the last week of the six-week teaching intervention. Thus it seems likely that when they prioritize the SFI, it is because of the preceding teaching. Here, it is important to emphasize that previous to the intervention, all students exhibited p-prims (see Saldarriaga (2011b)). As can be seen, episodes of No apparent p-prim are the exception rather than the rule. Most students still need help during the interview session to come to prioritize the *equilibrium SFI*.

The following interview corresponds to student 1 of the No apparent p-prim category in the case of the *equilibrium SFI*. "S#" denotes the student, "I" the interviewer, and the words in brackets are clarifying comments added by the researchers during the analysis.

I: I would like you to tell me how you answered the test and if you used the tank, how you applied it. So let's begin with the first case study.

S1: It is like here [pointing to the tank]. For instance, to open the in-valve and the out-valve in that way that both are the same, and so the velocity will always be the same as well (*equilibrium SFI*). So, I say that the force applied by the girl has to be equal to the total force that opposes the motion of the car.

4.1.2. Equilibrium SFI vs. force sustains motion p-prim

The *force sustains motion* or *continuous push p-prim* (diSessa, 1993) says that continuous effort is required to sustain motion. Vice versa, continuous motion is interpreted as the result of sustained effort. Hence, in the case of *force sustains motion*, constant effort explains constant velocity.

Two students exhibit competition between the *equilibrium SFI* and the *force sustains motion p-prim*. Student 10 clearly prioritizes *equilibrium SFI* by the end of the episode. We are not so certain about concluding the same for student 8, hence we do not indicate a priority for student 8 in Table 2. The below interview with student 8 explains why we are uncertain. This episode also illustrates the difficulties of transferring knowledge and how unstable knowledge is at these early stages when the students are still testing the plausibility of different explanations. The episode begins with the student giving an explanation that resembles the *force sustains motion p-prim*:

I: So what is happening in this case?

S8: That the girl is pushing the car constantly and so the velocity of the car doesn't change (*force sustains motion p-prim*).

I: So tell me, why is it that the velocity of the car doesn't change?

S8: Because the force that the girl is applying is constant (*force sustains motion p-prim*).

At this point the interviewer realizes that this student had chosen a different explanation when answering the test previous to the interview. In an attempt to understand the student's shift of reasoning, the interviewer reminds the student of this previous explanation. The student then appears to be constructing an explanation that is consistent with the *equilibrium SFI*. However, it then becomes evident that the student is not very confident in her explanation. The episode ends with the student seemingly prioritizing the *equilibrium SFI*. However, given the uncertainty reflected in the student's answers, we take a conservative approach and do not conclude about the student's priority by the end of the episode.

I: You said before that the force that the girl is applying is equal to the total force that resists the motion of the car. Is this the same you are explaining now?

S8: Yes (*equilibrium SFI*).

I: What do you mean by the force that resists the motion of the car?

S8: Like the floor. The girl can give the car a very high velocity but the floor doesn't let it go at such a high velocity.

I: Did you apply the tank in this case?

S8: Yes, because this [water in the tank] could be in 20, right, and then if the in-valve goes to zero, the velocity...[stays silent for a few seconds]... It could also be that there is an opposing force by the floor.

I: Which is the force that the girl is applying in that case?

S8: Here [pointing all around the tank].

I: What are you pointing at?

S8: Oh that's the velocity [pointing to the tank] and the force is here [pointing at in-valve].

I: Yeah that is the acceleration resulting from the force. And which would be the force that opposes the motion of the car?

S8: Here [pointing at out-valve].

I: So are you saying that this [opposing] is equal to this one [applied]?

S8: Yes because you can have the in-valve at 4 and the out-valve as well. There has to be velocity in the tank already for the car to keep moving the

same (*equilibrium SFI*).

I: What do you mean by the same?

S8: With the same velocity.

4.1.3. Equilibrium SFI vs. overcoming p-prim

The *overcoming p-prim* says that change is the result of one influence winning over a competing one and achieving its “intended result” (diSessa, 1993). This p-prim is related to the *force sustains motion p-prim*, however it differs in that it takes as its starting point the difference between two opposing forces rather than a single force. This difference must be positive to sustain velocity. Students using the *overcoming p-prim* interpret the car’s constant velocity as the result of the force applied by the girl continuously winning over (being greater than) a resistance force. This interpretation clearly contradicts the idea of the *equilibrium SFI*. Six students exhibit competition between the *equilibrium SFI* and the *overcoming p-prim*. All of them appear to prioritize *equilibrium SFI* by the end of the episodes. The following episode for student 3 is representative.

I: I would like you to tell me how you answered the test and if you used the tank, how you applied it. So let's begin with the first case study. Did you use the tank in this case?

S3: Uhhh, not necessarily the tank but the resistance force and the applied force.

I: Could you tell me how you used that?

S3: Yes, can I read the question? [Looks at the text]. The car moves at a constant velocity because the force that the girl is applying to the car is greater than the total force, which resists the motion of the car. See, if the car is moving at a constant velocity and the velocity does not decrease it's because there is not enough force to stop it (*overcoming p-prim*).

I: How would that be in the tank?

S3: Wouldn't it be like adding 2 [size of inflow] and, how do you say that?

I: Removing?

S3: Yeah, and removing 2 [size of outflow]. No, adding 2 and removing 1. That way the tank will fill because it will keep having velocity.

I: What do you mean? What will happen with the velocity in that case?

S3: It will increase.

I: Is that what is happening in this case?

S3: No, the velocity is the same.

I: Does it tell you something?

S3: Oh yeah! It would be like in the tank when it is 2 and removing 2, like if it was the same (*equilibrium SFI*).

After this, the student takes a pen and confidently marks on the test the option: “the force applied by the girl is equal to the total force resisting the motion of the car.”

4.1.4. Equilibrium SFI vs. proportional to net flow p-prim

The *proportional to net flow p-prim*, which we have not found in the literature, appears to have one shared property with the *overcoming p-prim*: students take both the applied force and the resistance force into account to reason about the change in velocity. However these p-prims differ in that for *overcoming* it is only the *sign* of the net flow that matters, while for the *proportional to net flow p-prim* there is an explicit assumption that the stock varies in exact proportion to the *size* of the net flow. For instance, if the applied force is 2 and the resistance force is 1, the net flow is constant and equal to 1. In this case, a student using the *proportional to net flow p-prim*, would assume velocity to be positive, constant, and proportional to 1—however smaller than if the net flow had been 2.

The *overcoming* and *proportional to net flow p-prims* are indeed similar. However, we believe that the *quantitative* proportionalities involved in the *proportional to net flow p-prim*, are activated specifically by students’ exposure to the water tank analogy. The *proportional to net flow p-prim* may reflect students attempt to accommodate the idea of change over time (the stock changing *every period of time* in proportion to the size of the net flow) into their existing idea of *overcoming* (the

stock changing *instantly* in the direction of the sign of the net flow). At the outset, we suspect the *proportional to net flow p-prim* to be more resistant to change than the *overcoming p-prim* because it is more complex and thus harder to influence by teaching with the tank analogy.

Two students exhibit competition between the *equilibrium SFI* and *proportional to net flow p-prim*. Student 4 appears to prioritize the p-prim by the end of the episode, while it is rather unclear whether student 7 ends up with a priority.

In the fragment below, the interviewer inquires student 4 repetitively in an effort to try to understand the reasoning underlying the *proportional to net flow p-prim*⁶.

I: Ok, so what would happen with the velocity if the out-valve is closed and the in-valve is opened?

S4: It would increase. Ummm, it means that the out-valve would also have to be opened, like in 1, for the velocity to stay constant.

I: You mean in less or more than the in-valve?

S4: In less, because if it was more, all the velocity would decrease and the car wouldn't be able to keep moving.

I: Aha.

S4: While if the deceleration is lower than the acceleration, the car will be able to keep moving normally.

I: And what would happen with the velocity?

S4: It will stay the same (*proportional to net flow p-prim*).

I: So let's say that the in-valve is 2 and the out-valve is 1, will the velocity stay the same?

S4: Yes! Because the acceleration is all the time 2 and the deceleration is removing 1 (*proportional to net flow p-prim*).

I: What would happen if these two valves were the same?

⁶ To keep the structure of our results section, we present this example of *proportional to net flow p-prim* here. However, a clearer example of this p-prim is provided in section 4.2.4, where this p-prim is shown to compete with *change SFI*.

S4: It could also be, yes, but the tank will have to have something in it already.

I: Oh ok, so let's assume there is something in it already, what would happen in that case with the velocity?

S4: It would stop.

I: What do you mean?

S4: For instance, uhmm, it stays the same. No, it will flow out. No, yes, it will flow out. I mean the deceleration will make it go out because the velocity is not accumulating but going out. I mean, if it is getting and removing the same, it wouldn't keep any velocity to move (*proportional to net flow p-prim*).

I: What if 1 goes in and 1 goes out? Let's say that the velocity is in 2 and the in-valve is 1 and the out-valve is 1. One goes in and one goes out. What happens with the velocity?

S4: It will stay at the same position, constant (*equilibrium SFI*).

I: Is that what is happening in this case?

S4: [Looking at image in test]. Yes [smiles], yes it could be.

Despite the last line in this fragment, the episode ends with the student going back to prioritizing *proportional to net flow p-prim*.

4.2. Coming to see the *change SFI*

The second context presented to the students consists of the girl in the previous context, doubling the force applied on the car. Students are asked to predict what will happen with the velocity of the car.

This context is used to provoke transfer of the *change SFI*. Seeing *change SFI* in the context of motion involves interpreting any change in velocity as the result of a difference between applied and resisting forces. Table 3 shows the particular p-prims that appear to compete with the *change SFI*. Otherwise, Table 3 has the same format as Table 2.

Table 3. *Coming to see the change SFI*

Context	SFI	P-prims involved	Students	Prioritizes:	
				SFI	P-prim
Double applied force	Change	<i>No apparent p-prim</i>	10	10	
		<i>Dying away</i>	1, 9	1, 9	
		<i>Equilibration</i>	2, 3, 5, 6, 7, 8, 12	2, 3, 5, 6, 7, 8, 12	
		<i>Proportional to net flow</i>	4		4

4.2.1. No apparent p-prim

Student 10 is the only one that does not undergo any apparent conflict when coming to see the *change SFI*. From the very beginning the student predicts that the car's velocity will keep increasing given that the applied force is higher than the resistance force. In this case the role of the interviewer is only to determine whether the student is indeed giving the right prediction for the right reasons.

I: Then the girl doubles the force applied on the car. How will the velocity develop?

S10: It will increase.

I: Why would it increase?

S10: Because the girl applied more force on the car.

I: Why isn't the velocity increasing in the previous case?

S10: Because the girl didn't apply too much force on the car.

I: Is the double of force enough for the velocity to start increasing?

S10: Yes.

I: Why doesn't the velocity stay constant?

S10: Because the girl applied a greater force.

I: Greater than what?

S10: Than the resistance, and that's why the velocity increases (*change SFI*).

4.2.2. *Change SFI vs. dying away p-prim*

Dying away (diSessa, 1993) involves the idea that an object's motion simply has to diminish as the object moves or as time goes. Hence, *dying away* conflicts with the idea of “unlimited” motion. The following episode is representative of the competition between *change SFI* and *dying away p-prim*.

The student in this episode uses *change SFI* to predict that the car's velocity will increase when the applied force doubles. However, the student also predicts that velocity will *have to* begin decreasing after a while. After explaining that velocity will increase, the student reconsiders:

S9: The velocity will increase. But it will have to decrease at some point (*dying away*).

I: Well, that could indeed be the case afterwards.

S9: Well, so if we don't think about when it slows down, then I say that the velocity increases.

I: How is that possible?

S9: Because the force applied by the girl is greater than the resistance (*change SFI*).

In this case, the episode ends with student 9 prioritizing *change SFI*.

4.2.3. *Change SFI vs. the equilibration p-prim*

Similar to student 10, students in this category use the *change SFI* to predict that doubling the applied force leads to increasing velocity. However, the students in the current category predict that velocity will not increase forever; it will eventually stabilize. When asked to explain their predictions, all students use the *equilibration p-prim* (diSessa, 1993). Systems are assumed to have a *natural* state of equilibrium to which it comes back after a destabilizing intervention occurs. We believe that in addition to this, *equilibration p-prim* involves a sense of *limit*. Students believe that velocity cannot keep increasing forever, therefore they assume that, after a while, the

resistance force will have to increase as much as the applied force to take the system back to equilibrium.

Seven students exhibited competition between the *change SFI* and the *equilibration p-prim*. However, despite this high priority use among students, the *equilibration p-prim* does impose significant challenges for coming to see *change SFI* in the context of motion. All seven students exhibiting *equilibration* explicitly state that for the velocity to go back to constant, the resistance force will have to increase too, but that otherwise, the velocity will keep increasing. The following example is representative. The student predicts that if the applied force doubles, the velocity would increase for a while and stay constant afterwards:

I: When does the velocity become constant?

S3: I don't know.

I: What makes you think that it will increase for a while and stay constant afterwards?

S3: Because if I push a car the velocity will increase but it will stay the same after a while. It won't increase (*equilibration p-prim*).

I: What would need to happen for the velocity to stay constant afterwards?

S3: The resistance force.

I: What about the resistance force?

S3: It will have to increase.

I: How much?

S3: As much as the applied force.

4.2.4. Change SFI vs. proportional to net flow p-prim

We showed in section 4.1.4 how *proportional to net flow p-prim* interfered with student 4 coming to see *equilibrium SFI* as an explanation for constant velocity. Here, in the case of double force, *proportional to net flow p-prim* imposes again challenges for student 4 to grasp *change SFI*. The student considers that a net flow of 2 is enough for velocity to increase, but not a net flow of 1. After predicting that the velocity will

increase and then stay constant when the applied force doubles, the interviewer asks the student why the velocity will be constant afterwards:

I: So the velocity becomes constant.

S4: Yes because see, if the in-valve is 4 and the out-valve is 2, the velocity will keep increasing (apparently *change SFI*). But if the in-valve is 2 and the out-valve is 1, the velocity will stay constant (*proportional to net flow p-prim*).

I: 2 and 1?

S4: Yes, it could be 2 and 1, because the in-valve will give the 1 that will always stay, and the out-valve will always make 1 go away, and so the velocity will always be constant (*proportional to net flow p-prim*).

The last comment by S4 says that every period 2 units come in, of those units 1 is removed, leaving 1 in the stock every period. This episode ends with student 4 prioritizing the *proportional to net flow p-prim*.

4.3. Coming to see the *flowing SFI*

The next context is that of a toy car that is given a sudden push and afterwards slows down to a halt. Students are asked to explain why the car slows down.

The purpose of this context is to trigger transfer of the *flowing SFI*. Seeing the *flowing SFI* in the context of motion involves interpreting any change in velocity as the result of forces controlling flows. In other words, using the *flowing SFI* implies recognizing that velocity only changes through the action of forces, particularly; an object's velocity decreases only if a resistance force is acting on the object. The difference between the *flowing SFI* and the *change* and *equilibrium SFIs*, is that while the two last ones have to do with direction of change (increase, decrease, constant), *flowing SFI* has to do with the very possibility of a change in the stock to occur. Neither equilibrium nor change in the stock is possible without the existence of flows in the first place. Table 4 shows the p-prims that appear to compete with the *flowing SFI*.

Table 4. *Coming to see the flowing SFI*

Context	SFI	P-prims involved	Students	Prioritizes:	
				SFI	P-prim
Push and slow down	Flowing	<i>No apparent p-prim</i>	1, 3, 12	1, 3, 12	
		<i>Force sustains motion</i>	4, 6, 8, 9, 10	6, 8, 9, 10	4, 6
		<i>Dying away</i>	2, 5, 7	2, 5	2

4.3.1. *No apparent p-prim*

Three students (1, 3 and 12) recognized, without any apparent conflict with other interpretations, the need of a resistance force when asked to explain why the car slows down after the push. The following episode for student 12 is representative. After the student explains why the car slows down – “is like in the tank, when there is a force that opposes to the motion of the car,” the interviewer asks for clarification:

I: How is it that the opposing force makes the velocity decrease?

S12: I knew that because of the tank.

I: How is that?

S12: I mean, the in-valve is opened and the out-valve has to be opened too because see, the velocity decreases. So it can be that the velocity increases and decreases afterwards because the in-valve is opened at first, then closed, and then the out-valve is still opened (*flowing SFI*).

4.3.2. *Flowing SFI vs. force sustains motion p-prim*

The *force sustains motion* or *continuous push p-prim* (diSessa, 1993) consists on the idea that a continuous effort is required for continuous motion to occur. In the situation of the car that is initially pushed and afterwards slows down to a halt,

students use *force sustains motion* to explain that the car slows down because of the “lack of applied force.”

Five students exhibit competition between the *flowing SFI* and the *force sustains motion p-prim*. Three of these students (8, 9, 10) clearly prioritize *flowing SFI* by the end of the episodes. One student (4) prioritizes *force sustains motion*. Finally, student 6 accommodates her explanations to fit both the *flowing SFI* and *force sustains motion p-prim* under particular conditions.

Despite their significant length, we have chosen to include the episodes for students 4 and 6 in this section. We do so because, in addition to illustrate the competition between the *flowing SFI* and *force sustains motion p-prim*, these episodes offer a rich general illustration of the variety of ways in which transfer can occur. In the first example transfer is unstable; it progresses only to regress a few minutes later. In the second example transfer occurs but it is fragmented; it occurs in one context but not in another.

The first episode begins with student 4 explaining that the “car’s velocity finishes” because “there is not a force being applied on the car any more” (*force sustains motion p-prim*). Then, in an attempt to help the student notice the need for an outflow for a stock to decrease, the interviewer asks the student “what would happen with the velocity if the out-valve was removed.” After this prompting the student realizes *momentarily* the need for a resistance force (*flowing SFI*). Then she goes back to *force sustains motion* and remains prioritizing this explanation until the end of the episode:

1. I: Can you tell me what is happening in this situation?

S4: Here the velocity is fast at the beginning and then the car stops. It is like playing with a toy car in real life. I push the car and it will stop after a while when the velocity finishes.

I: Why does the velocity finish?

S4: Because the car does not have enough force to continue.

I: You mean there is not more force?

S4: There is not more applied force to continue (*force sustains motion p-prim*).

I: Did you apply the tank here?

S4: No.

I: Could you apply it now?

S4: Yes.

I: Tell me.

S4: For instance, I can fill it up.

I: How can you fill it up?

S4: Opening the applied force.

I: How do you do that in real life? In the case of the car you were talking about for instance?

S4: Pushing.

I: Ok, so we push it.

S4: Then we close the in-valve. I mean, we push the car once and it stays there moving. We pushed it already, it continues alone.

I: Does the valve stay opened?

S4: Ehh, no, I close it. I mean because after I push the car, I take away the applied force and I open the out-valve, which is when I push the car and let it go alone. Then when I let it go, the velocity decreases because it does not have an applied force any more. In the tank it would be like filling it up through the in-valve and empty it through the out-valve.

I: Ok, so let's say that we don't have the out-valve and we do the same, we apply a force, so it opens and closes immediately. What happens with the velocity then?

S4: It will stay constant.

I: What makes the velocity finish then?

S4: The applied force. Oh no, I mean the deceleration, the resistance force (*flowing SFI*).

Not convinced that the student really believes that the resistance force is responsible for the car's decreasing velocity, the interviewer asks the student to

explain once more what is happening in the situation under study. The student then explains:

S4: Eh, for instance, if I take a car and start playing with it, the car will move as far as I push it. When I let the car go, it will stop by itself. I mean it is natural that it stops.

I: What makes it stop?

S4: The lack of the applied force (*force sustains motion p-prim*).

In contrast to student 4, student 6 appears more confident about the *flowing SFI* but ends the episode by reserving the *flowing SFI* for the case with resistance and using *force sustains motion p-prim* for the case with no resistance.

2. I: Can you tell me what is happening in this situation?

S6: Now the girl gives it only a push, she is not pushing it continuously as before. Now she only gives it a push, and so the velocity will normally finish if there is a force that is opposing (*flowing SFI*). It is natural that the velocity decreases, that it comes a time when the car stays at a point.

I: You just said that if there is an opposing force it is normal that the car stops, but you explained before that the car stops because the force applied by the girl decreases. Which do you believe is the case?

S6: I don't know [reading her own answer to the preceding test]. I say it is because there is a force resisting the motion of the car.

I: What makes you think that?

S6: Because if there is a force that is opposing to the push that the girl gave to the car, I would say that the velocity decreases because of this opposing force (*flowing SFI*). But, if it is, for instance, that the surface is slippery and the girl gives the car a push, I would say that the car stops because the force applied by the girl decreases until zero (*force sustains motion p-prim*).

4.3.2. *Flowing SFI vs. dying away p-prim*

While the students using *force sustains motion* use the “lack of applied force” to explain the car’s decreasing velocity, the students using *dying away* see the decrease in velocity as a cause in itself. For instance, when the interviewer asks student 2 in the fragment below “how the out-valve for velocity opens,” the student explains that the valve opens “because the velocity decreases.” This suggests that rather than seeing the valve as the cause for the change in velocity, the student sees the decrease in velocity as the cause for the change in the valve.

Three students exhibit competition between the *flowing SFI* and the *dying away p-prim*. Student 5 clearly prioritizes the *flowing SFI* by the end of the episode. Student 2 keeps moving back and forth from one interpretation to another seemingly prioritizing both *dying away* and the *flowing SFI*. Student 7 mentions the resistance force as a cause for the decreasing velocity, however, she does not provide any further explanation of why she thinks this is the case. This makes it difficult for us to determine whether student 7 indeed prioritizes the *flowing SFI* over *dying away*. The following episode is for student 2.

I: Can you tell me what is happening in this case?

S2: That the velocity increases for a while and it decreases thereafter.

I: Aha. And what is the velocity here [in the tank]?

S2: Lets say that here the acceleration is in 10, then it closes and the out-valve opens, and so the velocity decreases.

I: And what makes this [out] valve open? Or why does it open?

S2: That valve opens because the velocity decreases (*dying away p-prim*).

I: So you mentioned before that the car stops because the force applied by the girl in the push decreases until it becomes zero. Is that the same you're saying now?

S2: Yes because see, the car gets to a position where the push doesn't go more. As the car moves the velocity decreases (*dying away p-prim*).

I: What do you mean that decreases? The force or the velocity?

S2: The velocity [stays silent for a few seconds]. There is a force resisting the motion of the car. It means that the velocity gets, lets say to 8, and this one [resistance force] increases until the velocity gets to zero, then the car doesn't move any more (*flowing SFI*).

After this, the episode goes on for quite a while with the student seemingly mixing or going back and forth between the *flowing SFI* and *dying away p-prim*.

This last episode is of particular importance because it not only shows the competition between the *flowing SFI* and the *dying away p-prim*, but it also serves to illustrate a methodological difficulty that can occur when trying to distinguish between instances of *force sustains motion* and *dying away* in students' explanations. Notice that at some point during the episode, the student accepts that "the decrease in the applied force" is the cause for the decreasing velocity, which suggests the use of the *force sustains motion p-prim*. However, when the interviewer tries to clarify further this explanation, the student uses two ideas that suggest the use of the *dying away p-prim*: "the push doesn't go more" and "the velocity decreases as the car moves." In this particular case, our decision was to code the student's explanations as instances of *dying away* rather than *force sustains motion p-prim*. This decision however is not random. This kind of interpretative difficulties in coding knowledge elements, have to be resolved by looking at the fullness of the reasoning exhibited by the student throughout the full interview. In the case of student 2, instances of *dying away* clearly occur before and after this specific episode.

4.4. Coming to see the *storing SFI*

The last context is that of a toy car that is given a sudden push under no-resistance conditions. Students are asked to predict what would happen with the velocity of the car after the push.

The purpose of this context is to trigger transfer of the *storing SFI*. Seeing the *storing SFI* in the context of motion involves seeing velocity as having the property of being accumulated or "stored." In other words, the *storing SFI* involves seeing velocity as a

stock. As a special case, coming to see the *storing SFI* implies realizing that velocity can remain stored (be different from zero) also when its flows are zero. When this is the case, the *flowing SFI* also applies: if the flows of a stock are zero (that is non-existent), there is no way for the stock to change; it remains the same. The two SFIs differ in that the *storing SFI* refers to the cumulative nature of a stock, while the *flowing SFI* refers to the conditions under which a change in the stock is possible. The examples below show how students use the *flowing SFI* to further explain their use of the *storing SFI*. Table 5 shows the p-prims that compete with the *storing SFI*.

Table 5. *Coming to see the storing SFI*

Context	SFI	P-prims involved	Students	Prioritizes:	
				SFI	P-prim
Push under no-resistance	<i>Storing</i>	<i>No apparent p-prim</i>	1	1	
		<i>Force sustains motion</i>	4, 6, 8, 9, 10	4, 6, 8, 9, 10	4
		<i>Dying away</i>	2, 3, 5, 12	2, 3, 5, 12	
		<i>Dying away +Ohm's</i>	7		7

4.4.1. *No apparent p-prim*

Only student 1 used *storing SFI* without any apparent conflict with other interpretations –except for a confusion caused by a drawing of a car slowing down:

I: Now what would happen if we put the car on a very slippery floor so smooth that it does not oppose any resistance to the motion of the car? What would happen with the velocity?

S1: It would stay constant. I mean it wouldn't stop (*storing SFI*).

I: Is this what you said before?

S1: I said the velocity would decrease, because in the image the velocity

always decreases [image on the test corresponding to previous situation of motion under resistance conditions].

I: Oh I see. You mean the image from the previous situation. Ok, and what if there is not any resistance force, what do you think would happen with the velocity?

S1: Then it will stay constant (*storing SFI*).

I: So tell me how does this happen? What would be the difference between the situation here [resistance] and here [no-resistance]? Could you explain that using the tank?

S1: Here [no-resistance situation], the in-valve opens and then it closes, and since both valves are closed the water will always stay the same (*flowing SFI*).

4.4.2. Storing SFI vs. force sustains motion *p*-prim

The force sustains motion p-prim imposes challenges for accepting the *storing SFI* because students find it challenging to conceive that an object can keep moving without the action of a continuous force. Five students exhibit competition between the *storing SFI* and the *force sustains motion p-prim*. Four of these students clearly prioritize the *storing SFI* by the end of the episodes. Student 4 prioritizes both *force sustains motion* (for real life situations), and the *storing SFI* (for the situation represented by the tank). Finally, we are cautious about making any definite conclusion about student 8. We present here the episodes for students 4 and 8.

Student 4 initially explains that without any resistance the car's velocity will remain the same (*storing SFI*). Then, apparently reasoning about her experiences with real life objects, she predicts that the car's velocity will decrease because of "lack of applied force" (*force sustains motion p-prim*). The episode ends with the student prioritizing both *force sustains motion p-prim* (for real life situations), and the *storing SFI* (for the situation represented by the tank).

1. I: Now there is not any resistance force acting on the car. What does it mean that there is not any resistance?

S4: If there is not any resistance, the velocity will stay in the same point (*flowing SFI*).

I: And how would the out-valve be?

S4: Closed.

After this the interviewer asks about the car's velocity once more and the student answers changing her initial prediction. Then, after a new prompting by the interviewer, the student returns to her initial prediction, before changing it once more later:

I: Ok, so we put the car on the surface and we give it a push, what happens with the velocity?

S4: That when you push the car, the velocity will decrease by itself. I mean since it doesn't have the applied force any more, it will decrease (*force sustains motion p-prim*), and at the end the car stays at the same point.

I: Aha, so let's look at this again. As you said before, if there is no resistance force the out-valve would be closed. We give the car a push, what happens with the velocity then?

S4: It will stay constant (*flowing SFI*).

I: Will the car stop?

S4: No [stays silent a few seconds] (*storing SFI*). In the real life it will, but here, according to the tank, it won't. Here the velocity will stay in the same point. I mean, the out-valve is not opened; therefore the velocity will stay in the same point (*flowing SFI*). But in real life one applies a force and at the end the car stops because it doesn't have the applied force to go on (*force sustains motion p-prim*).

I: Which would be the difference between the situation in the real life and the tank?

S4: That in real life the car is real. In the tank it is very different because the deceleration will stay closed, and so the velocity will stay constant (*flowing*

SFI). This is very different from the real life because, for instance, one pushes a car and as the time goes the velocity decreases because it doesn't have the applied force (*force sustains motion p-prim*).

I: Could it be that in the real life the out-valve usually does not stay closed because there are resistance forces?

S4: It can be as well. Well, in the real life I say that the velocity decreases. But in the case of the tank, I say that the velocity stays constant.

In the case of student 8, the struggle to solve the conflict between *storing SFI* and *force sustains motion p-prim* becomes very explicit. By the end of the episode, it appears as if she prioritizes the *storing SFI* over the *force sustains motion p-prim*. However, the last answer by the student suggests that she may still think of the lack of applied force as the cause for the decrease in velocity in the case with resistance.

2. I: So now the girl gives the car a push but now there is not any resistance force acting on the car. What would happen with the velocity?

S8: It increases and decreases afterwards.

I: Why does it increase and decrease?

S8: Because it could be...[stays silent for a few seconds]. It is not so much that it decreases because...[stays silent for a few seconds]. Maybe the water, with the tank! The water can be in the tank and so the car will keep moving. I mean, the velocity that it's already there...[stays silent for a few seconds] (*storing SFI*). No, with only a push it won't be enough for it to move for a long while. The velocity decreases (*force sustains motion p-prim*).

I: Why does it decrease?

S8: Because the velocity that the girl applied is weak (*force sustains motion p-prim*).

I: What is the difference between putting the car on the very slippery floor and on the normal one?

S8: Oh I understand, I understand now. No, the car will keep moving, that's what I think because there is nothing that opposes and makes the car stop. So the car will go on with its same velocity (*flowing SFI*).

I: And in this case [situation with resistance]?

S8: The velocity decreases.

I: And why does it decrease?

S8: Because the floor opposes (*flowing SFI*) and the girl applies a force like very, very, how can I say this? Like very weak (*force sustains motion p-prim*).

4.4.3. Storing SFI vs. dying away p-prim

The *dying away p-prim* imposes challenges for accepting the *storing SFI* because students find it difficult to conceive that an object can simply move forever. Four students exhibit competition between the *storing SFI* and the *dying away p-prim*. All of them clearly prioritize the *storing SFI* by the end of the episodes.

The following example represents a full episode during which the interviewer attempts to help student 3 to deal with conflicts between the *storing* and *flowing SFIs* and the *dying away p-prim*. The student appears comfortable when explaining that the car will keep moving at a constant velocity in the absence of any force. However, similar to student 4 (episode in section 4.4.2), the student's observations of her own experiences with the velocity of real world objects *dying away*, creates challenges for prioritizing a single interpretation. Nevertheless, the student appears comfortable about prioritizing the *storing* and *flowing SFIs* over *dying away* by the end of the episode.

I: Now what happens in this case? What does it mean that there is not any resistance?

S3: That if I put the acceleration in 5 for instance, the deceleration will always be 0.

I: Ok, so the girl pushes the car, what happens with the velocity?

S3: It will stay equal to the push.

I: What do you mean by "equal to the push"?

S3: For instance, if I apply a force of 2 [when the car is at rest–i.e., velocity is zero], the velocity will get to 2 and it will stay there all the time. It won't

change (*flowing SFI*). But it will stop after a while.

I: What would make it stop?

S3: I don't know [smiles]. That is what confuses me, that there is not resisting force but things almost always stop [laughing] (*dying away p-prim*).

I: Would it be because normally there are resisting forces?

S3: Aha.

I: And if there was not any, what do you think will happen with the car?

S3: It will go on.

I: What makes you think that?

S3: I imagine the car on a slippery surface and the car will just go on and on (*storing SFI*). Because if there is not any resisting force, it couldn't stop (*flowing SFI*).

4.4.4. Storing SFI vs. dying away and ohm's p-prims

In addition to *dying away*, student 7 exhibits another intuitive knowledge element called *ohm's p-prim* (diSessa, 1993). In the case of motion, *ohm's p-prim* says that the velocity reached by an object is directly proportional to the force applied and inversely proportional to the resistance. This p-prim differs from the *proportional to net flow p-prim*, where velocity is proportional to the difference between in- and outflows. In the latter case, velocity is zero when the two flows are equal. That does not have to be the case for *ohm's p-prim*.

Only student 7 exhibits the *ohm's p-prim* in the context of the push under no-resistance conditions. In this particular case, the student uses *ohm's p-prim* to reason about the relationship between "slipperiness" and velocity: the more slipperiness (or less resistance), the more velocity. Notice that this relationship implies an association of slipperiness with the increase rate (inflow) rather than the decrease rate (outflow) of velocity. This interpretation complicates reasoning about the very idea of resistance as an opposition. This is evident in the fragment below, when the student uses the terms "slipperiness" and "resistance force" apparently referring to them as different rather than associated concepts. In this episode the student uses *ohm's p-*

prim to predict that slipperiness gives high velocity after the push, and *dying away p-prim* to predict a subsequent decrease in velocity. Although the episode does not strictly show competition—in the sense that the student does not even use the *storing SFI*, we present the episode here because we believe that *ohm's p-prim* hinders the assimilation of *storing SFI* by leading the student to focus on the inflow and disregard the outflow.

I: So now the girl gives the car a push but now there is not any resistance force acting on the car. What would happen with the velocity?

S7: It increases and decreases thereafter.

I: Can you explain why?

S7: It increases because the floor is slippery (*ohm's p-prim*) but it decreases because it won't keep moving the whole day (*dying away p-prim*).

I: What will make it stop?

S7: The velocity.

I: What do you mean?

S7: Because, I push the car, right? And it moves for some time, but then it stops after a while. I mean, let's say that the velocity gets tired, it calms down (*dying away p-prim*).

I: Why does the velocity decrease?

S7: Because first the car goes fast because the floor is very good (*ohm's p-prim*), but then the velocity decreases because there is a resistance force (*flowing SFI*).

I: What do you mean by a resistance force?

S7: The car cannot go on, the velocity gets tired (*dying away p-prim*).

I: If you applied the tank, would that make sense? That even without a resistance force the velocity would decrease?

S7: Yes...[looking at tank]. Yes, if I put the out-valve in 1.

I: How does that valve open?

S7: As I said before, the girl pushes the car and it goes fast for a while because it's slippery (*ohm's p-prim*) until it stops.

I: Why does it stop?

S7: Because the velocity in the car ends (*dying away p-prim*).

The episode goes on for a while and ends with the student still reasoning in terms of *dying away* and *ohm's prim*.

5. Discussion and opportunities for further research

Our motivation for using the tank analogy in teaching comes from the extensive repertoire of students' inappropriate use of intuitive knowledge of dynamic systems documented in the science education literature. In addition to its pervasiveness across science domains, intuitive knowledge has been shown to be strongly resistant to formal teaching, imposing a key challenge for education. Our purpose has been to respond to such a challenge by testing the effectiveness of a water tank analogy to stimulate students to refine their use of intuitive knowledge of basic dynamics of motion.

To do so, we exposed eleven seventh grade students with no previous formal education in physics to the tank analogy. For 14 hours, over a 5-weeks period, the students worked in pairs, first to learn the tank analogy, then to re-use learnt lessons in the context of motion. We interviewed the students individually during the 6th week of intervention, and subsequently analyzed the interviews with a focus on understanding: (1) what *stock and flow insights* (SFIs) students attempt to transfer from the tank analogy to motion; (2) what *phenomenological primitives* (p-prims) intervene in this process of transfer; and (3) what is the outcome of transfer, in terms of changes in students' knowledge.

We focused on student transfer of four particular SFIs: *equilibrium*, *change*, *flowing*, and *storing*. We observed six p-prims that intervened in transfer: *force sustains motion*, *overcoming*, *proportional to net flow*, *dying away*, *equilibration*, and *ohm's p-prim*. Our results show that p-prims such as *force sustains motion*, *overcoming*, and *proportional to net flow* stimulate instantaneous change thinking, and therefore conflict with the idea of velocity accumulating over time. Likewise, *dying away* and

equilibration stimulates thinking about “spurious” causes—such as velocity “getting tired” or inexistent tendencies towards a “natural” state of equilibrium, and therefore conflict with the idea that velocity needs flows to change. In general, p-prims make it difficult for students to deal with tank assumptions that depart from everyday conditions – such as no resistance forces.

Competition between p-prims and SFIs was pervasive in our results. At first, only five students exhibited no apparent conflict when transferring one of the four SFIs, and only one student (#1) showed no conflict when transferring three out of four SFIs. All other students exhibited conflict for all SFIs. However, throughout the episodes of learning, SFIs tended to gain priority. The majority of the students refined their knowledge after further guidance on using the tank analogy to reason about the motion contexts explored. Student explanations show that the tank analogy helped them find plausibility in behavior and causal explanations that they saw as impossible before the intervention – such as that velocity can be “stored” and therefore it can be different from zero in the absence of a force.

However, some p-prims, which are widely used by students, are deeply engrained and resistant to change. This is the case for the *force sustains motion p-prim* which competed with three SFIs. It was resistant to change for three students. The *dying away* was also challenging. Student 2 had difficulties prioritizing *flowing SFI* over the *dying away p-prim*. Likewise, students 4 and possibly student 7 prioritized the *proportional to net flow p-prim* over two SFIs, and this did not change despite guidance offered by the researcher.

Student 4 is an interesting case in light of knowledge change theory. Kapon and diSessa (2010) argue that differences in learning paths can be explained by differences in student’s prior knowledge repertoire. Student 4 was the one who most clearly showed evidence of the *proportional to net flow p-prim*. In contrast to the rest of the students, this student prioritized *all* competing p-prims over SFIs in *all* contexts explored.

While p-prims can be *conflicting* with scientific knowledge, p-prims may also have a *supporting* role in learning (diSessa, 1993, Kapon and diSessa, 2010). For teaching with the tank analogy, this possibility is explored in Saldarriaga (2011b), it is not explored here.

The episodes of successful refinement of knowledge in our study, suggests that the tank is a useful and effective instructional analogy. Both p-prims and the SFIs represent knowledge that applies across contexts and domains. Therefore, we expect knowledge competition to be observed in students learning of other dynamic systems. Moreover, one should expect that after many experiences with the tank, it will be increasingly easy for students to recall and re-use SF knowledge to advance and refine their understanding across systems. This process can be helped by the use of SF diagrams (SFDs) where the same tank-like symbols are used for all systems. However, as evidenced in our interviews, the tank analogy is not always easily triggered whenever it is useful, and therefore, suggestions and probing by teachers are likely to be essential.

Interestingly the use of the tank analogy or SFDs satisfy the two main requirements for learning defined by diSessa:

- (1). "...Understanding should evolve toward compactness, involving few principles that are as general as possible...This specific knowledge might be particular forms of the principles for particular situations or strategies adapted to do the work of interpreting diverse situations in common terms." (diSessa, 1993, p. 190).
- (2). "Learning should provide that p-prims are subordinated to formal principles, and organized according to cuing priorities that allow them to be recalled in a coordinated way." (diSessa, 1993, p. 143).

The SFIs constitute a set of compact principles that can be applied across diverse situations. Moreover, the SFD provides a structure around which knowledge elements (both useful p-prims and SFIs) can be placed and articulated in a coordinated way.

This structure may also work as a cuing tool where several knowledge elements are recalled in association to one another. For instance, thinking of *storing* works as a cue for *flowing*, which in turn works as cue for thinking of the actions controlling the flows.

Our research can be extended in several directions. Some important issues to explore include: how efficient will the tank, or other SF analogies, be for older students with perhaps a different repertoire of prior knowledge? How will student ability to reason about SF systems develop with more training and time for maturation? How will different sequences of teaching/probing influence the results (e.g. start with the storing SFI)? How will students' existing knowledge influence students learning of more advance topics (e.g. feedback giving rise to exponential growth/decay or oscillations, or nonlinearities giving rise to e.g. s-shaped growth)? This involves investigating the transfer of SFIs for *feedbacks* and *nonlinearities*. Finally, how appropriate are students' ideas about the instantaneous change SFI? Further studies may have to employ other methods than those used here to distinguish instantaneous and accumulating relationships and to distinguish linear and nonlinear relationships.

6. Conclusion

This paper has dealt with the use of a tank analogy when teaching the physics of motion. Our findings show that transfer from the tank analogy to the context of motion does occur. But it occurs through a general mechanism of negotiation in contrast to simple assimilation. For transfer to occur, it is not sufficient for students to assimilate the stock and flow (SF) knowledge being transferred. SF knowledge has to compete in plausibility with students' intuitive knowledge of the target situation. Hence, teaching with a tank analogy faces many of the challenges found in recent educational research. When these challenges are dealt with, our results suggest that a tank analogy in particular, and SF diagrams (SFDs) in general, can be powerful tools for teaching dynamics in any domain and context. Further qualitative research should attend to details and extensions; quantitative research is needed to investigate the effectiveness of repeated teaching with tanks and SFDs.

References

- Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science*, 18(4), 237-261.
- Carraher, D., & Schliemann, A. D. (2002). The transfer dilemma. *The Journal of the Learning Sciences*, 11, 1-24.
- Clement, J. J. (2008). *Creative model construction in scientists and students: The role of imagery, analogy, and mental simulation*. Springer.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, 30(10), 1241-1257.
- diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10(2/3), 105-225.
- diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction*, 25(4), 523 - 565.
- diSessa, A. A. (2009, June). *The construction of causal schemes: Learning mechanisms at the knowledge level*.
- Forrester, J. W. (1961). *Industrial dynamics*. Productivity Pr; Student Edition.
- Forrester, J. W. (1968). *Principles of systems*. Cambridge, EUA : Wright-Allen.
- Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge University Press.
- Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, 30, 141-158.
- Kapon, S., & diSessa, A. A. (2010). Instructional explanations as an interface---the role of explanatory primitives. *AIP Conference Proceedings*, 1289(1), 189-192.
- Legendre, M. F. (1997). Task analysis and validation for a qualitative, exploratory curriculum in force and motion. *Instructional Science*, 25, 255-305.
- Lobato, J. (2003). How design experiments can inform a rethinking of transfer and vice versa. *Educational Researcher*, 32(1), 17-20.
- Lobato, J. (2006). Alternative perspectives on the transfer of learning: History, issues, and challenges for future research. *Journal of the Learning Sciences*, 15(4), 431 - 449.

- Lobato, J., & Siebert, D. (2002). Quantitative reasoning in a reconceived view of transfer. *The Journal of Mathematical Behavior*, 21(1), 87-116.
- Mestre, J. P. (2005). Framing the transfer problem. In J. P. Mestre (Ed.), *Transfer of learning: Research and perspectives*. (pp. vii-xxvi). IAP - Informaiton Age Publishing Inc. (Original work published 2005)
- Saldarriaga, M. (2011). *A case study on "reverse transfer": When learners modify a water tank analogy to fit physics intuitive knowledge*.
- Saldarriaga, M. (2011). *Intuitive knowledge of dynamic systems: Educational theory benefiting system dynamics teaching*.
- Saxe, G. B. (1989). Transfer of learning across cultural practices. *Cognition and Instruction*, 6(4), 325-330.
- Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review*, 247-261.

Appendix

What do we know about why objects move?

Instructions

Circle the answer you personally think is the best.

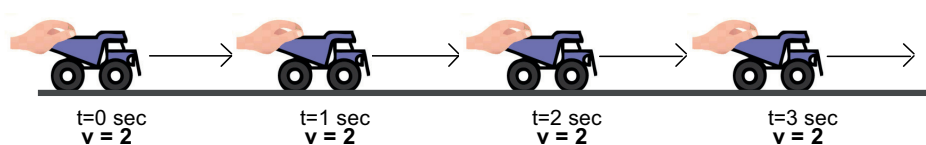
Do not skip any question and answer all of them.

For each question you can only circle ONE answer.

Remember that if something is constant it means that it is not changing.

Use the following description and the picture to answer questions 1 and 2.

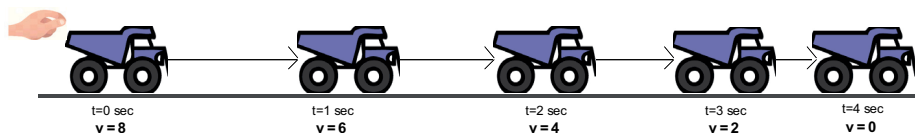
A girl is pushing a toy car across the floor. As a result, the car moves at a constant velocity, as shown in the picture.



- This happens because the force applied by the girl:
 - is equal to the weight of the car
 - is greater than the weight of the car
 - is equal to the the total force which resists the motion of the car
 - is greater than the total force which resists the motion of the car
 - is greater than both the weight of the car and the total force which resists the motion of the car.
- If the girl in the previous question doubles the force that she is applying on the car, the car then moves:
 - with a constant velocity that is double the velocity in the previous question
 - with a constant velocity that is greater than the velocity in the previous question, but not necessarily twice as great
 - for a while with a velocity that is greater than the velocity in the previous question, then with a velocity that increases thereafter
 - for a while with an increasing velocity, then with a constant velocity thereafter
 - with a continuous increasing velocity.

Use the following description and the picture to answer question 3.

Assume the toy car is not moving and then the girl gives it a short push. The car moves for some time with a steadily decreasing velocity until it stops again, as shown in the picture.



3. This happens because:

- (A) the force applied by the girl decreases until it becomes zero
- (B) there is a constant force resisting the motion of the car
- (C) there is an increasing force resisting the motion of the car
- (D) the constant force resisting the motion of the car wins over the force applied by the girl
- (E) velocity has a natural tendency to finish.

Use the following description to answer question 4.

The girl puts the car from question 3 on a completely smooth surface so that the surface does not create any resistance to the car's motion. Neither are there any other forces resisting the motion. The car is not moving and the girl gives it a short push.

4. After the short push, the velocity of the car:

- (A) stays constant and different from zero
- (B) stays constant and equal to zero
- (C) decreases steadily
- (D) increases for a while and decreases thereafter
- (E) stays constant and different from zero for a while and decreases thereafter.

Paper 3:

*A case study on “reverse transfer”:
when learners modify a water tank analogy
to fit physics intuitive knowledge*



A case study on “reverse transfer”: when learners modify a water tank analogy to fit physics intuitive knowledge

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Abstract

Dynamic systems can be conceptualized in terms of *stocks* and *flows*. Stocks represent things that can be accumulated over time, and flows are the rates at which stocks change. In the field of System Dynamics, the Stock and Flow (SF) model is usually introduced through a *water tank or bathtub analogy*. In a series of sessions with school and university students we used the tank analogy as a teaching tool in physics. The purpose was to help students reorganize their intuitive knowledge of Newton’s First and Second Laws. While this worked successfully in many cases, some students did the opposite move. They modified the water tank analogy to fit their intuitive knowledge of motion. We call this phenomenon “*reverse transfer*”. Here, we present five episodes from individual interviews with three seventh graders and two university students. Since numerous investigations find that dynamic systems are complex and challenging for learners, phenomena such as reverse transfer may not come as a surprise. It remains to see if this phenomenon can be observed in other context than those involving dynamic systems.

Keywords: stock and flow diagrams, intuitive knowledge, phenomenological primitives, dynamic systems, analogies, transfer of learning, knowledge change.

1. Introduction

An analogy consists of a representation of a *source* system used to emphasize similarities between the source and a *target* system. When an analogy is used to support transfer, the common motivation is that the learner's understanding of the source system is unproblematic, while the target system is not well understood. Provided the analogy is appropriate in that the same knowledge can be shown to apply to source and target, learners are expected to see both systems as consistent and to use the knowledge learned in the source to refine their knowledge of the target system (see Figure 1). However, transfer can be complicated and other outcomes of transfer are also possible.

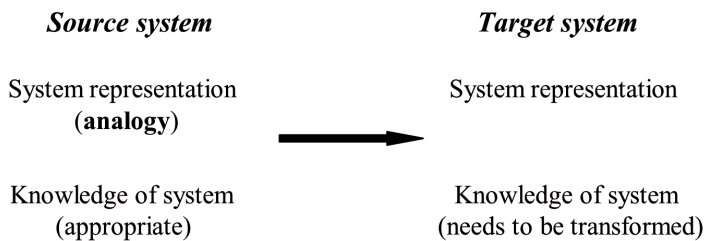


Figure 1. Elements involved in transfer with analogies

On the first hand, even if the analogy and target system can be seen to be consistent from a scientific perspective, learners may come to perceive an analogy as *inappropriate* for the particular target system. If so, learners are not likely to be motivated to transfer knowledge and thus establish consistency for themselves. Inconsistencies between source and target cause no problem for the learner and transformation of the learner's existing knowledge of the target does not take place.

If, on the other hand, the learner perceives the analogy as appropriate, there are three possible outcomes. First, the learner can attempt, without success, to establish

consistency between source and target system, in which case the learner's existing knowledge of the target system will likely remain unchanged. Second, the learner establishes consistency between the source and the target system by successfully *transforming his existing knowledge of the source to the target*. And third, the learner establishes consistency between the source and the target system by *modifying the analogy in such a way that it fits his scientifically incorrect intuitive knowledge of the target system*. His knowledge of the target system remains unchanged. For this phenomenon we use the term "*reverse transfer*" since transfer is inappropriate and goes in the opposite direction of what was intended. Using this term we do not claim that the learner's knowledge of the *source* system changes; only his representation of the source system is modified.

In this paper we focus on *reverse transfer*. While reverse transfer can be appropriate in cases where the analogy is not appropriate, our focus is explicitly on cases of inappropriate reverse transfer where the analogy is appropriate. We use five case study episodes to illustrate how reverse transfer occurs when using a *water tank analogy* to support transfer to motion systems. We show how three seventh graders and two undergraduate students modify the tank analogy until it fits their existing intuitive knowledge of motion systems.

The water tank is an analogy to a generic *stock and flow* (SF) system (Forrester, 1961; Forrester, 1968). The analogy consists of a water tank with pipes and valves for adding to and removing water from the tank. The amount of water in the tank changes as water is added or removed over time. Stocks are everything that is stored *as water in the tank* (e.g, people, money in a bank account); and flows are the ways in which those stored things change *as the flows through the valves in the tank* (e.g, births and deaths of people; saving and withdrawal of money).

Previous studies of transfer cannot account for reverse transfer since they work under the assumption that what changes during transfer is *knowledge*, while representations of *source* and *target systems* are assumed to remain unchanged (Beach, 1999; Bransford & Schwartz, 2001; Carraher & Schliemann, 2002). In contrast, our findings

support a wider view of transfer where learners' representations of analogies cannot be taken for granted and as unchangeable.

The paper is organized as follows. First, we review different approaches that attempt to account for diverse complexities of transfer. Next, we describe our experimental design. We present the water tank system and describe how it serves as an analogy to a *stock and flow* (SF) system in general and to motion in particular. Then, we describe students' existing intuitive knowledge of motion. This corresponds to the knowledge that should ideally be transformed when using the water tank analogy for transfer. Finally, we present and discuss the five episodes of reverse transfer. We conclude with a discussion of further research.

Before we move on, it is important to clarify our use of the term *system*. In transfer literature, the word *situation* is commonly used to refer to the source and target *contexts*. In dynamic systems "situation" can both mean the system context (e.g. a tank with pipes) and the current state of the system (e.g. amount of water in the tank). To avoid confusion, we use the term *system* instead of *situation*. When referring to existing literature however, we conserve the term that is originally used.

2. Complexities of transfer

The first approach aimed at accounting for the learning that takes place during transfer was Thorndike's theory of *identical elements*. In a series of experiments, Thorndike studied the accuracy of student quantity estimates in one situation after learning to estimate the same quantity in another situation. For instance, Thorndike and Woodworth (1901) studied the accuracy of student estimates of the area of circles and triangles, after they had practiced estimating the area of rectangles. The researchers observed that abilities to estimate areas did not generalize across situations; transfer only occurred to the extent that the situations shared identical elements. Hence, shared identical elements across situations, was, according to Thorndike's approach, a good predictor of the likelihood of occurrence of transfer.

However, recent research has shown that identical elements *are not sufficient* for transfer to occur. Consequently, alternative approaches have been proposed¹. Lobato (2003) attempts to answer the question of “what makes an analogy appropriate or inappropriate.” In an experiment on students’ understanding of slopes and linear functions, she initially concluded that transfer of the ability to estimate slopes across situations was *poor* despite students’ high performance in a source task. However, after reanalyzing the data, Lobato observed that students *did* make generalizations and transferred knowledge across situations. But these generalizations were not necessarily those that she had initially defined as “counting as transfer” based on an expert’s understanding of slope. Instead, Lobato observed that students’ idea of slopes was connected to a *visual* component of “stair steps”. The presence of this visual component in a target task determined the occurrence of transfer. For instance, when presented with a task of a playground (“including a vertical ladder and a steep ramp, connected on top by a horizontal platform”), two students focused their attention on different “rise” and “runs” that, from their perspective, would form a “stair step” with a slope (e.g., the height of the ladder as the rise and the length of the platform as the run). Lobato concluded that, although students’ choices of “rise” and “runs” were incorrect, students transferred knowledge based on what they perceived as salient and generalizable from the task in which their knowledge of slopes was initially acquired.

However, even if a learner identifies generalizable aspects of a source task, attempts to transfer knowledge to other target situations can lead to conflict and competition between this knowledge and the learner’s existing knowledge of the target. Competition of knowledge has been shown to be recurrent in math and physics, since students bring to formal education a significant repertoire of very resistant intuitions that are abstracted from and reinforced by daily experiences with the physical world. In cases of competition, the likelihood of occurrence of transfer is determined by the learner’s ability to reconcile new and existing competing knowledge. Proper

¹ See Lobato (2006) for a review of research in transfer.

reconciliation implies that students *transform their existing knowledge of the target* (Brown & Clement, 1989; Carraher & Schliemann, 2002; Clement, 1993; Kapon & diSessa, 2010; Saldarriaga, 2011c).

For instance, Clement (1993) studied transfer in connection with Newton's Third Law (for every action, there is an equal and opposite reaction). Clement presented students with diverse situations showing deformation (e.g., a spring being compressed by a hand, a flexible table being deformed by a book) to help students transfer the idea of *springiness* from these situations to the situation of a book resting on a rigid table (not showing deformation). Some of the students successfully changed their previous idea of the table simply *blocking* (rather than exercising a force on the book) for the idea of a "microscopic springiness" between the book and the rigid table. This new idea made the situation of the book and the rigid table consistent with the analogy of the spring being compressed.

However, learners do not always achieve reconciliation in this way. Rather than transforming their knowledge, learners can *modify the source* in such a way that it becomes consistent with their intuitive knowledge of the target. This phenomenon, which we call *reverse transfer*, is the focus of this paper. This possibility is yet to be further explored in learning research. A key assumption in transfer literature has been that transfer is the application or transformation of knowledge across *given* situations. However, this view has been challenged (Beach, 1999; Bransford & Schwartz, 2001; Carraher & Schliemann, 2002). Carraher and Schliemann (2002) argue that "Situations and contexts cannot be treated exclusively as "givens" because to a large extent they are mental constructions (Carraher et. al., 2001)." Learners can actively change a situation to create relations with other situations (Carraher and Schlieman, 2002), or to make the situation more compatible with something they already know (Bransford and Schwartz (2001). It is these transfer phenomena we set out to investigate in this paper.

Our focus is on transfer of knowledge across *dynamic systems*. In the interview episodes we present in this paper, students modify the water tank analogy to fit

existing intuitive knowledge of basic dynamics systems of motion. Studying transfer of knowledge across dynamic systems is particularly interesting for two reasons. First, from a learning perspective, dynamic systems are distinctively challenging because they involve two general dimensions: a causal structure, and the behavior (change) generated by this structure. Hence, interpreting a dynamic system involves both understanding a causal structure and explaining behavior arising from that causal structure. In physics, most intuitive knowledge focuses on observed patterns of behavior and misses the underlying causal structure. Second, from a pedagogical perspective, the interdisciplinary and cross-domain character of dynamic systems opens interesting opportunities for teaching and research. Research has the opportunity to test tools aimed at providing unifying, coherent frameworks, and to investigate how students learn from and with these tools (Jacobson and Wilensky, 2006).

3. Experimental design

3.1. The water tank analogy and the stock and flow diagram for motion

Consider the water tank system in Figure 2. Here, the water accumulates in the tank as water flows in and out through the pipes, and the magnitude of the flows depends on the opening of the valves². The system is interactive; the valves can be opened or closed at different levels by dragging the handles, and the level of water in the tank can be observed to increase or decrease over time. How much the water in the tank increases or decreases over a time unit, depends on the difference between the amount of water coming in and going over that time unit.

² We explain to the students that in this tank system flows always correspond to valve settings and they are not affected by any other factors.

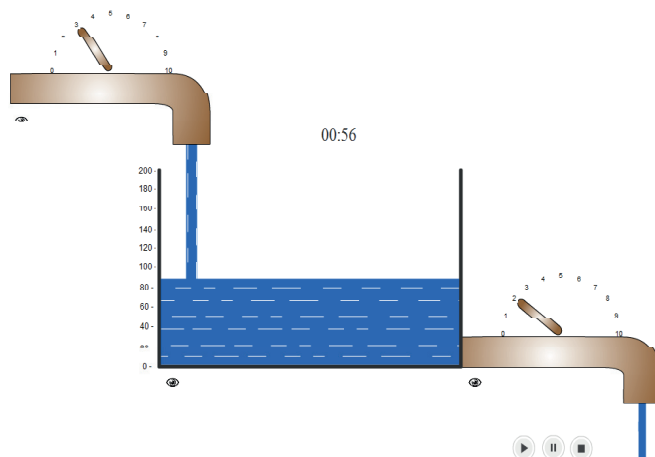


Figure 2. *Water tank system representation*

This water tank system is an *analogy* to the general stock and flow diagram (SFD) in Figure 3³. In this diagram, the rectangle represents the *stock*, and the pipes with valves represent the *flows*. Stocks are everything that is stored *as water in the tank* (e.g, people, money in a bank account); and flows are the rates at which those stored things change *as the flows through the valves in the tank* (e.g, births and deaths of people; saving and withdrawal of money). As in the water tank system, the only way to change any stock is through its flows, and its change over time (i.e., growth, decrease, equilibrium) is given by the difference between the in- and outflows. Flows are influenced by *actions*, A and B in the diagram. Actions are the equivalent to manipulating the valves in the tank to set a specific value for the flows. Simple arrows represent instantaneous cause and effect relationships. Thus, flows differ from stocks in that it requires “no-time” to change flows.

³ The SFD notation used in this paper is a slightly modified version of the one originally developed by Forrester (1961; 1968). The diagrams here have been drawn using iThink software.

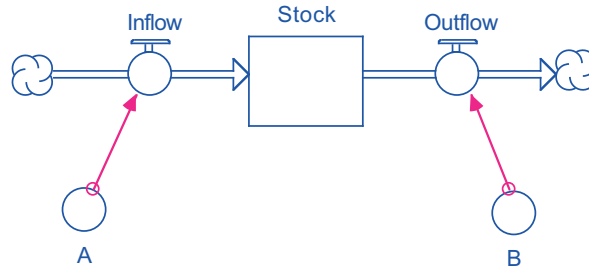


Figure 3. General stock and flow diagram

A particular example of a SF system is constituted by Newton's First and Second Laws of motion. Figure 4 shows how these two laws can be portrayed in a SFD. Newton's First Law describes the cumulative nature of velocity: velocity integrates (accumulates) its net acceleration (i.e., net change) over time. Newton's second law describes the instantaneous nature of acceleration: acceleration is directly proportional to the magnitude of the net force and inversely proportional to the mass of the object ($a=F/m$).

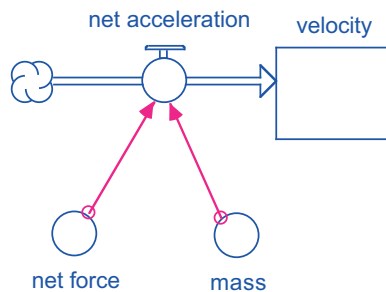


Figure 4. SFD for motion

This SFD for motion follows Newton's notation in which forces are aggregated into a *net* force and change in velocity is by definition *net* acceleration. However, in the system dynamics tradition, using stock and flow diagrams, we distinguish explicitly between in- and outflows when the flows are influenced by different mechanism. Figure 5, shows the SFD for motion when we disaggregate the flow of net

acceleration. Here *acceleration* denotes the change in velocity produced by forces in the same direction of velocity (same sign), and *deceleration* denotes the change in velocity produced by forces in the opposite direction of velocity (different sign). This use of words may conflict with a more traditional use where acceleration denotes positive net change and deceleration negative net change.

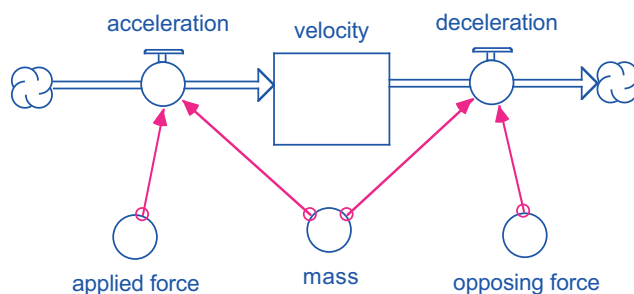


Figure 5. Disaggregated SFD for motion

Both SFDs represent the correct structure of a Newtonian motion system, nevertheless, the disaggregated model is not only closer to the water tank analogy; it also allows us to distinguish the ways in which different forces affect velocity. That is, since flows show how the state of a system is being controlled, aggregating the acceleration and forces into its net magnitudes may hide some information about the different causes acting on the object. For instance, “air resistance” involves a different causal structure than a “push” or the “force of gravity.”

The SFD in Figure 5 is simple and captures an idealized system with only exogenous forces (forces are not functions of velocity) and no other complicating factors. However, despite how basic this system is from an expert’s perspective, educational literature has found that students do not have Newton’s model in mind when dealing with motion phenomena. Rather they operate with simplified heuristics to explain and predict behavior. There is now a considerable literature describing a surprisingly large number of intuitive understandings used to explain behaviors generated by the system

in Figure 5. Of particular interest here is diSessa's (1993) work on phenomenological primitives (p-prims).

P-prims are small bits of knowledge that allow people to predict and explain behavior in the physical world. P-prims are assimilated from personal experience and they are activated and used at a rather unconscious level. They work more like "obvious" ideas that come to people's mind depending on what they perceive in a situation, rather than like ideas that are deliberately used. Consider the example of the *dying away p-prim*. Certain phenomena in the world appear to exhibit decaying patterns (movements come to a halt, coffee cups cool down, the sound of a bell decays). For such phenomena, *dying away* becomes an obvious intuition to satisfactorily (from the learner's perspective) explain and predict behavior. People believe that an object slows down and comes to a stop because motion *simply has to end*. Because p-prims are applied rather unintentionally and are based on daily life experiences, they become challenging for education when they conflict with scientific theory.

In our interviews we first present students with the water tank analogy in Figure 2; the students are not directly exposed to the SFDs in Figures 3, 4, and 5. We then ask students to indicate whether the situation of a car moving at a certain velocity is similar to the tank. If students find similarities between the tank and the motion system, we expect their explanations and predictions of structure and behavior to resemble and be consistent with the SFDs in Figures 4 and 5. Instead, some students modify the water tank analogy to make it consistent with *dying away* ideas and another p-prim called *force sustains motion*. We present such interview episodes in this paper.

3.2. Task and interview settings

The data used in this paper comes from two studies using clinical individual interviews with three seventh graders (Saldarriaga, 2011c) and two university students (Saldarriaga et al., 2011). Both studies had slightly different purposes and procedures. In spite of the differences, both studies generated instances of *reverse transfer*. Since reverse transfer took place in both research interventions, our data

suggests that reverse transfer with the tank analogy can occur not only at different schooling levels but also under different learning settings.

In both studies we began each interview by introducing the student to the animated water tank analogy in Figure 2. We first showed the student how to operate the valves (from zero to 10) and to turn on and off the simulation. In the study with university students, we gave the students a few minutes to freely *explore* the system and did not give any other instruction, unless the student was having difficulties operating the simulation. The original purpose of this study was to explore the generalizations made by the students *themselves* of the water tank, and to see how they would apply these generalizations to other diverse systems (e.g., people in a building, money in a bank account, CO₂ in the atmosphere, and a car's velocity).

In the study with school students we used a teaching sequence to help students familiarize themselves with the functioning of the water tank system. In this case, we did not ask for generalizations. Rather, we observed whether and how students applied the tank analogy to motion.

For both types of students, we subsequently asked whether they saw any relation between the tank and a car moving at a certain velocity. The university students were not exposed to any physical representation of the car; they were simply asked to *imagine* the situation. The school students were exposed to three short videos of a little toy car (Figure 6), moving at increasing, constant, and decreasing velocity. The interview episodes we present in the results section show how students answered to our question.



Figure 6. Car's motion presented to seventh graders

Interviews followed interviewing methods from educational research (diSessa, 2007; Ginsburg, 1997). The aim is gaining an in-depth understanding of a phenomenon

from the perspective of the learner. The role of the researcher is to try to grasp the meanings of students' way of reasoning, rather than to evaluate the correctness of this reasoning. The interviews were conducted in respectively university and school premises. The interviews were all conducted by the author, and in the case of the university students, an observer also attended the sessions. All interviews, except one which was audio recorded, were video recorded. All students were asked for consent for recording before beginning the interviews.

3.3. Participants

The three seventh graders in the study were from two public schools in Medellín, Colombia. None of them had received any formal teaching in physics previous to the interview. The students were selected by the science teacher at each school; with no particular instruction for the selection. The two university students followed different majors at the University of Bergen in Norway. None of them pursued a major in physics. The students were recruited from the common areas of the University ground and they signed up to participate in the sessions without any payment. None of the five students had any experience with explicit stock and flow thinking previous to the study.

3.4. Data Analysis

The interviews were video recorded and analyzed using software for live video coding. The interview fragments presented in this paper were transcribed verbatim and translated from Spanish to English for the Colombian students. The analysis was conducted with a focus on identifying: (1) the intuitive knowledge elements associated with motion dynamics (p-prims) used by the students, and (2) the relations established by the students between the car's motion situation and the tank analogy. The fragments are presented in a rather "raw" state. This allows us to better describe how the phenomenon of reverse transfer evolves and how it looks like in the case of the tank analogy.

4. Results: episodes of reverse transfer

In this section we present 5 episodes of reverse transfer, one for each of the 5 students. In these episodes, the students modify the tank analogy to fit two particular intuitive knowledge elements of basic dynamics of motion: the *dying away p-prim* and the *force sustains motion p-prim*. The three first episodes deal with *dying away* and the last two with *force sustains motion*.

4.1. Fitting the *dying away p-prim*

In the context of motion, the *dying away p-prim* (diSessa, 1993) involves the idea that an object's velocity diminishes as the object moves or as time goes by. This is basically the idea that an object *simply* cannot move forever because motion always has to get to an end. There is *no need for any particular cause* to explain the end of motion.

In the following three episodes, school students modify the tank analogy to fit the *dying away p-prim* in the situation of a toy car that is pushed. In slightly different ways, the students suggest small changes to the water tank analogy to accommodate the idea that the velocity will decrease, *without any particular cause*, as time goes by. The students identify the “push” as the action that controls the velocity inflow, but they make changes in the water tank analogy that remove the need for a similar action to control the velocity outflow. Hence, changes made by the students consist of modifying the outflow from water to time, assuming an outflow with no cause, or inventing the occurrence of an overflow of water. In this way, the students eliminate the need of any particular cause to explain the decrease in velocity—otherwise caused by the action of a resistance force.

In all episodes, “S” represents the student, “I” the interviewer, and “[]” is used for clarifying comments by the author.

Episode 1

School student 1 modifies the tank analogy so it fits the idea that “time simply has to pass for velocity to decrease”:

I: How do you think the tank could be applied to the case of the car?

S: For instance when we open the in-valve the tank fills up, and then the water decreases until the tank is empty.

I: And how does that apply to the case of the car?

S: It is like when somebody gives a push to the car, the velocity decreases until the car stops completely, like the water! The tank loses water until it gets empty again.

I: And what would be like the out-valve in the case of the car?

S: Uhhh...the time!

Episode 2

School student 2 creates an outflow with no real cause to explain the decrease in velocity. The student explains that “the out-valve is when velocity decreases”, which suggests that rather than seeing the valve as the cause for the change in velocity, the student sees the decrease in velocity itself as the cause for the change in the valve.

I: And how do you think the tank could be applied to the case of the car?

S: That the in-valve is when we push and the velocity increases, and the out-valve is when the velocity decreases.

I: And so the out-valve is when the velocity decreases.

S: Yeah!

I: And what makes the velocity decrease?

S: When the velocity decreases.

I: But for the velocity to decrease the out-valve has to be open, right?

S: Yes.

I: And how does that valve get opened? The in-valve opens when the girl pushes the car, what about the out-valve?

S: It opens by itself.

Episode 3

School student 3 invents an illogical outflow. Rather than a regular out-valve, the student uses overflowing as the mechanism through which the water in the tank decreases. Water reaching the maximum capacity of the tank causes the overflow. The student used this explanation to fit the *dying away* idea of velocity reaching a limit from which it *simply* has no other possibility but decreasing. The overflow outflow is illogical also because it would only limit the velocity, not cause it to die away.

I: How would the tank apply to the motion of the car?

S: The velocity would be like here [pointing to the water in the tank]. Depending on the force that I apply to the car, the velocity will increase at a certain pace. So if we increase it the in-valve, the velocity increases faster. But if I decrease it, the velocity will increase slower. For instance, with the car, if I push it harder, it will go faster. And here with the water, if I put the in-valve high, the water will increase fast, until the point where the water overflows and goes out of the tank.

I: Ok, so if we think of the velocity as water in the tank, why does the car stop?

S: Because it gets to a point where the car slows down.

I: Why does that happen?

S: It is like in the tank. If we leave it until it gets to the maximum, it will start overflowing. It doesn't have more capacity to fit the water so it overflows out of the tank. The water has to go out at some point, in the same way that the car has to stop at some point.

4.2. Fitting the *force sustains motion p-prim*

The *force sustains motion p-prim*⁴ (diSessa, 1993) says that a continuous effort is required for continuous motion to occur (this p-prim is also known by the name *continuous push p-prim*). Removing the sustaining effort causes motion to end. The *force sustains motion p-prim* is similar to however somewhat more comprehensive than the *dying away p-prim*. For *force sustains motion* the *lack* of an applied force is seen as the *cause* for the decrease in velocity. For *dying away*, the need for an explicit cause is not seen at all.

In the following two episodes, university students modify the tank analogy to fit the *force sustains motion p-prim* in the situation of a car's motion. In both episodes, the students express that the water tank would be similar to the car's motion *only if you remove the out-valve* from the tank. They affirm that velocity could be thought of as the water in the tank, and that the in-valve would then represent the gas pedal. The students assume that when you press the gas pedal, the velocity increases and when you stop pressing it, the velocity decreases. This modified version of the water tank fits the idea that to decrease the car's velocity it is sufficient to remove the applied force that sustains the motion. This is basically the idea that closing the in-valve in the tank is sufficient for the stock of water to decrease.

Episode 4

The following episode is particularly interesting because it illustrates not only the phenomenon of reverse transfer, but it also shows how university student 1 goes through a process of knowledge change that ends in the transformation of his *force sustains motion* idea.

⁴ diSessa uses the term *continuous push* for this p-prim. We use the term *force sustains motion* because it expresses more clearly the content of the idea involved by the p-prim.

The episode begins with the student affirming that, from his viewpoint, the water tank and the situation of a car's motion are not similar. Then he accepts that they can be similar *if* you remove the out-valve from the tank:

I: Do you think there is any relation between the tank and a car's motion?

S: No, I don't think they are similar.

I: Can you explain why you think that?

S: Well, yes, I actually think they are similar if you remove the out-valve. That might actually fit quite well. Then I think of a gas pedal. If you push the gas pedal, that is the same as opening the in-valve at full. And when you reach the ultimate speed, you cannot get any faster and at the same time the water will go out of the tank.

I: What made you think about removing the out-valve?

S: Well, we don't have to remove it, we can just keep it closed.

I: Yes, I see what you mean. So what made you think of keeping it closed?

S: Because when you increase your speed, you increase the water in the tank.

I: What would happen if the out-valve was opened?

S: Then you couldn't reach the speed as fast as otherwise.

After this last intervention by the interviewer, it is not really clear that the student is indeed removing the out-valve to fit the idea of *force sustains motion*. The interviewer tries to get a better idea of the student's reasoning:

I: You said that as you reach the ultimate speed, the water will go out of the tank, can you explain that better?

S: Well, you run out of fuel. If you keep the out-valve opened it will be like the car running out of fuel. And when we don't have more fuel, we cannot get speed. We will keep stopping after the fuel runs out.

I: So what is that in the tank?

S: [Laughs] I know, I am mixing two tanks here, one for the fuel and one for the velocity. But I guess you can mix them if you want to.

In these two last interventions by the student, he introduces a new stock of fuel as another “maintaining cause” for the car’s motion. Here, the cause of motion is the fuel, and the cause of the lack of motion is the lack of fuel. The student assumption is that the lack of fuel implies that the gas pedal would not be effective in bringing the car to speed anymore, and therefore, the car would stop moving. According to Newton’s Laws, the lack of an accelerating force is not sufficient for motion to cease. It only implies that the velocity will not increase anymore. In the case of the tank analogy this means that closing the inflow to the stock of velocity is not sufficient for the stock to decrease.

The episode continues with the student suddenly returning the out-valve to the tank and recognizing the need of the out-valve for the velocity to decrease. The student then goes through a process where he realizes the change in his own assumptions. Having witnessed this process of change, the interviewer tries to get the student to make explicit the differences between his previous and current assumptions:

I: What would have to happen for the velocity that is already accumulated to decrease?

S: Well we have to open the out-valve and close the in-valve, let go the gas pedal.

I: When you let go the gas pedal

S: You close the in-valve and you open the out-valve. Then the water keeps flowing out and the speed gets lower.

I: When you think of the out-valve, what would that be in a real situation with a car?

S: Maybe pushing the breaks? Maybe? [Laughs] And I was thinking about this fuel tank.

At this stage, the student is evidently affected by his change of mind. He is now thinking of “breaking” as the cause for the decrease in velocity and he laughs at thinking of his previous idea of the fuel tank. The episode ends with the student

recognizing his previous *force sustains motion* view and realizing that velocity cannot decrease simply by decreasing its inflow:

I: Ok, so let's review what happened here. First you had removed the out-valve and that made you feel that the tank was indeed similar to the car's speed. You still think that?

S: No [laughing].

I: What made you change your mind?

S: I was just saying what came to my mind [laughing evidently surprised].

I: I would like you to please clarify something for me. If you go back to when you removed the out-valve, did you have the idea that the velocity would decrease even without that valve?

S: Yeah, I did.

I: What did you think would make the velocity decrease?

S: I guess I was thinking that it wouldn't increase as much, but now I think that you cannot decrease velocity by simply decreasing the in-valve.

I: Did you have that in mind before?

S: No [Laughing]. I didn't. I was thinking that the velocity would decrease.

Episode 5

University student 2 disregards the role of the out-valve and assumes that the in-valve in the tank would represent *both* the gas pedal and the break. According to the student, the velocity will increase when the in-valve is higher than zero, and it will decrease when the in-valve is *zero*:

I: Do you think there is any relation between the tank and a car's motion?

S: Yes, it can be like how fast you switch. The in-valve would be like the gas pedal and the break for the car.

I: And what would be that in the tank?

S: Well first it can be like when it is filling up depends on how much you switch in the in-valve.

I: And what would be the out-valve?

S: I have no clue [laughing].

I: If the in-valve is the gas pedal and the break, how would the car stop?

S: Well, I guess you have to switch the out-valve and when the tank is emptied, the car stops.

I: Before, when you mentioned that the in-valve would be the gas pedal and the breaks, what made you think that?

S: Well, I was thinking in the car's speed filling up as the water in the tank.

I: Clarify something to me please, when you were thinking of the in-valve being the gas pedal and the break, did you think of the velocity decreasing?

S: Yeah, like if the valve is in zero, it is the break. And the gas pedal is when the in-valve is from 1 to 10.

Notice that the way the two university students use the tank to represent the car's motion seems, at first, to resemble Figure 4 with net acceleration. However, the students believe that the velocity will decrease when the flow is closed (zero represents the break) and not when the flow is negative as would be the correct interpretation.

5. Discussion and further research

After Thorndike's "simple" idea of transfer as a function of identifiable similarities between situations, investigations of transfer have evolved to account for many complexities observed in empirical data, e.g. the importance of the learner's perspective (Lobato, 2003). Yet, however, most of this work has been done under the assumption that what is transformed and adapted during transfer is knowledge, and that the source and target situations are given. In this paper, we have shown empirical data supporting a wider view of transfer in which the analogy or source situation is no longer given and constant but is also subject to change. Using data from previous investigations we found five episodes where students did modify a water tank analogy to fit their understanding of a target situation (motion of a car). Although the

possibility of learners transforming also the source and target situations has been advanced by some researchers (Beach, 1999; Bransford & Schwartz, 2001; Carraher & Schliemann, 2002), empirical evidence such as ours is perhaps unique in learning research.

Using data from previous investigations we found five episodes where students modify a source situation (water tank analogy) to fit their understanding of a target situation (motion of a car). The five episodes show how students modify the tank analogy to fit two intuitive knowledge elements (p-prims) associated with motion: *dying away* and *force sustains motion p-prims* (diSessa, 1993). Hence reverse transfer helped the students keep their p-prims unquestioned and unchanged.

The phenomenon of reverse transfer is either rare or otherwise tend to be invisible during transfer. None of the remaining students in the two original studies (9 seventh graders and 6 undergraduates) exhibited this phenomenon. Moreover, many of these students successfully transformed their intuitive knowledge of motion using the tank analogy (Saldarriaga, 2011c). Still, our results suggest that it may be important for teachers to be aware of possible reverse transfer. Reverse transfer reduces conflict and leaves inappropriate knowledge unquestioned. It may even reinforce learners' confidence in this knowledge.

Further research directed at reverse transfer will help understand when this phenomenon occurs and how it is cued. Both p-prim-like knowledge (diSessa 1993) and the tank analogy apply to diverse situations across different domains. We have observed that even if an analogy is rather generalizable from an experts' perspective, the outcome of learning with the same analogy can vary significantly across situations. For instance, previous to the episodes of reverse transfer, the 2 university students in this study had used the tank analogy *successfully* to reason about accumulation in the systems of the money in a bank account and people in a building. Hence, the same analogy can lead to productive learning in some situations while in other situations existing knowledge can conflict and compete, hindering the effect of the analogy. Physics is a particularly rich domain when it comes to intuitive

understandings; therefore, one could expect the phenomenon of reverse transfer to be more pervasive in this domain than in other domains were there is less prior knowledge. Nevertheless, difficulties with complex dynamic systems have been documented across diverse domains and disciplines (see Jacobson and Wilensky, 2006 for a review). To the extent that these difficulties are widespread, there may be a considerable potential for reverse transfer.

References

- Beach, K. (1999). Consequential transitions: A sociocultural expedition beyond transfer in education. *Review of Research in Education, 24*, 101–140.
- Bransford, J. D., & Schwartz, D. L. (2001). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*, 61-100.
- Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science, 18*(4), 237-261.
- Carraher, D., & Schliemann, A. D. (2002). The transfer dilemma. *The Journal of the Learning Sciences, 11*, 1-24.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30*(10), 1241-1257.
- diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2/3), 105-225.
- diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction, 25*(4), 523 - 565.
- Forrester, J. W. (1961). *Industrial dynamics*. Productivity Pr; Student Edition.
- Forrester, J. W. (1968). *Principles of systems*. Cambridge, EUA : Wright-Allen.
- Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge University Press.
- Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *The Journal of the Learning Sciences, 15*(1), 11-34.
- Kapon, S., & diSessa, A. A. (2010). Instructional explanations as an interface---the role of explanatory primitives. *AIP Conference Proceedings, 1289*(1), 189-192.
- Lobato, J. (2003). How design experiments can inform a rethinking of transfer and vice versa. *Educational Researcher, 32*(1), 17-20.

- Lobato, J. (2006). Alternative perspectives on the transfer of learning: History, issues, and challenges for future research. *Journal of the Learning Sciences*, 15(4), 431 - 449.
- Saldarriaga, M. (2011). *Learning with water tank analogy: How students' intuitive knowledge of basic dynamics of motion changes during transfer* .
- Saldarriaga, M., Christensen, D. L., & Moxnes, E. (2011). *Students' generalizations of a stock and flow analogy and their supportive and hindering roles in transfer*.
- Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review*, 247-261.

Paper 4:

*Students' generalizations of a stock and flow analogy;
support and hinders for transfer*

IV

Students' generalizations of a stock and flow analogy; support and hinders for transfer

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Abstract

Dynamic systems can be conceptualized in terms of *stocks* and *flows*. Stocks represent things that can be accumulated over time, and flows are the ways in which those stocks change. In the field of System Dynamics the Stock and Flow (SF) model is usually introduced through a *water tank or bathtub analogy*. Here we investigate what interpretations students make of this analogy. In a series of pilot sessions, the first author observed that some school students struggled to transfer the tank analogy to other SF systems (e.g., money in piggy bank, people in a bus). The students rejected the tank as a “fitting” representation for the systems in question, and we wanted to understand *why*. An actor-oriented view of transfer suggests that transfer depends on the personal generalizations made by the learner. Therefore, transfer needs to be studied from the learner's rather than from the scientifically correct expert's perspective. To explore which generalizations students make of the tank analogy and how these generalizations affect transfer to other systems, we conducted clinical interviews with 8 university students. We identified 10 generalizations that students make from the tank analogy. Some generalizations support, others hinder transfer. The 10 generalizations seem to influence not only the sort of systems the students propose as analogical to the tank, but also whether students accept the tank analogy as representative for systems proposed by us.

1. Introduction

The purpose of an analogy is to use a known situation to highlight aspects of a less familiar situation and to support transfer. Hence, when used in teaching, the teacher would usually expect the analogy to convey to the students the particular intended meanings he wants it to convey. However, in contrast to popular views and traditional research on transfer of learning, recent research shows that generalizations of an analogy made by learners may differ from those intended by the expert (e.g., (Carraher & Schliemann, 2002; Clement, 1993; Kapon & diSessa, 2010). Transfer depends not necessarily on whether the analogy and the target situation are structurally similar from the expert's perspective, but on the generalizations learners make of the analogy (Lobato, 2003). The purpose of this paper is to explore the generalizations students make of a *water tank analogy* and the role of these generalizations in transferring this analogy to other situations. The paper contributes not only to illuminate how generalizations of the water tank analogy support or hinder transfer, but also to advance general understanding of the phenomenon of transfer of learning.

The water tank analogy consists of a water tank with pipes and valves for adding to and removing water from the tank. The amount of water in the tank changes as water is added or removed over time. The two elements of the tank (the "amount of water in the tank" and the "flows") constitute an analogy to the concepts of *stocks* and *flows* (Forrester, 1961; Forrester, 1968). Stocks are everything that is stored *as water in the tank* (e.g, people, money in bank); and flows are the ways in which those stored things change *as water flows controlled by valves* (e.g, births and deaths of people; saving and withdrawal of money).

Because we are dealing with dynamic systems, different from most situations dealt with in the transfer literature, we use the term "system" rather than the term "situation". In dynamic systems, the word situation has two meanings. It could describe the system (e.g. a situation could be a person controlling the valves of a

water tank), and it could describe the conditions (state) of the system at a particular point in time (e.g. a situation could be that a tank is half full). Hence, we use the term system rather than situation to be precise.

In a series of pilot sessions in Colombia (in January 2010), the first author presented several six and seventh grade students with the water tank analogy. The aim was to observe students' general reactions to the tank analogy and whether they would find it plausible that the tank could be representative of other common systems. The students themselves proposed lakes, oceans, and sinks as exemplary similar systems. These contexts seemed, predictably, rather unproblematic for students –since all of them involved water. However, when the researcher proposed that the tank could also represent a bucket with sand, or a piggy bank, or people in a building, students responded in ways such as:

“No, the sand is different. The sand wouldn't have the same ease to flow out and so the tank could never get completely empty.”

“ No, a piggy bank only has a way in...”

“No, people can't flow through pipes.”

Students appeared to have problems accepting the tank as a plausible representation of these other systems and we wanted to understand *why*. From a systems perspective, student answers seemed peculiar and representative of a pre-stage of development of abstract thinking. Hence, one might expect that for instance university students would not be preoccupied with people flowing through pipes, and instead, find it easy to abstract the elements of the tank analogy and apply them to other systems.

To test this, we wanted to explore: (1) which generalizations students would make from the tank analogy, and (2) if, and how, these generalizations would support or hinder transfer from the tank analogy to other systems. After a pilot test, we conducted interviews with 8 university students in June 2011. We observed that the students were effectively *transferring knowledge* across structurally similar systems. However, some of the generalizations made by the students from the tank and

transferred across systems were not necessarily those we would have intended them to make. We identified 10 generalizations made by the students. These generalizations seemed to influence not only the sort of systems the students proposed as analogical to the tank, but also, whether they accepted or rejected other systems we proposed to them.

The paper is organized as follows. First we describe Lobato's (2003) actor-oriented view of transfer according to which, transfer needs to be studied from the perspective of the learner rather than from the expert. Next, we present our experimental design. We describe our interviewing methodology and the data analysis process through which we identified the 10 generalizations made by students of the water tank analogy. Finally we present the generalization in detail and describe how they support or hinder transfer, using interview episodes to illustrate. We conclude with a discussion of implications for the general understanding of the phenomenon of transfer of learning.

2. Complexities of transfer

The classical approach to transfer of learning has been that of *identical elements* (Thorndike and Woodworth, 1901)¹. From Thorndike's approach it is assumed that transfer would occur as far as the source and target situations share identical elements such as physical features or common stimulus. Here, transfer is seen as conditioned by the external appearance (to the learner) of the situations involved. Although the classical approach may still explain many cases of transfer, alternative approaches have been proposed to account for observed aspects of transfer that the traditional approach cannot account for.

An alternative approach to transfer of particular relevance here is the actor-oriented view of Lobato (2003). From the actor-oriented view, transfer is defined as a process

¹ See Lobato (2006) and Mestre (2005) for reviews on transfer theory.

of *personal* creation of relations between situations through which the learner comes to see situations as similar (Lobato, 2003; Lobato & Siebert, 2002). Lobato (2004) argues that this personal creation of relations occurs as learners actively generalize particular aspects of a situation by focusing on and isolating certain properties while suppressing others. In this view, *abstraction* is seen as a “constructive process in which the regularities abstracted by the learner are not inherent in the situation, but rather are a result of personal structuring related to learner’s goals and prior knowledge.” (Lobato, 2003, p. 441). Hence, one must consider that similarities between situations are in the eye of the learner. What is similar and transferable from the expert’s perspective may not be so from the learner’s perspective. Equally important, learners may be able to transfer aspects that go beyond external appearance. Consequently, Lobato suggests that transfer needs to be studied by focusing on “properties or regularities that appear to have become the focus of students’ attention while they are engaging [in transfer tasks]...” (Lobato, 2003; Lobato, 2004).

We use the actor-oriented approach to guide our analysis of students’ transfer of learning from the water tank analogy to other stock and flow (SF) systems. Dynamic systems have unique characteristics that make them particularly interesting for studies of transfer. First, they involve two dimensions: a causal structure and the behavior over time generated by this structure. Second, they have an interdisciplinary and cross-domain character. In our study we investigate transfer from the water tank analogy to SF systems in several other domains, with a particular focus on students’ generalizations and transfer of *structural* aspects of the analogy. The purpose of our study is to investigate the generalizations students “spontaneously” make of the water tank and how these affect students’ acceptance or rejection of the analogy as representative of other systems. We do not test any particular teaching intervention.

3. Method

In what follows, we describe participants, present the interview method and interface for the tank analogy, and discuss the method for data analysis.

3.1. Participants

The data used in this paper comes from in-depth individual interviews with 8 undergraduate students from the University of Bergen. The students came from different departments and none of them had any previous experience with dynamic systems and SF representations of such systems. The students were recruited from the common areas of the university ground and they signed up to participate in the sessions without any payment. The first author conducted the interviews under the vigilance of the second author. The interviews were video recorded and later analyzed with qualitative data analysis software. All students were asked for consent for video recording before beginning the interview.

3.2. Interview method and interface for water tank analogy

The purpose of the interviews was to explore transfer with the water tank analogy from the perspective of the learner. The actor-oriented view of transfer (Lobato, 2003) suggests that to do so, we need to gain access to those aspects of the analogy that become the focus of students' attention and which they generalize to other situations. With this purpose in mind, we followed interviewing methods from phenomenology (Kvale & Brinkmann, 2008) and educational research (diSessa, 2007; Ginsburg, 1997). Both methodologies aim at gaining an in-depth understanding of a phenomenon from the perspective of the learner.

The role of the researcher is to try to grasp the meanings of students' way of reasoning, rather than to evaluate the correctness of this reasoning. To gain clarity,

the interview sessions were structured with only small additions to or variations of standard questions. Since we were interested in the students' reasoning, we designed the interviews to enable an ongoing process of data interpretation as the interviews were carried out. Therefore, the interviewer was consistently asking the students to further develop particular concepts or ideas and even to self-interpret particular episodes of their own interviews. This embedded level of interpretation is fundamental in interviewing approaches from both educational and phenomenological research. This approach leads to interviews that are richer in *manifested* interpretations, in the sense that students' reasoning can be more directly "observed" in their statements. This is different from quantitative research where assumptions about reasoning must be based on students' choices or performance.

The interviews were conducted using a computer interface of the water tank analogy (Figure 1). The interface is interactive; the valves can be opened or closed by dragging the handles in steps from 0 to 10 liters per second. The level of water in the tank can be observed to increase or decrease over time. How much the water in the tank increases or decreases per time unit, depends on the difference between the amount of water coming in and the amount of water going out at each instant of time.

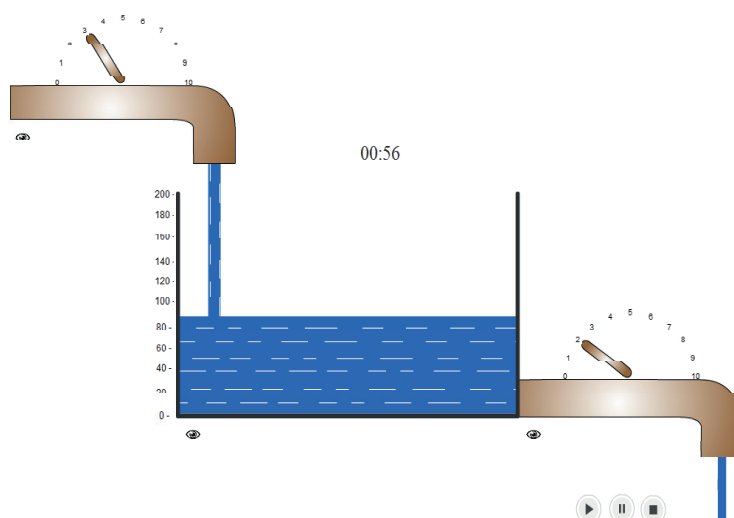


Figure 1. Water tank analogy interface

In what follows we introduce and explain each of the standard questions of the interview.

(1) I have this set-up here that I want to show you. You can explore it. Could you describe exactly what you see?

Each interview begins by introducing the student with the water tank analogy interface in Figure 1. First we show the student how to operate the valves and to start and stop the simulation. Then we give the student a few minutes to play with the simulation. No other instructions are given unless the student has difficulties operating the simulation. The interviewer refers to the water tank simply as a “set-up” to avoid using particular descriptions. The purpose is to explore the descriptions of the water tank made by the students *themselves*.

(2) Does this set-up remind you of anything else, besides this particular example?

(3) Could you describe the distinct similarities and differences between the set-up and what it reminds you of?

The purpose at this point of the interview is to get the students to describe those systems they perceive to be analogous to the water tank and why. The interviewer asks the student to describe what is similar and what is different between the water tank and *each* of the systems suggested by the student. The interviewer asks “is there something else it reminds you of?” trying to get the students to be exhaustive in describing all the situations they could think of.

(4) I would like you to notice some particular things about the tank. The water in the tank accumulates as time goes. The amount of water in the tank increases when water is added through this valve and it decreases when water leaves the tank through this other valve. Focus on how the water in the tank changes over time.

The interviewer describes the tank briefly and prompts the student to focus her attention on the *accumulation* of water in the tank. The purpose here is to investigate

how a minimum of prompting would change students' generalizations of the tank and the sort of analogous systems they would suggest. What we do here is to attempt to increase the student's awareness of the behavior of the system, in addition to its structure (the set-up). This interview question however, did not give "useful" results. The question was effective in stimulating students to think about *more* systems of application of the tank analogy, but the new suggestions were too few for us to draw reliable conclusions about the effect of the prompting on students' focus on accumulation.

(5) Does this remind you of anything else, besides this particular example?

(6) What makes you think about that particular situation? Follow up question: Could you describe the distinct similarities and differences between the set-up and what it reminds you of?

The student is asked once more to describe what the set-up reminds her of and why.

(7) If you think about people in a building, do you think there is anything different or common between this and the tank? Could you tell me about these differences or similarities?

(8) – (10). Question 8, 9 and 10 are similar to question 7, they differ only in the system proposed to the student: money in a bank account (question 8), CO₂ in the atmosphere (question 9), and a car's velocity (question 10). In these questions, as in question 7, the student is asked to describe whether the system explored has any relation to the tank. We use these particular systems because they should be sufficiently well known for any university student to be able to reason about them.

Finally, when discussing the bank account system, we also asked students "what if you gain interest on the money in your account? Could you use the tank to think about how the interest rate affects how much money you get in interests?" The purpose of asking this question was to give the students a system that did not fit the tank analogy. The interest rate affects the inflow to the stock through an *instantaneous*, rather than *cumulative*, causal relationship, and there is a feedback

from the stock of money to its inflow. The aim was to investigate the possibility that students were simply trying to “force” every system presented to them into the tank analogy, rather than reason thoroughly about the appropriateness of the analogy. Hence this question serves as a test of our methodology.

3.3. Data Analysis

The analysis of the recorded interviews consisted of four stages. Before the analysis started, the interview videos were directly coded using special software for qualitative data analysis. The software enables the researcher to split videos into smaller segments and assign to them particular codes. In this way, it is easy for the researcher to continuously revise the codes and revisit the respective interview segments associated with them, at any stage of the analysis.

In what follows we describe the four general stages of the data analysis. Nevertheless, it is worth mentioning that the actual analysis did not necessarily follow a one-way development through these stages. Constructing a theory from a corpus of qualitative data requires multiple cycles of revision, which implies going back and forth between the stages of analysis. A first cycle was carried out with data from a pilot interview that the first author conducted with one university student. To limit the chances of misrepresentations and inconsistencies, the first author conducted a full cycle of analysis. This was followed by cycles of analysis by the first and second authors aimed at testing the appropriateness and fitting of the coding.

Stage 1: Systems as unit of analysis

From the results of our pilot test interview, we had an intuition that the systems of application of the tank analogy were important. The student in the pilot interview appeared to emphasize different aspects of the water tank when applying it to different systems. Therefore, a natural first unit of analysis was the systems of application of the tank analogy. We segmented and coded the interviews videos into

episodes corresponding to each of the systems of application that the student suggested as analogous and those we suggested to them. The result was 11 systems of application: dam, waterfall, sink or bathtub, canal lock, sea tides or ocean, sand clock, “any place people go through,” people in building, money in account, CO₂ in atmosphere, and a car’s velocity.

Stage 2: Reasons as unit of analysis

In our second stage of analysis, we put in practice Lobato’s (2003; 2004) actor-oriented approach. We analyzed each of the systems of application looking for the reasons that students gave for proposing, accepting, or rejecting a particular system as analogous to the water tank. These reasons are basically student answers to the questions of *what makes you think about that particular situation? What are the differences and/or similarities with the tank?* In other words, reasons represent “what the tank is about” from the learner’s perspective. For instance, a learner may think that the tank is “simply about systems involving water”.

Student explanations would often contain *several* reasons to propose, accept, or reject a particular system as analogous. For instance, one student said that he thought of a canal lock because: “it also involves water,” and “the level of water rises or decreases inside the lock,” and “you can adjust how much water comes in and out of the lock.” We identified and coded each of these reasons separately.

We do not claim that the reasons students state denote *all* what the tank represents to them. Instead, our claim is that reasons represent attention *priorities*. In other words, reasons involve those aspects of the tank analogy that students attend to because they appear more immediately meaningful to them, or they are more immediately evoked by the systems proposed to them by the interviewer.

Stage 3: Generalizations from clustering of systems and reasons

The third stage of analysis involves multiple cycles and revisions. Having identified each student's reasons within each individual system of application, we analyzed the data across systems and students looking for patterns. The purpose was to determine whether reasons were common to multiple students, and in which systems they were used. Throughout this stage of analysis, we found that all the reasons used by students to generalize the analogy to other systems fell into one of 10 common reasons. We call these *generalizations*. We do not claim that our list of generalization is exhaustive. Further research could contribute to other generalizations or to make the list more robust by triangulating across more students and systems of application. Also, our own categorization may have missed associations that would be special to certain students. For instance, one student in our study had a particular focus on *aesthetic* aspects of the water tank. The student focused on a series of white stripes representing the motion of the water in the tank in the interface (Figure 1). The student explained that, to her, the motion of the water inside the tank was an analogy to aspects such as: how people communicate and interact inside the building, or how CO₂ distributes differently within the atmosphere. We did not include this particular association in our analysis. Like this one, there could be other possibilities of associations made from the water tank system; however, they may be rare, very specific, and not easily generalizable.

Stage 4: Supportive or hindering role of generalizations

Our final stage of analysis consisted in revising each generalization within each system of application of the tank analogy once more. At this stage it was evident to us that a student could use the same generalization to either accept or reject a system as analogous. For instance, a student could use the fact that “you *can* control how much comes in and out” to accept the canal lock as an analogous system. But the same student could use the opposite – the fact that you *cannot* control how much comes in and out, to reject CO₂ in the atmosphere as an analogous system. Hence, we identified

supportive and hindering roles of generalization for the different systems of application.

4. Results

First, we introduce and describe each of the 10 generalizations. Then, we report results regarding support and hinders for transfer, with a particular focus on generalizations that may hinder transfer.

Before we start, we report a result that lends support to the method we use. One of the application systems we proposed did *not* fit the tank analogy: the question about the effect of interest rate. Accordingly, *all* eight students answered that in this case the water tank was *not* a proper analogy. They all explained that the interest payments would depend on what already was in the bank account and that the interest payments would be like an extra flow in addition to the incomes flow. This suggests that students' reasoning during the interviews reflects their "natural" way of thinking rather than intentional attempts to make *any* application system fit the tank analogy.

4.1. Ten generalizations students make from the tank analogy

Here we describe the 10 generalizations illustrated by excerpts from students' statements in the interviews. These generalizations correspond to aspects of the water tank analogy that students perceive as salient and that triggers them to associate the tank with other systems. Table 1 below provides a concise definition of each generalization. Most of the time, student explanations contain more than one generalization. In this section however, we present the generalizations one-by-one.

Table 1. Ten generalizations of the water tank analogy

Generalization	Description
<i>Simply water</i>	The tank is seen simply as a representation of a system involving water. Focus is on the substance.
<i>Containing</i>	The tank is seen as representing things that are contained or stored inside a limited space.
<i>Rising</i>	The tank is seen as representing things that rise and decrease without necessary reference to how that happens.
<i>Lifting</i>	The tank is seen as representing a hydraulic system with a focus on the lifting capacity of water as its level is increased or decreased.
<i>Going in and out</i>	The tank is seen as representing things that go (or are put) in and out of a certain space.
<i>Controlling</i>	The tank is seen as representing systems where additions and removals can be controlled or regulated.
<i>Transporting</i>	The tank is seen as representing a system where things are transported or taken from one point in space to another.
<i>Accumulating</i>	The tank is seen as representing stocks whose change depends on how much is added and how much is removed.
<i>Conserving</i>	The tank is seen as representing a system in which what goes in is the same as what comes out.
<i>Fluidity</i>	The tank is seen as representing things having characteristics of fluids: has volume, fills all spaces of a container, and finds its way out.

4.1.1. Simply water

Simply water is an obvious generalization. Students see the *substance* as the most representative surface feature of the water tank system, and transfer occurs to other systems involving water. The following two statements are representative of instances

of *simply water* in the data. “I” refers to the interviewer, “S” to the students, and the words in brackets are clarifying comments added by the researchers during the analysis, for instance indicating where the interviewer is pointing in the interface.

1. I: What made you think of this example [canal lock]?

S: Because I focused on the water thing more than on the things going in and out. I focused more on things working with water.

2. I: Does this set-up remind you of anything else besides this particular example?

S: No, I don't think so. Maybe some water thing in the river where they make power. Just because it's like that...

I: And why does this [tank] make you think of that example?

S: I don't know actually. It's probably just because it's water...

4.1.2. Containing

Containing involves the idea that the water tank is representative of things that are kept in a limited space or have an identifiable boundary. Buildings, bank accounts, and canal locks are examples of systems that are perceived by students as having the property of containing. We code *containing* when the student emphasizes the role of the physical place containing things over the accumulation of things. The following two statements are representative.

1. I: What would be the differences and similarities between that [canal lock] and what we have here [tank]?

S: The canal and that one? Well, this as well is just a tank and not a full river, but I guess in this canal you will also lock the room where the boat is standing...

2. I: What made you think of the examples of revenues and people?

S:...It's really the fact that you have a place where there is what you have...So I think of a place that is closed that has an entrance and a place to go out.

4.1.3. Rising

Rising involves the idea that the water tank is representative of levels that increase and decrease. Here students' focus of attention is on the water level increasing and decreasing inside the tank. When students generalize *rising*, transfer occurs to systems that are characterized by visible changes in levels such as canal locks and sea tides. *Rising* does not imply that the student completely disregards flows. Rather, it implies that the student does not make specific references to *how* the flows affect the water level inside the tank. For instance, in addition to the quote in the example 1 below, the same student made reference to the "work of valves" for increasing and decreasing the level of water inside a canal lock. However, it is not possible to tell from her statements, whether she is thinking in terms of accumulation or in terms of an instantaneous lever system.

1. I: Does this set-up remind you of anything else apart from what you already mentioned?

S: Yes, it can be like, I don't know the name but the place that you use to, no it's actually not the same. But, it's the place that you use to move boats from one level to another. Yeah, you fill the tank to make the boat go up...

2. I: Does this set-up remind you of anything else besides this particular example?

S: Well water that changes over time. It happens all the time in the sea with the tides.

I: What made you think of the tides?

S: I don't know. Water that the level changes over time.

4.1.4. Lifting

Lifting is not necessarily an independent generalization but rather a "second stage effect" of *rising*. When focus is on the level of the water in the tank increasing and decreasing, the water tank can be seen as a hydraulic system with water having the

capacity to lift objects. In our data, *lifting* was only generalized to the system of the canal lock. Example 1 of *rising* (section 4.1.3) illustrates the association between “filling up the tank” (*rising*) and “making the boat go up” (*lifting*). The following statement provides further illustration.

1. I: What made you think of that canal?

S:...I think because...when you elevate the water [*rising*] you can elevate whatever is on it [*lifting*].

4.1.5. Going in and out

Going in and out is the idea that the water tank is representative of things that go in and out of a space. Here the main focus of attention is on the water coming in and going out, and not on the accumulation process in the stock. It could be argued that students focusing on what goes in and out could also be attending to the accumulation inside the tank – even if they do not mention it. However, as the actor-oriented approach recommends (Lobato, 2003), our data analysis focuses on what students *explicitly* indicate as influencing the generalizations they make of the tank. Our assumption is that students’ explanations reflect what students believe is *sufficient* to describe what the water tank is representative of from their perspective.

The following statements are representative of instances of *going in and out*. Notice that in the first example, the student does not make any explicit reference to the stock at any point in the explanation; her attention is evidently focused on the flows. Similarly, in the second example the student’s explanation involves *containing* as well as *going in and out*, but there is no particular attention for what happens inside the container.

1. I: Do you think there is any relation between the situation of people in a building and this [tank]?

S: Maybe, like if they go through a hole or something. Because here the water comes in and then out another way, so yeah.

2. I: You mentioned before the example of revenues, how is it related to the tank?

S: Because there is a coming in, and there is a place where you can decide to keep it [containing] but still there is a pipe where you can make the money go away. And the very important thing is that the two pipes can be different, it's zero to ten, so it can be 3, 4, 5, 6. And so the incomes can be different from the outcomes. So yeah, I think of that.

4.1.6. Controlling

Controlling is the idea that the water tank is representative of systems that can be controlled. Here focus is on the capacity to control, regulate, or adjust the flows or the stock in the water-tank system. *Controlling* has a deeper connotation than the sole presence of a physical mechanism for controlling – such as the valves in the tank. Based on our data (statements here and in section 4.2.2), we defined *controlling*, from the students' perspective, as involving one or both of two properties. First, *controlling* implies “to be in one's hands.” The student sees herself as *the actor* that has the power of exercising control in the system by adjusting or modifying the flows. Second, *controlling* may also mean that a system is controllable. This implies to know how something works, the factors it involves, and to be able to measure these factors.

Controlling appears to be a very common generalization of the tank analogy and to play a very important role in transfer. All students used *controlling* at some point during the interview, and it played a role in transferring to 9 out of the 11 systems. The following statements are representative.

1. I: Does this set-up remind you of anything else besides this particular example?

S: Yeah, it is like with the revenues, you get your incomes and your outcomes, and what you have. And you can manage how much you need to pay the rent,

to pay the food. And there is the income that depends on if you're working a lot or not.

2. I: Does it make sense to you [the student seems unsure about the people in a building example]?

S: That they are similar? The people and the water?

I: Aha

S: Yeah, I can see it now after the money example, kind of.

I: What is particular about the money example that made you realize that?

S: The fact that you can turn the valves on and off. The money and the water are closer I think.

I: Can you tell me about turning the valves on and off, what do you have in mind?

S: Well, you can decide how much water you want in the tank and out, the same with money and people.

4.1.7. Transporting

Students exhibiting *transporting* see the tank as a “transportation system” where things are moved (or go) from one place to another. Here, students focus on the continuously occurring in- and out-flows. Dams, waterfalls, and sand clocks are systems that are perceived by students as having the property of *transporting*. The following statements are representative. They illustrate students’ focus on “flowing” or “going through.”

1. I: Any other situations that this [tank] reminds you of?

S: Yes it can be just a place where people go through and there is no specific reason to stay in the tank, just going through.

2. S: Can you explain that [what makes you think of the river]?

I: Well it is probably because of the form.

S: What do you mean by the form?

I: It is like staircase. It reminds me of rivers when they have like fall and the water goes through it and the turbines make power. I don't know why it reminds me of that. It is because the water goes through it...

4.1.8. Accumulating

Students we code as exhibiting *accumulating* explicitly express that the water tank represents things that change *depending* on how much is added and how much is removed. This sort of statement suggests that the student is not only attending to what goes in and out of the tank, but she is also attending to the relationship between what goes in and out and how the stock changes over time. Nevertheless, despite the apparent sophistication of *accumulating*, it should not be assumed that those students we coded as exhibiting this generalization have a full understanding of accumulation processes. We do not have enough data to affirm that this is the case. Our only claim in this regard is that the student acknowledges the dependency of the stock on the flows. The following statements are representative. Notice that in the first example the student applies two principles of accumulation to the money in the bank system. He explains that the outflow will be zero if the stock is zero, and that the stock will increase if the inflow is higher than the outflow.

1. I: The next situation is money in an account.

S: Yeah! I think that would be a good example of this.

I: Why?

S: Because for many people when you have got the pay check and you want something nice then of course you buy it. A lot of money keeps flowing out of the account. And still you have to have this constant flow of money going out of the valve because you have to buy some food, but when the bucket is empty there will be no more flow and you cannot buy food. And if of course the money keeps flowing in more than it flows out you will fill the account with money. So that is a good example I think. They are closely related.

2. I: And the last situation is a car's velocity or speed. Would that have any relation to the tank?

S: Ummm, well I guess if you say that the speed is the water in the tank and the amount of accelerating that you're doing is this [invalve]. Like if you accelerate more then the speed will go up, and if you decelerate then the speed will go down. So that [invalve] is like acceleration and that [outvalve] is deceleration...It would be like increasing the speed at one rate, and decreasing the speed at another rate, and the combination of the two is what you see in the middle...

4.1.9. Conserving

Conserving involves the idea that the *nature* of what goes in has to match the nature of what goes out. For instance, if liquid water goes in, liquid water has to go out. When this is perceived not to be the case, *conserving* may create challenges for applying the tank analogy to other systems. Nevertheless, based on the only two episodes of *conserving* in our data, it is difficult to get a good idea of how hindering *conserving* can be for transfer. For instance, in one of the episodes the student seems to perceive the water tank as incomplete, however not necessarily inappropriate, to represent the CO₂ system. The reason for this is that the outflow is transformed after it leaves the stock. In the other episode, the student transfers *accumulating* ideas to a river system, however, *conserving* challenges her when she attempts to reason about evaporation as an outflow. Here we present the CO₂ episode. The other episode is presented in Section 4.2.

1. I: Would there be any difference between this situation [CO₂] and the tank?

S:...[trying to remember how photosynthesis works]...maybe so, it is the most different situation because I think the CO₂ is being transformed into other substances, but it's similar too, it's not completely different.

I: Can you tell us more about this thing of transforming?

S: I think there is an ongoing chemical interaction all the time with the CO₂. It

is interacting with other things.

I: And why is that different from the tank?

S: I just think there are more components interacting than just income and outcome.

4.1.10. Fluidity

The last generalization in the list is *fluidity*. In contrast to *simply water* where focus is on the *presence* of water as such, *fluidity* is characterized by a focus on the *properties* of water as a fluid: it has volume, it fills all spaces of the container, and it finds its way out. *Fluidity* creates challenges for transferring to particular systems where these properties are not perceived to be present. Distinguishing between *simply water* and *fluidity* is important because they are associated with different systems of application, and have different roles (support vs. hinder in transfer). There are only 3 episodes of *fluidity* in our data. In all episodes *fluidity* plays a hindering role. We present two here. The other episode is presented in Section 4.2. In the following episodes, the students use *fluidity* to judge the fitting of the tank analogy to the car's velocity and people in a building systems.

1. I: The last situation is a car's velocity or speed.

S: Nooo I don't think so [the car's speed is not similar to the tank], because when I think of this [tank] I think of volumes filling up.

2. I: What would be different and similar between the situation of people in a building and the tank?

S: Well, I think that if the water were people, then maybe when it gets really crowded more people would have to go out automatically. It could be people, I think, but again the water just goes one way and the people would probably go out the same way they came in.

4.2. Generalizations and their role in transfer

In addition to identifying the ten generalizations, we observed that these generalizations *support* or *hinder* successful transfer by contributing to or decreasing students' perception of the appropriateness of the tank analogy to represent a given target system. Students' perception of the appropriateness of the tank analogy is determined by whether what is generalized aligns or is in conflict with the student's understanding of the target system. Conflicts during transfer lead students to either: (1) reject or be hesitant to apply the analogy to the target system, or (2) modify the analogy to fit their ideas of the target system. In this paper we focus on the first outcome. The second phenomenon is more rare and is investigated in more detail in Saldarriaga (2011a).

We also observe that combinations of generalizations are used when transferring to some systems. However, these generalizations have different priorities depending on what system one is transferring to.

Our findings are summarized in Figure 2 and Table 2. Figure 2 shows the 11 systems of application (middle column) and the 10 generalizations (side columns). The first 7 systems in Figure 2 correspond to those proposed by the students themselves. The last 4 correspond to the systems we proposed to them². A continuous line connecting a generalization with a system, indicates that the generalization *supports* transfer to the given system. A dashed line indicates that the generalization *hinders* transfer. And the lack of a line indicates that no student articulated the generalization when transferring to the system.

² Two students also proposed systems related to money (student 4) and people (students 1, 4) before we proposed these systems to them.

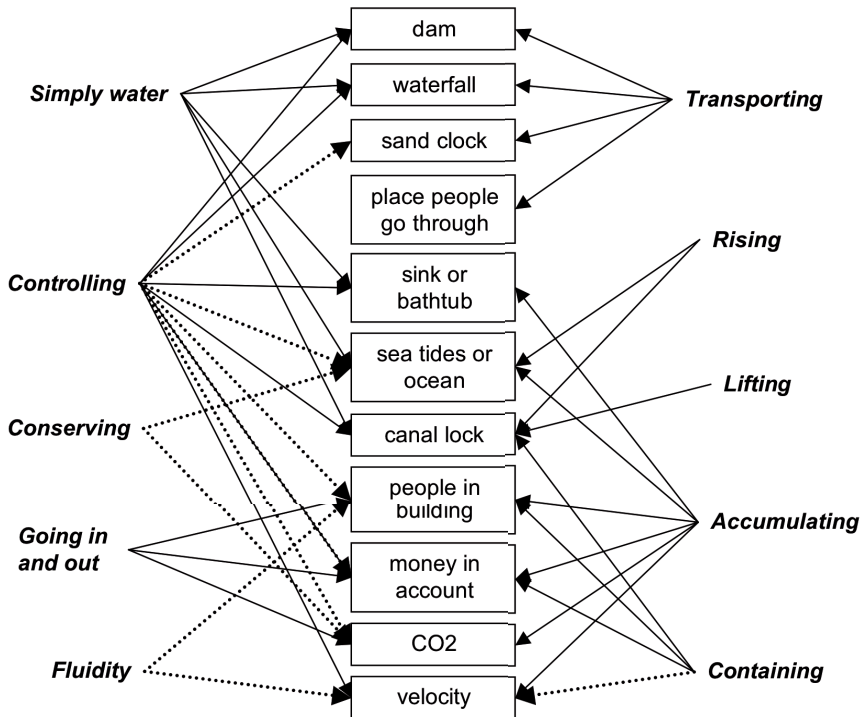


Figure 2. Generalizations and their associated systems

Table 2 complements Figure 2 by indicating the total number of instances of each generalization (last row) and the respective students (identified by numbers from 1 to 8) that used a generalization for a particular system (individual cells). The dark grey cells denote that transfer is hindered; they correspond to the dashed lines in Figure 2. The white cells denote support. The last column shows the students that did not indicate any association between the water tank and any of the systems proposed to them by the interviewer. This only occurred in the case of the car's velocity, and it occurred with 3 students. In these cases, the students expressed discomfort and said that they did not have enough knowledge about physics to comment about this example.

Total instances indicate the frequency and priority of the different generalizations. The most frequent and also the most conflicting generalization is *controlling* with 27 instances. The least frequent but both times conflicting is *conserving*. It may seem surprising that there are three instances of hinders for transfer for systems suggested by the students (*controlling* for sand clock and sea-oceans, and *conserving* for sea-oceans). In all three cases there are other generalizations that support and dominate the hinders.

Table 2. Generalizations instances. The numbers in the cells indicate the corresponding students that exhibited a specific generalization in a particular context.

	Simply water	Containing	Rising	Lifting	Going in and out	Controlling	Transporting	Accumulating	Conserving	Fluidity	No generalization
Dam	1					1	1				
Waterfall	1,2					1	1,2				
Sand clock						5	3,5				
Place through							4				
Sink-Bathtub	1,3,6,7,8	8				1,3,6,7		1,7			
Sea-Oceans	1,3,7		3,7			3	1	1			
Canal lock	3,4,5	3,4,5	3,4,5	3,4,5		3,4,5					
People building		2,3,4,5,8			2,3,4,6,7,8	1,4,5,7,8,2		1		3,5	
Money bank		2,4			2,3,4,6,7,8	1,3,2,4,7		1,5			
CO2					2,3,4,6,7	3,4,5,7		1,8	6		
Velocity		4,6				4		7,8		5	1,2,3
TOTAL INSTANCES	14	13	5	3	17	27	6	10	2	3	3

In what follows we present interview episodes illustrating the hindering role of *containing*, *controlling*, *conserving* and *fluidity*. We focus on hindering because these

are the generalizations that could cause difficulties when teaching and that it is important to be aware of. All examples in the previous section and in Table 1 illustrate how and when generalizations support transfer.

4.2.1. Conflicts with containing

Containing involves a focus on the tank as a limited space that stores water. Hence, *containing* is useful when thinking of systems that students perceive to have an identifiable physical boundary such as people in a building, money in an account, and a lock canal. In these cases, it seems obvious to the students that the building, the account, and the lock serve the purpose of containing people, money and water in the same way as the tank does. However, generalizing *containing* from the tank analogy also creates conflicts when thinking of velocity. This is illustrated in the following interview episode. Notice how *containing* imposes difficulties while *controlling* appears to help the student to see relations between the tank analogy and the context of a car's velocity.

1. I: The last situation is a car's velocity or speed. Do you think there is any relation between the car's speed and the tank?

S: Kind of, because like you can control both things [adding and removing speed][*controlling*], but for me really the tank is about having a place to fill [*containing*]. And with the car's speed is not really the same because you control your moving, from where you're coming to where you're going [*controlling*], but you don't really have a place like for the revenue or for the people in a building where they are in a closed place [*containing*].

4.2.2. Conflicts with controlling

Opposite to the supportive role that *controlling* played in the example above, *controlling* conflicts with transfer to several of the systems under study. *Controlling* appears to be a very common generalization of the tank analogy and to play an important role in transferring. *Controlling* had a role in transferring to 9 out of the 11

systems, and all students used *controlling* at some point during the interview (see Figure 2 and Table 2). Because *controlling* plays such an important role, we provide 2 exemplary episodes to ensure that the different characteristics of *controlling* are illustrated.

In the first episode *controlling* imposes challenges when the student attempts to think of CO₂ in the atmosphere. The student perceives aspects such as lack of knowledge or lack of ability to measure as aspects that make the CO₂ system uncontrollable. Also, the student focuses on the controllability of the outflow and disregards the inflow.

1. I: What do you mean by “we can’t regulate the way out” as you mentioned before?

S: Because we don’t have control over the atmosphere, yet of course. We can think of solutions, maybe by digging a hole in the sand deep in the water. That’s been proposed I think, but that’s difficult...[talks about technical limitations]...

I: What do you have in mind when you say “we can’t control the atmosphere?”

S: Indirectly we can of course, by regulating how much we let out, but when it first gets out there, there is nothing we can do with it, I think.

I: What makes you think that it is so uncontrollable?

S: Because it is so high up and it is so diffuse, abstract, there is a Norwegian word, diffused, for something you can’t touch.

I: Yeah, abstract.

S: We don’t have machines that can go up there and suck all that CO₂.

I: Define “abstract” for us. The way you mean it.

S: I mean we don’t know much about the things and we don’t have the knowledge to make this, we can’t control this yet because we don’t know much.

Another characteristic of *controlling* is “to be in one’s hands.” Students see themselves as the actors that have the power of exercising control by adjusting or modifying a factor. The following example illustrates this property of *controlling*

very well. The student apparently accepts that a third person such as an employer can also exercise control on her income. However, immediately after that, the student makes evident that she is still attributing *the controlling* power to herself when she explains that: in any case what the employer pays to the employee depends on how many hours *the person* works. Hence, the student recognizes *controlling* in a system when the controlling role can be traced back to her.

2. I: The next situation is money in a bank account. Do you think there is any relation to the tank?

S: Yes, I think so, except that you can't really control all the time how much money goes into the account, but here you can control how much water. But you can control how much money you spend, or you should be able to control it [laughing].

I: Why is it that you can't control how much money goes in the account?

S: Well you can sometimes but I mean, you have a certain job, and you have some income and I think, if you could decide for yourself how much money you wanted to come in, a lot of people would choose a lot more than they get. So, yeah, but of course you can decide how much you want to work or things like that.

I: So let me ask you something, you tell me if I am right or wrong about my interpretation. When you talk about controlling, you mean that *you* can control it.

S: Yes.

I: I ask this because then let's think about the income, the money that comes in your account, maybe your employer can control that?

S: Yes, they can, that's true but still they have to give you a certain amount of money if you work a certain amount of time. But they can control it, a little bit.

4.2.3. *Conflicts with conserving*

Conserving involves the idea that the nature of what goes in has to match the nature of what goes out. Systems involving changes in the nature of what is involved may conflict with students' expectation of conservation. We showed in Section 4.1 how a student recognized the water tank as incomplete to represent the CO₂ system. In the following example, *conserving* seems to hinder transfer when the student tries to reason about evaporation as an outflow to an ocean, where it causes the student problems that water molecules can be in both a liquid and a gaseous phase. Notice that at the beginning of the episode, before the conflict with *conserving*, the student transfers *accumulating* ideas to the river system.

1. I: So, does this set-up remind you of anything else?

S: Uhm the sea!

I: How is that?

S: Well like an ocean, or a sea, or anything with water will have more water when is added, like when is raining or like when it is spring, the rivers get very high because all the snow in the mountains is melting. But the water in the rivers decreases because no more water is added, because it is like going somewhere else [*accumulating*]. I mean, it does go somewhere else up in the ocean. I am sorry, I have taken nature studies before so I am really into the ocean stuff, so it kind of reminds me of that, but not with that [pointing to outvalve]. Well the rivers and such go to the ocean but it's not like the oceans get empty. Lakes get empty but the water doesn't go away, it just evaporates.

I: So what would be the differences between the ocean, the example you have in mind, and the tank?

S: Well, here water is added but it doesn't like go through something and go away, it just evaporates or it just stops being added. It's not like it goes somewhere else, or it does but not in the same way than this [tank], I think. Most of the water is evaporated.

4.2.4. Conflicts with fluidity

Fluidity is characterized by a focus on the fluid property of water. This generalization conflicts with transfer to the systems of people in a building and a car's velocity. Students do not perceive people and velocity as having the properties of distributing homogeneously across a limited space, occupying volumes, or finding its way out. The following episode illustrates this.

1. I: The first situation is people in a building.

S: No!

I: No what?

S: No, I don't think so, they are not similar.

I: If they are not similar, does it mean that they are very different?

S: Well, you can put of course a bunch of people in a building and it gets more and more to the top, but this is not the same because water will fill each room, I think. Ahh, when you say that, I think of filling a building with water from the bottom to the top, which makes the rooms all filled and you can't do that with people.

I: I think I understand. It is like you cannot fill every empty space with people. Is that what you mean?

S: Yeah and I am a realist so maybe that is why I think like that. So that's why I don't think they are related. You can of course think that they are related if you want to, but I don't feel like.

5. Discussion and conclusion

Our motivation for using the tank analogy in teaching comes from existing literature documenting an extensive repertoire of people's *intuitive understandings* of world phenomena that commonly differ from established scientific knowledge. Research in education documents intuitive understandings among students and teachers in domains such as math and physics (Confrey, 1990; Driver & Easley, 1978), while

system dynamics research describes similar understandings of dynamic systems in decision makers in climate change (Moxnes & Saysel, 2009; Sterman & Sweeney, 2007), business (Sterman, 1989; Sweeney & Sterman, 2000), natural resources management (Moxnes, 1998), and social systems (Sweeney & Sterman, 2007). Because these intuitive understandings have been observed to be pervasive and to frequently survive after formal teaching, a key challenge for education is to identify and test tools and instructional interventions that help students refine their understanding (Cobb et al., 2003; Cobb, McClain & Gravemeijer, 2003; diSessa & Cobb, 2004).

In particular, instructional analogies have been shown to provide opportunities for refining learners understanding of scientific concepts (Brown & Clement, 1989; Clement, 1993; Duit & Kesidou, 1988; Gentner, Loewenstein & Thompson, 2003). Saldarriaga (2011c) provides evidence of successful refinement of students' understanding of basic dynamics of motion when using a water tank analogy. Saldarriaga's findings suggest that the tank analogy is a promising tool to help students transform their intuitive knowledge of dynamic systems of motion.

However, Saldarriaga (2011c) and previous studies of analogical reasoning and knowledge change (Kapon and diSessa (2010) also show that successful refinement of knowledge requires that learners see the knowledge associated with an analogy as more plausible than the learner's existing knowledge of the phenomenon in question. Hence, in this paper we set out to explore whether students find and accept as plausible the use of a tank analogy across dynamic systems in different domains.

To explore students' acceptance or rejection of the plausibility of using the analogy in diverse systems, we used Lobato's actor-oriented method for studying transfer. This approach says that we should not focus on what we expect learners to generalize and transfer from the tank analogy, rather to focus on what learners themselves perceive as generalizable. Specifically, our methodology consisted of asking students to suggest systems that they associated with the tank and to give reasons of their suggestions. We also proposed systems to the students, and asked them to explain

why they accepted or rejected the proposed systems as analogical.

The results obtained by using this methodology can be seen in terms of two general insights:

First, we observe that the water tank analogy effectively stimulates appropriate associations with dynamic systems. On one hand, *all* systems suggested by the students as analogous to the water tank correspond to dynamic systems (i.e., dam, waterfall, sand clock, place people go through, sink or bathtub, sea tides and ocean, and canal lock). On the other hand, *none* of the students accepted the water tank as an appropriate analogy for the case of the non-dynamic, instantaneous relationship between interest rate and income flow (interview question 8). To the extent that all students suggested dynamic systems and recognized a non-dynamic one when presented to them, we can conclude that the water tank analogy activates ideas that are useful for thinking of dynamic systems.

Second, despite the previous results, we also observed that the water tank analogy may activate associations that differ from the dynamic properties it is intended to convey. On one hand, *all* students focused at least once on surface features of the water tank such as substance and geometrical properties. On the other hand, only 10 out of 103 instances of generalizations exhibited by the students dealt explicitly with the *accumulating* property of the water tank, which is the intended generalization to transfer when using the tank analogy. Instead, *controlling* was the most widely used generalization, and also the one that was most often a hinder for transfer.

These two main insights have specific implications for how we teach with the tank analogy and other SF analogies. Teachers and practitioners should be aware that an analogy may trigger generalizations that are different from what is intended. Therefore intended generalizations need to be pointed out and emphasized. Possible unintended generalizations need to be made explicit by inquiring learners to describe the associations they are making. Otherwise, some generalizations such as *controlling* may easily remain “silent”. If we can help students find plausibility in the use of the tank analogy, further refinement of students’ knowledge of the target system is likely

to occur.

Finally, our work opens new opportunities for future research. The list of generalizations we have identified and described is neither exhaustive nor definitive. Further research may help refine our descriptions of these generalizations and to uncover new ones. Our data set provides more robust evidence for some generalizations than for others. Particularly, we believe that *controlling* is perhaps the most challenging and resistant generalization of all.

References

- Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science*, 18(4), 237-261.
- Carraher, D., & Schliemann, A. D. (2002). The transfer dilemma. *The Journal of the Learning Sciences*, 11, 1-24.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, 30(10), 1241-1257.
- Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, 32(1), 9-13.
- Cobb, P., McClain, K., & Gravemeijer, K. (2003). Learning about statistical covariation. *Cognition and Instruction*, 21(1), 1 - 78.
- Confrey, J. (1990). Chapter 1: A review of the research on student conceptions in mathematics, science, and programming. *Review of Research in Education*, 16(1), 3-56.
- diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction*, 25(4), 523 - 565.
- diSessa, A. A., & Cobb, P. (2004). Ontological innovation and the role of theory in design experiments. *Journal of the Learning Sciences*, 13(1), 77 - 103.
- Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education*, 5(1), 61-84.

- Duit, R., & Kesidou, S. (1988). Students' understanding of basic ideas of the second law of thermodynamics. *Research in Science Education, 18*, 186-195.
- Forrester, J. W. (1961). *Industrial dynamics*. Productivity Pr; Student Edition.
- Forrester, J. W. (1968). *Principles of systems*. Cambridge, EUA : Wright-Allen.
- Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(2), 393-408.
- Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge University Press.
- Kapon, S., & diSessa, A. A. (2010). Instructional explanations as an interface---the role of explanatory primitives. *AIP Conference Proceedings, 1289*(1), 189-192.
- Kvale, S., & Brinkmann, S. (2008). *Interviews: Learning the craft of qualitative research interviewing*. Los Angeles: Sage Publications, Inc.
- Lobato, J. (2003). How design experiments can inform a rethinking of transfer and vice versa. *Educational Researcher, 32*(1), 17-20.
- Lobato, J. (2004). *Abstraction, situativity, and the "actor-oriented transfer" perspective*. In *Paper presented as part of the symposium, J. Lobato (chair), rethinking abstraction and decontextualization in relationship to the "transfer dilemma."* Annual meeting of the American educational research association. San Diego, CA.
- Lobato, J. (2006). Alternative perspectives on the transfer of learning: History, issues, and challenges for future research. *Journal of the Learning Sciences, 15*(4), 431 - 449.
- Lobato, J., & Siebert, D. (2002). Quantitative reasoning in a reconceived view of transfer. *The Journal of Mathematical Behavior, 21*(1), 87-116.
- Mestre, J. P. (2005). Framing the transfer problem. In J. P. Mestre (Ed.), *Transfer of learning: Research and perspectives*. (pp. vii-xxvi). IAP - Informaiton Age Publishing Inc. (Original work published 2005)
- Moxnes, E. (1998). Overexploitation of renewable resources: The role of misperceptions. *Journal of Economic Behavior and Organization, 37*, 107-127.
- Moxnes, E., & Saysel, A. K. (2009). Misperceptions of global climate change: Information policies. *Climate Change, 93*, 15-37.
- Saldarriaga, M. (2011). *A case study on "reverse transfer": When learners modify a water tank analogy to fit physics intuitive knowledge*.

-
- Saldarriaga, M. (2011). *Learning with water tank analogy: How students' intuitive knowledge of basic dynamics of motion changes during transfer* .
- Sterman, J. D. (1989). Misperceptions of feedback in dynamic decision making. *Organizational Behavior and Human Decision Processes*, 43(3), 301-335.
- Sterman, J., & Sweeney, L. (2007). Understanding public complacency about climate change: Adults' mental models of climate change violate conservation of matter. *Climatic Change*, 80(3), 213-238.
- Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, 16(4), 249-286.
- Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *Syst Dyn Rev*, 23, 285-311.
- Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review*, 247-261.

Appendix

Appendix A

Tank and Car Interfaces

Here we describe the design principles of the tank and car interfaces used for the experimental sessions. Both interfaces were designed by the PhD candidate and programmed by Mauricio Munera, a system dynamics master graduate from the University of Bergen. The interfaces were designed to support the respective teaching sequences used during the interventions (see Appendix B). The visual interfaces were programmed in Flash software, and integral equations were used for the underlying model. We describe the features of each interface in what follows.

1. Tank Interface

Figure 1 in the next page shows a screen shot of the tank interface. The interface is interactive; the valves can be opened or closed by dragging the handles, and the students can observe the water accumulating in the tank. The change in the level of water in the tank is given by the difference between the amount of water going in and out of the tank (i.e., $\text{Stock}(t) = \int(\text{inflow} - \text{outflow})dt + \text{Stock}(t_0)$). The valves change from zero to ten in steps of one; and they can be changed at any time during the simulation. Three buttons on the right bottom corner allow the student to pause, restart, and stop the simulation. The indicator over the tank shows the duration of the simulation in minutes and seconds, which correspond to minutes and seconds in real time. To the left of the tank, a scale indicates the amount of liters of water in the tank. The simulation stops automatically when the tank is completely full.

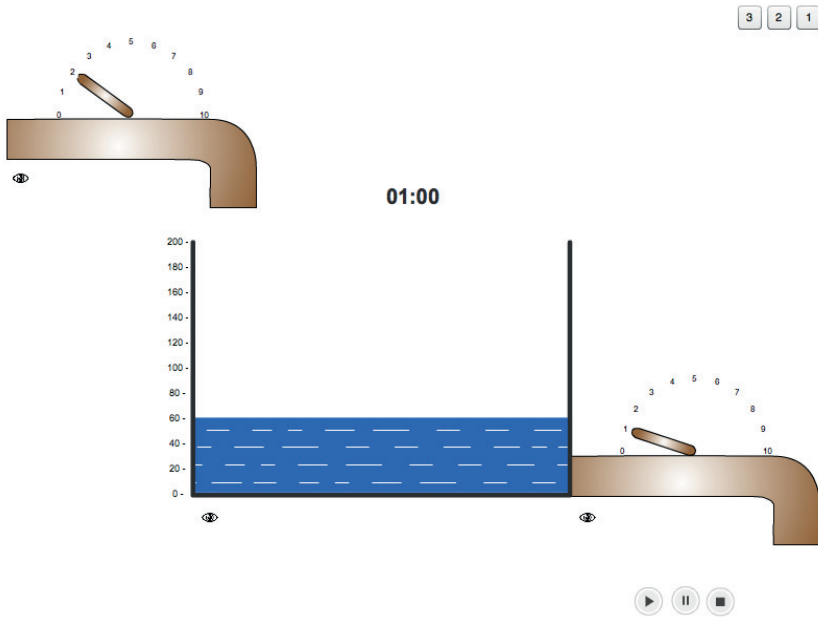


Figure 1. Tank interface

Also, three buttons below the tank and the two pipes allow the user to hide the corresponding elements. This option enables the teacher to create different learning scenarios for the students—e.g., hide the tank and ask students to predict how the level of water is changing given certain values for the in and out-valves. Finally, an initial set-up page allows the teacher to create different scenarios by pre-setting different conditions for the different variables in the interface and the underlying model. Figure 2 shows a screen shot of the set-up page including all variables that can be changed. Up to 10 scenarios can be pre-set. The different scenarios can be accessed from the buttons on the top right of the interface.

VARIABLE	Scenario1	Scenario2	Scenario3
initialTime	0	0	0
finalTime	200	200	200
timeStep	0.025	0.025	0.025
reportingValuesTimeInterval	0.125	0.125	0.125
flowsControlButtonsVisible	false	false	false
initialInflow	0	0	0
inflowValuesIncreaseStep	1	1	1
inflowMinValue	0	0	0
inflowNumberOfValues	11	11	11
inflowVisible	true	true	true
initialOutflow	0	0	0
outflowValuesIncreaseStep	1	1	1
outflowMinValue	0	0	0
outflowNumberOfValues	11	11	11
outflowVisible	true	true	true
maxWaterLevel	200	200	200
tankNumberOfAxes	10	10	10
initialWater	0	0	0
waterLevelText	true	true	true
tankVisible	true	true	true

Figure 2. Tank interface set-up page

2. Car Interface

Figure 3 shows a screen shot of the car interface. The car interface represents the application of the tank analogy to the motion of a toy car in one dimension. Most of the visual elements of the tank interface are kept as they were except for the following changes: (1) names for the accumulation in the tank (“velocity”) and the inflow and outflow valves (“acceleration” and “deceleration”); (2) a toy car which moves according to the velocity accumulated in the tank; and (3) the additional variables of applied force, resisting force, and mass.

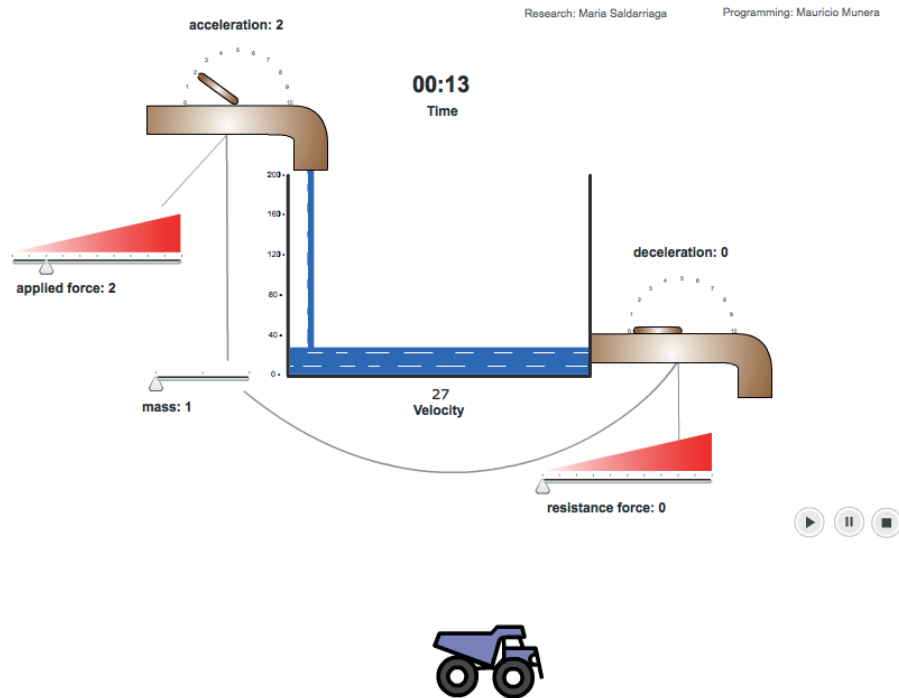


Figure 3. Car interface

In the car interface the valves of acceleration and deceleration cannot be opened directly. They open and close in response to the applied force and resistance force sliders respectively. Mass can be varied from 1 to 3 units. The effect of changing the mass is represented by cubes piling on top of the truck—with each representing 1 unit of mass (Kg). As in the tank interface, in the car interface most variables can be pre-set by the teacher to create different scenarios for the students. Table 1 shows the equations used for the different variables in the car interface. These equations are given by Newton's First and Second Laws. Forces are given in Newtons (N). A Newton is equivalent to 1 Kg*(m/s²). The friction coefficient is an average coefficient for a normal surface.

Table 1. Car interface equations

<i>Variable</i>	<i>Value of equation</i>
<i>Velocity</i>	Velocity (t) = $\int(\text{acceleration-deceleration})dt + \text{velocity}(t_0)$.
<i>acceleration (m/s²)</i>	applied force /mass
<i>deceleration (m/s²)</i>	resistance force/mass
<i>resistance force (N)</i>	g*mass*friction coefficient
<i>g (acceleration of gravity) (m/s²)</i>	9.8
<i>friction coefficient (dimensionless)</i>	0.2

Appendix B

Teaching Sequences

In this section we present the teaching sequences used by the PhD candidate during the interventions with seventh grade students in Colombia. Two sequences were used in association with the two interfaces described in Appendix A: the tank teaching sequence and the car teaching sequence. Here we present the tank teaching sequence. The car teaching sequence follows the same structure of the tank teaching sequence; we describe briefly this sequence at the end of the section. Teaching sequences are divided into two sessions, each session corresponding to a different day of intervention (2 to 3 hours). Table 1 shows when each sequence was used during the six weeks of the intervention. The test used in sessions 3 and 6 is presented in Appendix C.

Table 1. Intervention Design

<i>Session</i>	<i>Activity</i>
1	<i>Tank Teaching Sequence</i>
2	<i>Practice tasks with Tank Interface</i>
3	<i>Test on car motion</i> <i>Pre-interview about test answers</i>
4	<i>Car Teaching Sequence</i>
5	<i>Test on car motion</i>
6	<i>Post-interview about test answers</i>

Tank Teaching Sequence

Purpose of the sequence: to provoke and refine the ohm's, change takes time, dying away, canceling, and dynamic balance p-primis in the context of the tank¹.

Use the Tank Interface with this sequence. You will need to pre-set 7 scenarios. Each scenario is described at the beginning of the respective section where it is used.

Session 1

Teacher (T): Hi, thanks for being here. Today we will be spending some time together. And we will do this every (Tuesday) for the next weeks. We wont have exams with marks. We will have different activities, some of which you will do together and some others which you will do individually. Ok, so we are ready to start.

1. Section take-home message: change does not take time in action-to-flow relationships

Introduce the student to the tank interface. Use scenario 1 (shows only the inflow pipe and valve, keeping the rest hidden).

T: Here we have a pipe with a valve. You can open and close the valve by clicking on and dragging the handle. Then you need to click on start to begin.

Let the student experiment with the valve for some time, then set the valve to 10.

T: Could you open the valve to 10?

T: Could you close the valve?

T: Could you describe what happens to the water coming out when you do that?

¹ All text in italics corresponds to recommended speech for the teacher/researcher. Text in normal format corresponds to clarifying or instructional notes.

T: How long does it take for the flow of water to change when you open or close the valve?

Show the stock (tank) of water.

2. Section take-home message: change takes time in inflow-to-stock relationships—inflows accumulate into stocks over time

T: Now here we have a tank.

T: Could you make the water in the tank be 60 liters?

T: How would you do that?

T: How much water is being added to the tank every second?

T: How long would it take to have 18 liters if we add 1 liter every second?

T: What if we add 2 liters every second?

T: And what about 3?

Help the students adding the water second by second if necessary.

T: How long does it take for the water in the tank to be 60 liters after you open the valve?

T: Could you make it be 100 liters?

Interrupt before the stock gets to 100 liters.

T: Could you do that in a shorter time?

T: Could you make it in no time?

3. Section take-home message: No Ohm's p-prim—stock is not proportional to inflow

Use scenarios 2 and 3 (scenario 2 has an inflow of water of 10 and a low initial level of water (20). Scenario 3 has the same inflow (10) and a high initial level of water (110). In both scenarios the tank is initially hidden and the inflow is visible.

Present scenario 2.

T: How much water do you think there is in the tank? Why?

Present scenario 3.

T: How much water do you think there is in the tank? Why?

Show the stock in both scenarios.

4. Section take-home message: change takes time in outflow-to-stock relationships –outflows deaccumulate from stocks over time

Use scenario 4 (initial stock of 100 and outflow hidden).

T: The amount of water in the tank is currently 100, could you make it be zero?

T: How would you do that?

Help the student identify the need for an outflow. Show the outflow.

T: Now we have another pipe through which the water can go out of the tank.

T: How much water is being taken out of the tank every second?

T: How long would it take for the 100 liters to go out if we remove 1 liter every second?

T: If we remove 2 liters every second?

T: And if we take 5 liters every second?

Help the students removing the water second by second if necessary.

T: How long does it take for the water in the tank to be 0 liters after you open the valve?

Interrupt before the stock gets to 0 liters.

T: Could you do that in a shorter time?

T: Could you make it in no time?

5. Section take-home message: No Ohm's p-prim-stock is not proportional to outflow

Use scenarios 5 and 6 (Scenario 5 has an outflow of 2 and a low initial level of water (10). Scenario 6 has the same outflow (2) and a high initial level of water (80).

Present scenario 5.

T: How much water do you think there is in the tank? Why?

Present scenario 6.

T: How much water do you think there is in the tank? Why?

Show the stock in both scenarios.

Session 2 – First Part

T: Ok, last week we began exploring how the tank works. From now on we will call these (pointing to the respective valve) the in-valve and the out-valve. Today we will continue exploring the tank.

1. Section take-home message: the net flow is the rate of change of the stock and change takes time in net flow-to-stock relationships

T: So, if our objective is to fill the tank, we may think about the inflow as contributing to fill the tank while the outflow acts against it. Does it sound right to you?

T: Could you add some water to the tank? For example, 60 liters.

T: What would happen to the water in the tank if the inflow was 4 and the outflow 2?

T: What would happen to the water if it was the contrary: inflow 2 and outflow 4?

T: So, how much increases or decreases the amount of water in the tank every second?

T: Now, if the outflow is 6 can you set the inflow valve so that the stock increases by 1 every second?

T: If the inflow is 6 can you set the outflow valve so that the stock decreases by 1 every second?

T: Now, if the outflow is 2 can you set the inflow valve so that the stock increases by 4 every second?

T: If the inflow is 2 can you set the outflow valve so that the stock decreases by 4 every second?

T: So the stock increases or decreases every second in an amount that is equal to the inflow minus the outflow. In other words, it is what goes in minus what goes out. Is that right.

2. Section take-home message: overcoming (positive net flow) is only necessary to keep the stock increasing.

T: Now, could you add some water to the tank? 40 for example.

T: Now, if the outflow is 5, could you set the inflow so that the amount of water in the tank increases?

T: Now, could you set the inflow so that the only condition is that there is some water in the tank? Any amount.

T: What happens if the inflow is 4 for instance?

T: So, an inflow higher than and outflow is necessary to make the amount of water in the tank increase, but it is not necessary to have some amount of water in the tank. That is, the inflow can be lower than the outflow and we will still have water, at least for a while more. Right?

T: Does this always apply?

T: What happens when the tank is initially empty?

T: Lets see, if the tank is empty and the outflow is still 5, do you need the inflow to be higher than the outflow to have some water in the tank?

T: Yes, so when the tank is empty, we do need the inflow to be higher than the outflow to have some water in the tank. Right?

T: But after we have some water, we do not need the inflow to be higher than the outflow, unless we want the amount of water to increase. Does it sound right?

3. Section take-home message: canceling is necessary to keep the stock constant, and dynamic balance is the result of canceling.

T: Now, could you add some water to the tank? 40 would be fine again.

T: Now, if the outflow is 5, could you set the inflow so that you keep the tank from getting empty?

T: Could you use a lower inflow? How much lower?

Guide the student to use an inflow of 5 in case he did not do it by himself.

T: Could you make the stock stay at 50?

T: So, an inflow equal to an outflow would keep the amount of water constant. Right?

T: What if the inflow and outflow are the same but the tank is empty.

4. Section take-home message: the water does not die away, it flows away– stocks only change through their flows

T: With the outflow set to 0, could you make the stock of water get to 80 and stay there?

T: What is happening with the amount of water?

T: What would happen with it if you don't do anything with the valves?

T: Now, could you empty the tank?

T: Is there any other way you can do that in addition to opening the outvalve?

Students would probably talk about evaporation; guide them to understand this as another outflow.

Session 2 – Second Part

Practice tasks with tank interface

You will need to pre-set 8 scenarios similar to the ones used in session 1 and the first part of session 2. This time however, the scenarios should be pre-set to show the stocks and hide the in and out valves. For each scenario, students will have to determine a combination of in and outvalves that can produce the change in the amount of water in the tank. Each scenario is described at the beginning of the respective section where it is used.

T: Now we will have some challenges to pass before we move on. Remember that before we tried to guess the amount of water in the tank just by looking at the water being added or removed. Then we discovered that different combinations of “amount of water in the tank” and “water being added or removed” are always possible. This means that the amount of water in the tank and the water being added and removed are not necessarily both low or both big. Instead, the higher the amount of water added to or removed from the tank, the greater its positive or negative change.

We will have today similar challenges, but this time you will have 8 different ways in which the amount of water in the tank could change and you will have to determine what are the possible combination for the in and out-valve that could make the water in the tank change in a given way.

1. Section take-home message for practice: the net flow is the rate of change of the stock of water, and change takes time in net flow-to-stock relationships

Use scenario 1, 2, 3 and 4.

Scenarios 1 and 2 present an increasing stock of water. Scenario 1 has an inflow of 10 and an outflow of 9. Scenario 2 has an inflow of 1 and an outflow of 0.

Scenarios 3 and 4 present a decreasing stock of water. Scenario 3 has an initial stock of 10, an inflow of 9, and an outflow of 10. Scenario 4 has an initial stock of 10, an inflow of 0, and an outflow of 1.

Give the students a piece of paper and a pen and let them go through all the scenarios from 1 to 8 writing down their hypothesis about the values for the inflow and outflow. Then move through the scenarios again with the students asking the following questions for each scenario.

T: What is happening with the amount of water in the tank? Is it increasing, decreasing, or is it constant?

T: And if it is (increasing) this is because of what? How much water is being added and removed every second?

T: Are there different combinations that will cause the amount of water in the tank to change in this way?

Show the valves.

2. Section take-home message for practice: overcoming (positive net flow) is only necessary to *keep* the stock increasing. Canceling is necessary to keep the stock constant and dynamic balance is the result of canceling. And water does not die away, it flows away—stocks only change through their flows

Use scenarios 5, 6, 7 and 8.

Scenarios 5 and 6 present a constant and different from 0 stock of water. Scenario 5 has an initial stock of 10, and inflow and outflow equal to 1. Scenario 6 has an initial stock of 10, and inflow and outflow equal to 0.

Scenarios 7 and 8 present a constant and equal to 0 stock of water. Scenario 7 has an inflow and outflow equal to 1. Scenario 8 has an inflow and outflow equal to 0.

T: What is happening with the amount of water in the tank? Is it increasing, decreasing, or constant?

T: And if it is (increasing) this is because of what? How much water is being added and removed every second?

T: Are there different combinations that will cause the amount of water in the tank to change in this way?

Show the flows.

Car Teaching Sequence

The car teaching guides students exploration of the car interface. This sequence follows the same structure of the tank teaching sequence. The purpose in this case is to help students re-engage the “take-home” messages activated previously in the context of the tank and to use them to make sense of the car’s motion. The following are the take-home messages of the car teaching sequence:

1. Velocity accumulates over time: velocity is a stock.
2. Change does not take time in force-to-(de)acceleration relationships.
3. Forces are the actions that control the flows of (de)acceleration
4. Change takes time in force-to-velocity relationships.
5. No Ohm's p-prim: velocity is not proportional to forces
6. Overcoming (positive net force) is only necessary to *keep* velocity increasing.
7. Canceling is necessary to keep the stock constant.
8. Velocity does not die away, it flows away: velocity only changes through its flows.

Appendix C

What do we know about why objects move?

Instructions

Circle the answer you personally think is the best.

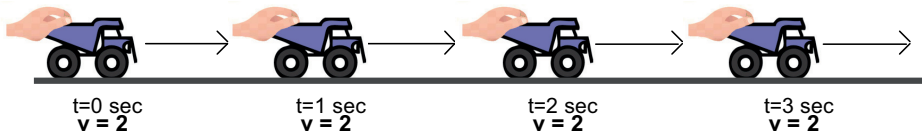
Do not skip any question and answer all of them.

For each question you can only circle ONE answer.

Remember that if something is constant it means that it is not changing.

Use the following description and the picture to answer questions 1 and 2.

A girl is pushing a toy car across the floor. As a result, the car moves at a constant velocity, as shown in the picture.

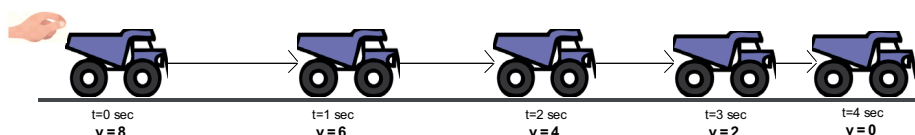


1. This happens because the force applied by the girl:
 - (A) is equal to the weight of the car
 - (B) is greater than the weight of the car
 - (C) is equal to the total force which resists the motion of the car
 - (D) is greater than the total force which resists the motion of the car
 - (E) is greater than both the weight of the car and the total force which resists the motion of the car.
2. If the girl in the previous question doubles the force that she is applying on the car, the car then moves:
 - (A) with a constant velocity that is double the velocity in the previous question
 - (B) with a constant velocity that is greater than the velocity in the previous question, but not necessarily twice as great
 - (C) for a while with a velocity that is greater than the velocity in the previous question, then with a velocity that increases thereafter

- (D) for a while with an increasing velocity, then with a constant velocity thereafter
(E) with a continuous increasing velocity.

Use the following description and the picture to answer question 3.

Assume the toy car is not moving and then the girl gives it a short push. The car moves for some time with a steadily decreasing velocity until it stops again, as shown in the picture.



3. This happens because:

- (A) the force applied by the girl decreases until it becomes zero
(B) there is a constant force resisting the motion of the car
(C) there is an increasing force resisting the motion of the car
(D) the constant force resisting the motion of the car wins over the force applied by the girl
(E) velocity has a natural tendency to finish.

Use the following description to answer question 4.

The girl puts the car from question 3 on a completely smooth surface so that the surface does not create any resistance to the car's motion. Neither are there any other forces resisting the motion. The car is not moving and the girl gives it a short push.

4. After the short push, the velocity of the car:

- (A) stays constant and different from zero
(B) stays constant and equal to zero
(C) decreases steadily
(D) increases for a while and decreases thereafter
(E) stays constant and different from zero for a while and decreases thereafter.