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# THE DEVELOPMENT OF CONCEPTUAL UNDERSTANDING MEDIATED BY COMPUTATIONAL REPRESENTATIONS

**Abstract.** This research seeks to investigate in a fine-grained detail the development of conceptual understanding of a phenomenon, through the use of computational representations (dynamic and interactive computer-based representations). The common idea that representations are powerful in shaping the way people understand the world leads to the underlying conjecture that representations may have a major role in a development process that progresses from naïve understanding of a phenomenon to a more elaborate one. In order to understand the development of students' conceptual understanding, through the mediation of the computational representations, I follow students exploring physical concepts using a computational simulation. I develop an analytical framework that views students' actions in this context, as operating in two dimensions: representational and physical-conceptual dimensions. Reasoning in this "two-dimensional model" may lead to inconsistencies, which drive changes in conceptual entities and relations. I try to identify how these changes are mediated by the interaction with the computational representations used.

## 1. INTRODUCTION

The research proposed in this paper seeks to investigate, in fine-grained detail, the development of conceptual understanding of a phenomenon, through the use of computational representations. The idea that motivates this work is that representations are powerful in shaping the way people understand the world. This may imply that representations could have a major role in a development process that progresses from naïve understanding of the world to a more elaborated one. The objective of this work is to investigate how such a development happens through the use of representations. The paper is based on two first pilot studies. These pilot studies provided empirical data on which I developed the analytical framework presented here. More studies are planned in the near future to provide stronger empirical evidence. In what follows, I lay out the theoretical foundation for the claim that the use of computational representations may shape in particular ways the development of conceptual understanding. Then, I describe the simulation used for the study and explain the methods I use. Finally, I provide some evidence from one episode and exemplify how I analyse it, to give some flavour of how the analytical framework of the two-dimensional system can capture the mediation of conceptual change by computational representations.

## 2. THEORETICAL FRAMEWORK

How can representations facilitate the development of conceptual understanding?

One of the important characteristics of representations is that they emphasize and highlight some aspects of a phenomenon and suppress others (Norman, 1993, Zhang & Norman, 1994, Scaife & Rogers, 1996). Scientists make use of this characteristic when they use representations in a way that helps them organize their perception, and attend to the aspects they view as essential to the phenomena they investigate (Latour, 1999, Lynch & Woolgar, 1990 and Goodwin, 1994). In somehow similar sense, I hypothesize, educational representations help organize students' perceptions and facilitate their conceptual understanding of a studied phenomenon. Since most scientific conceptual models make use of abstract (and "invisible") constructs (force, energy, phase, current etc.), good educationally designed representations can highlight those theoretically important aspects, and make them more perceivable and easier to attend to. For example, working with a graph representation of velocity, a student began to focus her attention on the direction (what is negative velocity?) as an important aspect of the concept of velocity (Nemirovsky, 1994). Another example is working with representations of motion that are at multiple levels of abstractions helps students attend to important components of motion that are essential for normative conceptualisation of motion phenomena (White, 1998).

Computational representations have still additional characteristics. Since they are dynamic and interactive, they enable students to experiment with these abstract objects and manipulate them. In a sense, the computational representations constitute a world in itself that has interacting elements to attend to and relations among them. The correspondence between the computational representation and the observed phenomenon can help students develop their understanding, I hypothesize, through a process of experimentation and reconstruction.

To understand the development of conceptual understanding through the use of representations I use diSessa' model of conceptual change. I develop an analytical framework that is based on diSessa's notion of coordination classes (diSessa & Sherin, 1998). A coordination class is a kind of concept that seems to be important in science learning, and its prototypical task is to get information from the world. When trying to get a particular class of information from a world full of rich phenomena, it is necessary to know how to focus attention at the right aspects and pick out the features in the current context that relate to the information needed. An example that diSessa and Sherin give is the ability to "see" forces in the world: what knowledge allows a student to see force in a situation? What knowledge allows a student to determine how big the force is and in what direction it acts?

Getting information from the world means basically two things: 1. To have "readout strategies". These are strategies of selecting attention and determining and integrating observations to get specific information. 2. To have an appropriate "causal net" – this is the body of knowledge and reasoning strategies that determines the inferences from the readout information. The development of conceptual understanding happens with changes made in the causal net and in readout strategies.

Since I am interested in understanding how conceptual understanding develops, building on this construct is helpful. However, the original coordination class construct makes no reference to any mediation by representations and focuses primarily on conceptual processes that occur through the unmediated interaction with the world. I thus develop an extended framework that implements the notion of coordination class for dealing with the development of conceptual understanding through the mediation of representations. This framework refers to coordination of two-dimensional system, namely, coordinating information from a representing world, which is mapped into information about a phenomenon in the world. I contend that the layer of representation as a phenomenological filter (or highlighter) on top of the natural phenomenon plays an important role in the process of this development. A dynamic and interactive simulation can be seen as a world in its own term. It has elements moving around and interacting with each other, and acting by some causal relations that apply in this representational world. While the simulation could be seen as a world in its own term, it is still a representation of another phenomenological world. Coordinating information from both the representation and the phenomenon can be modelled by using readout strategies and causal net in each dimension. In addition, students map aspects of the phenomenon on the screen onto aspects of the phenomenon in the world. What the students do when they work with the simulation, I claim, is coordinating a two-dimensional conceptual system.

My conjecture is that by trying to coordinate understanding of two worlds: the representational world and the physical world, students go through a process of reconstruction and refinement of their understanding in a way that is more in line with normative scientific model of the phenomenon.

## 3. METHODS AND DATA COLLECTION

As a pilot study, I have conducted two sessions with two students. Eric was in 10th grade and Nathan was in 11th grade. They both studied physics at school and stated that they like physics. Each session lasted an hour and a half. In the first half an hour we had a discussion about oscillation organized around playing with physical pendulums, and we played with a simplified mode of the simulation. The rest of the time was dedicated to exploration of the simulation. I intervened occasionally to understand what they were doing and how they were thinking about the situation. The sessions were videotaped. The camera was usually focused on the screen and captured most of what happened on the screen including mouse movements and the dynamic aspects of the simulation. Most of the sessions were transcribed including speech transcriptions, hands gestures and what happened on the screen as the students were speaking.

In analysing the sessions, I try to make inferences of any development of their understanding, and to observe how the way they used and reasoned with the representations shape the way they came to understand the phenomenon. I use the following analytical tools for this.

I suggest that reconstructions and refinements in the two-dimensional model may occur due to inconsistencies or breakdowns in the exploration process. I expect to find evidence for development of conceptual understanding around points of breakdowns. Whenever the students encounter an impasse there is a potential that they will challenge their current understanding. This may lead either to a breakthrough (by overcoming the impasse) or to a breakdown. After identifying these points of breakdown, I look for evidence for how the students follow up on these events, assuming that resolutions or at least attempts for resolutions (have they made these attempts) would lead to refinements in conceptual understanding. I will apply a finer grain analysis on these phases based on coordination classes to understand the kinds of changes happen in causal net and readout strategies.

To understand how conceptual refinements are mediated by the use of computational representations, I examine the following: a. what is the type of breakdown that led to the conceptual refinement? If the breakdown is across dimensions, it means that the use of representations was necessary for the occurrence of this breakdown. b. What representational phenomenology do the students notice? I hypothesize that what the students notice in the representations affects what questions and issues are potentially to be explored. What the students notice in the representation is partly influenced by their knowledge structure, but also by what is made salient by the representational design. What theoretical aspects of the phenomenon are highlighted and are made more salient by the designer? How the students follow these, and how they shape the students' exploration?

## 4. THE SOFTWARE AND ITS REPRESENTATIONS

The oscillation simulation was designed, by Andy diSessa, to help students understand some key aspects of forced oscillation and resonance. Conventional representations and simulations of forced oscillation and resonance fail to highlight some of these aspects, such as "phase hops" and "phase locking". The idea of the simulation is to focus on the phases of the oscillator and of the periodic impulse (which I will call later "the hit") so students could watch the phases move with reference to one another. The system simulates an oscillating object that, periodically, gets an impulse from a driving force (figure 1).

Many of the parameters are adjustable. For example, one can change the duration in which the hit is given, or the initial phase in which it is given.

There are four linked representations: (1) the simulation of the oscillation - a ball moving back and forth represents the oscillator, and a sound (beep) represents the hit (2) The energy bar – indicates the energy of the oscillator (3) The phase wheel – an arrow circling around represents the phase of the oscillator and the same sound (beep) represents the hit. (4) The bar animation – two bars moving on the screen represent the phase of the oscillator (the red bar) and the phase of the hit (the blue bar). Every cycle, the hit is given when the blue bar "hits" the cross sign. As the blue and the red bars move, the gap between them varies as a result of the hit given and also of the difference in frequencies (if there is one).

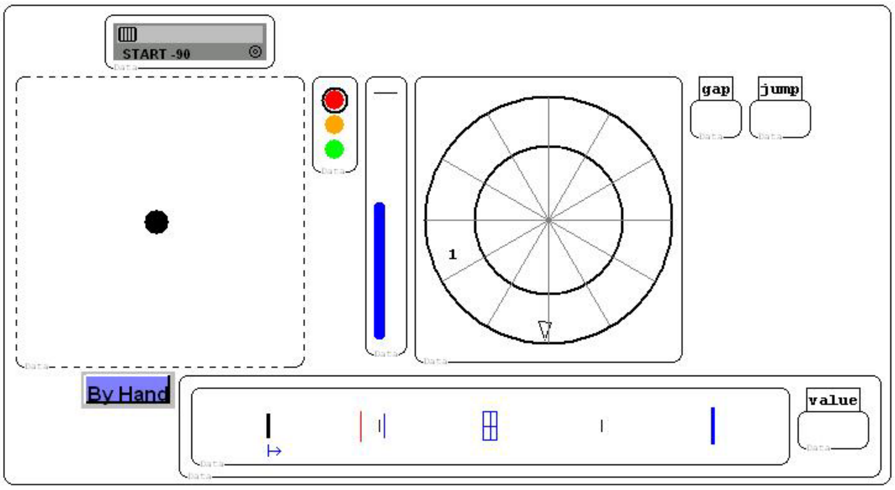



*Figure 1 - The oscillation simulation*

One of the most interesting phenomena that is demonstrated in this simulation is “phase locking”. Consider the case where the oscillator’s and the hit’s frequencies are slightly different. That means that the hit will be given in different phases every cycle. However, after a number of cycles the system is stabilized, meaning that the hit is now given at the same spot in every cycle.

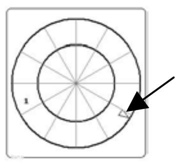
## 5. ANALYSES AND EVIDENCE

We now look at one episode from the first study. In this episode the students begin to explore the elements of the simulation and to make sense of their meaning and their mapping to the represented world.

In the first part of this episode Nathan *notices* that the location of the arrow at the time when the hit is given is moving on the phase wheel. Later on, Eric *notices* that the gap between the two animating bars grows over time. Trying to conceptualise the meaning of these representational phenomena in terms of the referent world leads them to explore their first exploration problem.

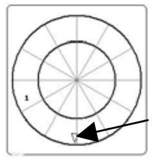
(8) Nathan: Seems like it's really right here (Points to the phase wheel at phase=30)

(9) on the... um... [Eric: On the middle?] the forth one from...*(Points again to the phase wheel on the fourth segment from the segment marked with 1)*



(10) *(Keep looking at the animation for another 6 cycles. The phase of the hit "moves" from phase = 30 towards phase = 0)*

(11) Nathan: Ah, so it does it, it does it right... there in the middle *(Points to the phase wheel representation on phase = 0)* here.



Nathan attends to the phase wheel representation, and reads-out information at the representational level using multiple observations to indicate, "arrow shifting".

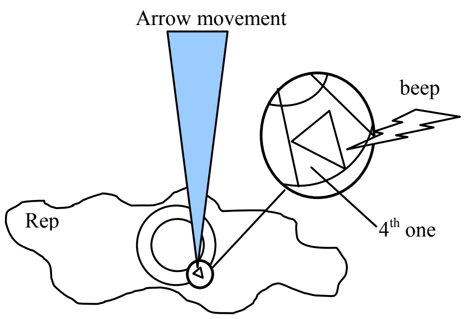



*Figure 2 - Arrow shifting from the "forth section to the middle"*

As shown in the diagram, he coordinates three different readouts:
1. The arrow circling around.
2. The sound of the beep that is heard every cycle.
3. Some location indicators such as the segments on the phase wheel.

This coordination helps him *notice* that the location of the arrow, in which the hit is given, moves on the phase wheel and forms a trajectory that moves towards the "middle" (phase=0). This *noticing* of an interesting representational phenomenology has a potential for a conceptually important exploration, if the students choose to explore what causes this phenomenology. At this point, Nathan only notes this interesting phenomenology without pursuing it any further.

Following this segment, Nathan asks Eric what is the red bar on the simulation (or in other words, what does it represent). Eric begins with a detailed mapping of the representational elements to the physical elements, and then generates the following explanation and prediction of what should the simulation do next:

(18) So, when we can see that the hit is going faster *(Points to the blue bar)*

(19) cause the gap is getting bigger *(Shows the gap with two fingers)*

(20) so soon it will hit it *(Points to the right hesitating)* when it's... going this way *(Points to the left)*,

(21) it's bad, cause it'll wreck… it will ruin the momentum...[Nathan: um] I think

Eric *notices* an increasing gap between the blue and the red bar at the representational level ("cause the gap is getting bigger").

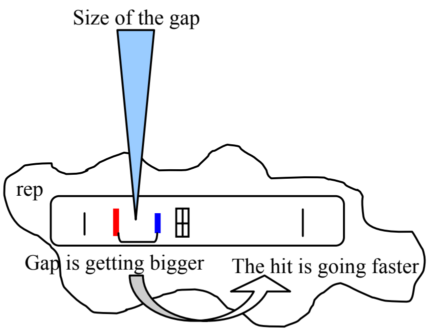



*Figure 3*

This is an example of a causal relation in the causal net pertaining the representational dimension: if the gap between two moving objects increases, it means that one of the objects is faster than the other. This inference has nothing to do with the underlying phenomenon of the oscillator, but is part of the logic pertaining to dynamic representations. Questions concerning the underlying phenomenon that is represented by the gap and its increase do not come into focus at this point: What exactly causes the hit to "go faster"? What causes the gap?

Although Eric does not try to understand what causes the gap in term of the underlying phenomenon in the physical world, he does try to infer the correspondent phenomenology in the physical world from the representational phenomenology (lines 20-21). The statement "the hit is going faster" reasoned at the representational dimension is mapped into the same statement at the represented physical phenomenon. This statement now gets processed through the causal net pertaining the physical phenomenon. Two causal relations are explicit in Eric's reasoning at this level:

a. If the hit is faster, over time, the hit will be given at the opposite direction. This is a simple translation of what he realized happening in the simulation and how it will appear in the world. Still, even this simple reasoning is based on the causal net pertaining to how mechanical objects behave in the world (rather than how representational objects do). The first inference is based on some understanding of phase behaviour – continuous phase change means that the hit is given every time in a different spot on the cycle, thus at some point it will be given when the ball travels back. There is an *implied assumption* that is not explicit in Eric's explanation and that is that the hit will keep going faster more and more (probably in a linear fashion). Without this implied assumption the causal relation "the hit is going faster → soon it will hit it when it's going this way" does not work.

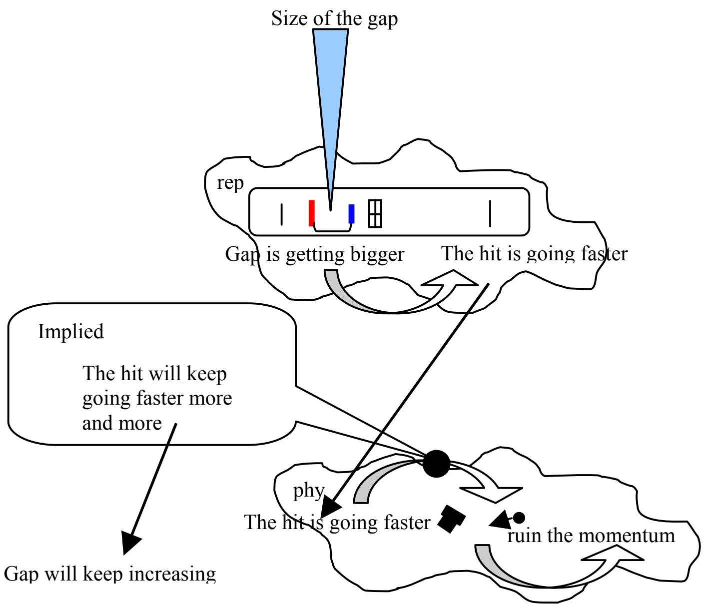



*Figure 4*

b. If the hit is given in the direction opposite to the motion of the ball → it will ruin the momentum. This inference is related to the destructive impact of a hit being given in the opposite direction. As a non-naïve physics student, Eric also infers that a destructive hit will wreck the momentum.

Eric keeps watching the simulation expecting that what he just stated would happen. This, of course, requires also that he would map back his expectation to the representing world. After watching for several cycles he says:

(23) Eric: Well, actually no.

(24) *(Keep watching for another 5 cycles)*

(25) Eric: Can we restart it?

It is hard to tell what exactly led to the realization that what was expected did not happen, since it is not obvious which representation Eric was attending to. Several options are possible: he could have realized that the gap stopped growing (by looking at the bar animation), or he could have noticed that the hit is not given in the opposite direction (by looking at the phase wheel and the bar animation), or by attending to the energy bar he could have seen that the energy does not going down (related to "ruin the momentum"). In any case, this is a *breakdown* that has some potential for revisions and refinements of their conceptual understanding:

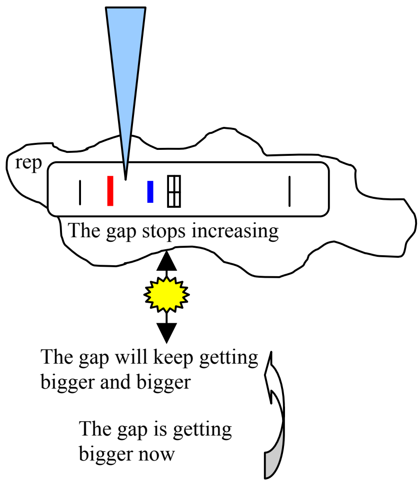



*Figure 5*

By Attending to the causal relation (part of it was only implied): "the gap is getting bigger now → the gap will keep getting bigger and bigger", they could start analysing how the gap grows and what might be causing the gap – which is key to understanding forced oscillation and phase locking.

## 6. PRELIMINARY FINDINGS

I introduced an evolving analytical framework for analysing students' conceptual understanding through the interaction with computational representations. In particular, I am interested in capturing any development in students' conceptual understanding of the phenomena and how it is mediated by the use of the representations. These preliminary findings are based on first pilot studies for this research. More studies are planned in the near future.

Although in the pilot study described above there was no substantial conceptual change observed (the main reason was the difficulty of the task), I could point to potential situations where conceptual change might have happened. In the short analysed episode there was one point of breakdown. This breakdown had a good potential for seeking resolutions and making refinements of conceptual understanding. A follow up on this breakdown did not reveal any substantial change in the students' conceptualisation, in this case. What still apparent in this analysis is the description of the students' current conceptual understanding and how its various components (readouts, causal relations and mapping relations) contribute to the inevitable emergence of the breakdown.

The process of exploration was driven by the interaction with the simulation: questions were raised, puzzles were attempted to be resolved, hypotheses and expectations were made and breakdowns occurred that were also attempted to be resolved. I attribute at least some of this dynamics to the interaction with computational representations. The breakdowns occurred happened when students tried to map phenomenologies across dimensions. These mapping relations are responsible to transfer inferences from one dimension to the other and thus to line up understandings of both dimensions. As we saw in this episode, understanding in one dimension was not in line with the other, what may drive the process of refinements of conceptual understanding.

The exploration focused on issues such as: how the gap grows? Why the gap grows? What is the effect of the growth of the gap on the oscillation? Why doesn't the gap grow in a linear fashion? These questions happen to be conceptually important for understanding forced oscillation, and they address difficult issues that are at the heart of this phenomenon. These exploration questions were generated and explored as a consequence of the interaction with the simulation, by attending to interesting phenomenologies that were *noticed.* For example, only in this short episode, the students *noticed*:

- Arrow shifting from the forth section to the middle.
- The gap is getting bigger.
- After a while, the gap does not increase anymore (implied from: "well, actually no").

It is important to note that what they noticed was not only determined by the salient aspects of the representation, but also by their existing knowledge of the situation and specific expectations that they had with regards to how oscillating objects behave. Still, the design may have substantial part in their noticing, which is a subject for a future empirical investigation.

## 7. CONCLUSIONS

The development of conceptual understanding was an objective for study in much research work, some of which were in a similar grain size as my suggested analysis. However, there is hardly work done on how representations mediate conceptual understanding by analysing process data at this grain size level. I use the construct of coordination class, as I view it as a good candidate to provide powerful explanations as to how conceptual change happens and what changes in conceptual change. I extend this construct to explain the development of conceptual understanding through the use of computational representations. The analytical framework thus includes two conceptual systems – one that operates on the representational level and another that operates on the physical-conceptual level. I hope that by applying this analytical framework on several case studies of students working with sophisticated computational representations, I will be able to capture the process of conceptual change.

I demonstrated how the suggested analytical framework is able to capture the changes in the students' conceptual understanding and help tracing the development process. This study can contribute to the understanding of how new computational design may facilitate and support learning and conceptual understanding.

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