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Conceptual development through computer simulations: a case study in physics

Desarrollo conceptual a través de simulaciones computacionales: un estudio de caso en física

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Abstract

This paper investigates how students engage with a simulation, during problem solving, and learn. It is a case study with three groups of university students solving a thermodynamics problem (Carnot cycle) assisted by a computational simulation specifically designed for that circumstance. Coordination Class Theory is used to interpret the results. These reveal that there are three distinct types of interaction between students and simulation that promote the conceptual development of the participating groups.

Keywords: Computer simulation; Conceptual change; Coordination Class Theory; Thermodynamics.

Resumen

Este trabajo indaga cómo los estudiantes se involucran con una simulación, durante la resolución de un problema, y aprenden. Es un estudio de caso con tres grupos de estudiantes universitarios que resuelven un problema de termodinámica (ciclo de Carnot) asistidos por una simulación computacional específicamente diseñada para esa circunstancia. Se utiliza la Teoría de Clases de Coordinación para interpretar los resultados. Estos revelan que existen tres tipos distintos de interacción entre los estudiantes y la simulación que promueven el desarrollo conceptual de los grupos participantes.

Palabras clave: Simulaciones computacionales; Cambio conceptual; Teoría de clases de coordinación; Termodinámica.

I. INTRODUCTION

Computer simulations are clearly within the vast set of technological devices that intervene not only in the advance of scientific ideas, but also in the teaching of physics in classrooms. It is thus not surprising that the Physics Education Research (PER) community has dedicated attention to the relation between learning and computer simulations. Numerous studies report positive effects of simulations on students' learning (Smetana & Bell, 2012). While a large number of studies report that beneficial impact, much less research has been focused on the details of how those tools interact with the learning process of students in-depth (Velasco & Buteler, 2017). Among these less frequent examples, Krajcik and Mun (2014) showed that computer simulations allow for deeper conceptual learning. Simulations function as a bridge between theory and practice (Ronen and Eliahu, 2000) with dynamic animations allowing students to arrive

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at an integrated conceptual understanding (Lowe, 2004). Some studies probed into the ways simulations can participate in conceptual development at a finer grain level, using Coordination Class Theory (diSessa & Sherin, 1998) as a theoretical lens (Kluge, 2019; Sengupta et al., 2015 and Parnafes, 2007) Within this view of learning, these authors were able to reveal how the representations provided by these devices participate in certain mechanisms of conceptual change.

Kluge (2019) showed, for the case of a situation involving a heat pump, that the simulation is a meeting point between theory, existing knowledge and experience. It enables students to connect previous knowledge with physical principles. The study also shows that simulation caters for exploring by incorporation and displacement, disregarding some aspects and focusing on others. These issues are crucial for the process of conceptual learning.

Sengupta et al. (2015) were able to identify that conceptually integrated video games could favor and support conceptual change by helping students bootstrap their intuitive reasoning about the physical world. This work was carried out on the concept of force and the authors report that specific traits of video games can help students make contact with the physical world and therefore to activate additional productive intuitive resources.

Parnafes (2007) showed that multiple representations make conceptual inconsistencies explicit, and that, in addition, the interactive dynamics of the simulation builds bridges between the real world and other representations.

In spite of the valuable contributions of these authors to the understanding of how simulations can participate in different mechanisms of conceptual change, there are good reasons to go further in this direction. The existing studies were carried out in particular contexts and given the context dependence of the phenomenon studied, it is important to find out whether the same dynamics are replicated or if new ones can be unveiled. Also, while previous research has reported how some specific features of the simulations participate in conceptual development, it is key this interaction between simulation and students' reasonings unfolds as the problem-solving task occurs, and what different learning opportunities arise in each moment.

The goal of our research is to unveil the potentialities of computer simulations for specific stages of conceptual learning during problem solving as described by Coordination Class Theory. In particular, we analyze the case of a problem situation involving the analysis of a Carnot cycle, addressed by undergraduate students.

II. THEORETICAL FRAMEWORK

Coordination Class Theory was born as a proposal to add precision to the description of the conceptual change process. The main purpose was to clearly define the meaning of the term "concept" and to focus on the process of conceptual change (diSessa & Sherin, 1998). Within this perspective, knowing a concept consists of being able to get relevant information from the world, across varied situations (diSessa, 2002).

A Coordination Class is a model for particular kinds of concepts, among which are physics concepts. The main function of a Coordination Class is to allow people to read a particular kind of information out of situations in the world. This reading takes place through specific processes and strategies. Many of the difficulties people have are related to the context and circumstances in which they carry out those particular strategies and processes.

The architecture of a coordination class includes two elements: extraction and inferential net (diSessa, Sherin & Levin, 2016). Extractions allow people to focus their attention on certain information of the phenomenon at hand. The inferential net is the total set of inferences people make to turn those information read-outs into the required relevant information.

According to this theory, "using" a concept in different contexts may well imply retrieving different pieces of knowledge and/or articulating them in different ways. The particular knowledge and the particular way it is coordinated in specific applications of the concept is called a concept projection. When projecting a class, students bring in different elementary pieces of knowledge (incorporations), they establish links between those elements (connections), create elements of the inferential net (inferences) or disregard some of them, (displacements)

Typically, students exhibit two characteristic difficulties in creating a new coordination class: the problem of span, and the problem of alignment. Span refers to the ability (or lack thereof) to recruit and coordinate the elements of the class in a sufficiently large set of contexts in which the concept is relevant. Alignment refers to the possibility of obtaining the same relevant information by means of different projections of the concept.

The theory also establishes a stronger form of alignment: articulate alignment, or articulation. Articulation happens when students are not only able to determine the relevant information in different circumstances, but can also explicitly relate those different projections, noting differences and similarities between them. This stronger form of alignment is a metaconceptual process which is a natural extension of the theory in its original form. figure 1 shows a schematic diagram of these elements (Buteler & Coleoni, 2016). For more details, we suggest addressing diSessa and Wagner (2005).

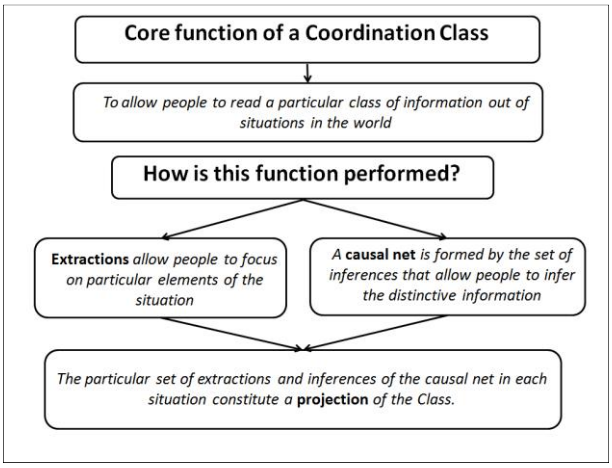


FIGURE 1: Schematic representation of theoretical elements that constitute a Coordination Class.

III. RESEARCH CONTEXT AND METHODS

The present work intends to address the following research question: *How do computer simulations assist conceptual development throughout a problem-solving task on thermodynamics?*

Our analysis will focus on a small-group discussion in a collaborative environment as students interact with a computer simulation. The students interviewed volunteered to participate in the study. They had passed a thermal physics course (second year of a career in physics) three months before the interview, with similar grades.

A. The problem-solving task

During the first minutes of the problem-solving session, students worked on their own. Once conflicting ideas or doubts were detected, they were offered the simulation. It was students who decided when and how to make use of it. They were completely free to explore, analyze, execute and control the simulation's parameters in whatever way they chose to.

An ideal monatomic gas performs n carnot cycles between two water reservoirs, initially at temperatures T1 and T2, with T1>T2. Assuming that both reservoirs have the same mass m.

- Respect to reservoir 1 (T1), choose an answer:
  - The temperature decreases
  - The temperature does not change
  - Other:.................................
- Respect to reservoir 2 (T2), choose an answer:
  - The temperature increases
  - The temperature does not change
  - Other:.................................
- Respect to reservoir 1 (T1), choose an answer:
  - Reservoir 1's entropy decreases after n cycles.
  - Reservoir 1's entropy increases after n cycles.
  - Reservoir 1's entropy does not change after n cycles.
  - Other: ....

FIGURE 2. Problem task.

B. The simulation

Three different sets of previous results informed the design of the simulation. i) Simulations that offer greater opportunities for the user to change parameters and manipulate the model are potentially more useful to foster conceptual advancement (Adams, Reid, LeMaster, McKagan, Perkins, Dubson & Wieman, 2008). For this reason, the simulation was designed to allow adjustment of reservoir temperatures and masses (figure 3, upper left). ii) Realistic schemes favor the connection between models and phenomena (Martinez, Naranjo, Perez, Suero & Pardo, 2011); Also, animations offer opportunities for students to activate the most intuitive reasonings about the phenomenon (Lowe, 2004).

Thus, an animation of a device operating as a Carnot machine was included (figure 3, bottom). It consists of a cylinder, with a mobile piston on one of its ends. Contact with either hot or cold reservoirs are represented by colored edges on the cylinder and dashed lines indicate instances where heat flow stops and the process becomes adiabatic. This simple animation offers an explicit depiction of heat flowing to and from the gas and work being done on and by the gas. iii) Simulations that represent temporal events by means of spatial representations have a better chance of fostering users' conceptual understanding (Parnafes, 2007). Following this idea, two x-y plots of bath Temperature and Entropy vs cycle were included (figure 3, upper right).

The simulation was designed with the Easy Java Simulation platform in html language.

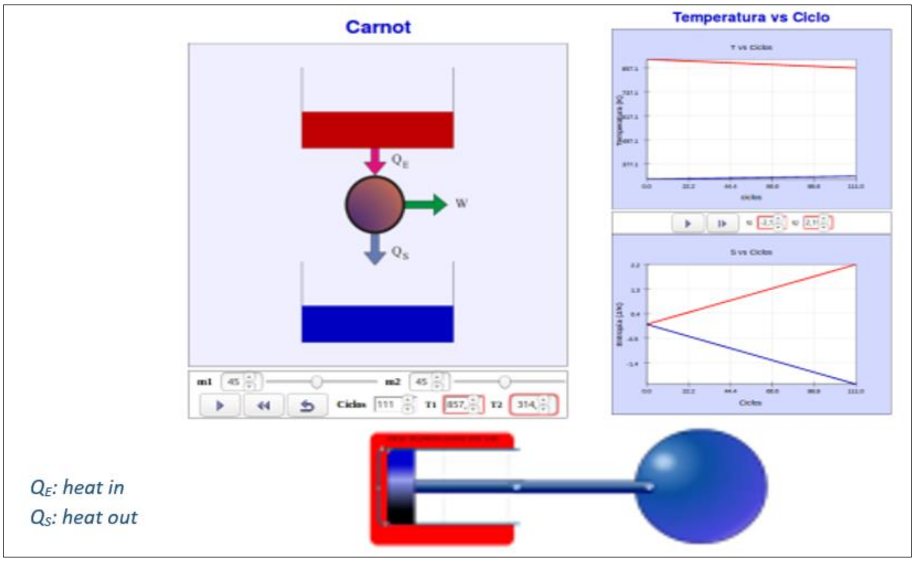


FIGURE 3. Screenshot of the simulation designed.

C. Data Collection

Problem solving sessions were video-recorded. During the interview students discussed their decisions, relations, changes of mind, etc. The interviews lasted a bit over 120 minutes. They were conducted by a researcher who was not the students' instructor. Elements proposed by Halldén (2007) were considered: the interviewer's mission was to follow students' ideas and to enable them to fulfill their project, as opposed to guiding their reasoning. Interviewer's interventions were oriented at asking for deeper explanations, checking understanding, or highlighting differences between students' reasonings.

The analysis was carried out on the audio-video data obtained during the interviews. It involved two distinct instances. A first stage consisted of an individual (one single researcher) revision of the videos as they were transcribed. In a second stage, these were reviewed by a research team as proposed by Jordan and Henderson (1998). This collaborative viewing is powerful for neutralizing preconceived notions of individual researchers and discourages the tendency to see in the interaction what one is conditioned to see or even wants to see.

IV. RESULTS AND ANALYSIS

We made a specific purpose to identify the different ways in which students coordinate the elements of the class and how the simulation intervenes in those dynamics. Through the analysis of the interviews, three different types of interactions were observed between students and the simulation.

A. Interaction type 1: Extractive interaction

This fragment corresponds to the initial step of one of the groups. These students explain the process of a Carnot cycle on a PV diagram, but they cannot associate this diagram with a concrete physical process. Moreover, despite pointing out the cycle in the diagram, students are unable to recognize what happens to the gas. The same is true for reservoirs. They know some things about their idealization but little about their nature. Therefore, they cannot choose any of the answers proposed. After that, the interviewer offers them the simulation:

S_1

1.Int: I get the feeling that they have to see a concrete case of what a machine that performs a Carnot cycle does, right? to understand what happens with these two reservoirs that you drew here... Maybe this simulation can help.

\\ Students interact with the simulation for a couple of minutes. They focus specifically on the animation, where they look at the gas process and the heat flows:

2.N: Look what's going on there. I think I can see the process now. There the temperature increases but there the temperature decreases, doesn't it?

3.F: I don't know if that's showing you temperature... Here in the animation, you can see the heat flows...

4.N: Well... there the heat flows out... there the temperature increases... That would be like the two reservoirs.

From CCT, it is possible to identify *extractions* from the new representations offered by the simulation. As can be inferred from the transcription, the program offers new representations that were not present in the statement of the problem, and the students are mainly oriented to extracting this new information: what is the process about (turn 2) and the specific moment of heat exchange and its direction (turns 3 and 4). These extractions let them start reasoning about temperature. They connect specific aspects of the animation with what they have first represented in a PV diagram. In this way, they have different opportunities to address their difficulties such as what process the gas undergoes, what the reservoirs do, among others. Until that moment the students were stuck in their understanding of the phenomenon since they could not connect their knowledge with the problem and the questions posed.

We define this type of interaction as **E*xtractive***: the simulation contributes new representations that become a source of new extractions (as defined by CCT). These new extractions are inputs for the development of new projections. Students recognize new information that allows them to acknowledge new aspects of the phenomenon.

B. Interaction type 2: Inferential interaction

Throughout this fragment, students begin to interact differently with the simulation. Using the representations provided by the program, they develop new inferences. In the following excerpt we show how students use the simulation to infer what happens with reservoirs' temperature.

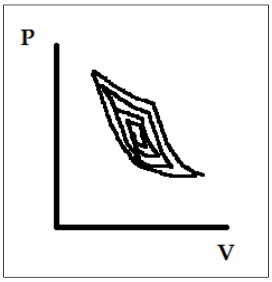
S_2

1.F: Then the reservoirs are going to maintain their temperature...the idea is that they maintain their temperature so that they continue fulfilling the cycle...

2.N: Of course, that's what I think because if temperature decreases...

3.F: It would not complete the cycle...

4.F: Of course, if we have the reservoirs and this [for the T_1] *has to make the cylinder go and return, hasn't it? If when I come back here the temperature is lesser this cylinder is not going to go there ... it is going to get here* [pointing to the piston of the simulation]*. Because that temperature you lost here [*pointing to the gas in the simulation] *is going to make the gas chamber not so hot and it won't get to the end now. Then the next cycle is going to come here for the other reservoir and when I get back there [*pointing to the piston in the simulation] *... because it was not at the same temperature as before.*



5.N: Well, I think the initial cycle has this graph (see figure)*. Suppose you don't have constant* [he points reservoir]*. Start with a T1, and suppose you don't add heat to the reservoir. So, when a cycle ends you have a lower temperature* [he points the gas]*, you don't get to T1 but brake earlier. In other words, if you do nothing, the temperature of reservoir 1 will decrease and the other will increase the temperature because you are going to be delivering heat.*

In this excerpt the students develop inferences using the representation provided by the simulation. They identify heat flows and start to conjecture what happens with the piston if the reservoir's temperature goes down (turn 4). They infer that if heat is flowing out of the hot reservoir, the piston will expand its volume and, in consequence, the gas will reach temperature not as low as on the first cycle. The same happens with compression and the high temperature of the isothermal curve (turn 5). So, the temperature of the reservoirs is modified in each cycle (the hot one cools down and the cold one heats up) and this can even be represented on the PV diagram of the Carnot cycle for reservoirs that modify their temperature (turn 5).

We define this type of interaction as ***Integrated***. The simulation does not just provide extractions (as in extractive interactions): it becomes part of students' explanations. In this sense, elements of these representations begin to function as support for students to elaborate new reasonings, ideas and speculations. This includes the use of graphics, animations and/or representations provided by the simulation that allow them to develop inferences. It is characteristic of this type of interaction that students explicitly involve the simulation in their explanations.

C. Interaction type 3: Projective Interaction

In the following excerpt, another group of students are invited by the interviewer to estimate an equilibrium temperature for the reservoirs. In the first instance, students use the heat-balance equation to propose the average temperature of the two reservoirs as their final equilibrium temperature. By contrasting with the simulation, they identify that work extraction causes the equilibrium temperature to be lower than the mean.

S_3

1.P: I think it is the average
2.E: The average?... Well, I think that the heat flows with a constant rate...
3.P: It remains the same …
4.E: It is the same, so the average makes sense...
5.P: If you still doubt, compute it… You know the masses, suppose a coefficient...
\\They take the pencil and they write down the heat equation...
P: Well as you can see, it is the average
6.E: Yes. You're right
7.Int: Do you agree that it's the average?
8.E-P: Yes, we do…
9.Int: Ok, so according to your input the average temperature must be...?
10. P: 250 K…
\\They run the simulation
12. E: The result is 245K … Well, stop… The problem is that we are not considering dissipations, isn't? The temperatures are going to be the same but there is a loss of energy.
13. Int: Is the simulation considering dissipations?
14. P: No, I don't think so...
\\They run the simulation but with different temperatures.
15. *E: It doesn't fit again. Wait...We are not considering* [during their computation] that the gas is doing work. That energy is going out, so the temperatures are not going to converge at the average. They must fit to a value less than the average.
16. P: Yes, it is not because of the dissipation. It is because of work.

Students initially complete a projection basing their inferences on the formalism of the heat equation. This leads them to conclude that the equilibrium temperature of both reservoirs will be the mean temperatures (turn 7). However, when contrasting it with the result of the simulation they doubt what they obtained. Simulation offers the opportunity to manipulate parameters, and even to simulate the phenomenon under different conditions. This let students convince themselves that something was wrong with their prediction and made them look for another explanation.

From the dissonance with the result of the simulation, the students begin a process of articulation. They have two projections that are not aligned so they check their inferences again. After some executions of the simulation, they identify that the presence of an amount of work done by the machine implies that the equilibrium temperature must be lower than the average (turn 16 and 17). It is important to highlight that simulation fosters this process of articulation. The multiple representations offer the opportunity to make explicit conceptual inconsistencies and make students work on aligning their own projection with simulation results. This was previously reported by Parnafes (2007).

In this fragment, the simulation presents a different role in the conceptual development of the students. It is used to compare with the projection constructed by the discussion group. We define this type of interaction as *Projective*.

V.DISCUSSION

In this work we focus on the study of conceptual development assisted by simulations. From Coordination Class Theory, we focus on analyzing the mechanisms of interaction that occur during the problem solving involving this resource. We address the following research question: *How do computer simulations assist conceptual development during a problem-solving task on thermodynamics?*

Students' conceptual development showed different interaction types with the simulation. In the first instance, students presented great difficulties in dealing with the problem situation. Faced with the difficulty, they begin to interact with the simulation. The animation provides them with new representations that serve as a bridge between the model and the phenomenon (link that was weak), as well as allowing them to focus on important aspects of the phenomenon. It is important to remember that similar aspects were reported by Segnupta (2015), who finds that these representations function as bootstrap for students' reasoning. However, the study allowed us to look further. Simulation during this stage worked as a provider of new extractions. Students here recognized new information. We call these interactive dynamics *extractive*.

In a second instance, they abandoned the passive posture of receiving new information and began to use that information and make inferences with it. At this stage, representations began to be part of their explanations and discussions. The analysis reveals that the students constructed new inferences from the representation, that is, they built relationships that were neither in their minds nor in the simulation. We define this type of interaction as an *inferential* type.

Ultimately, students use the simulation to check their predictions. We say this type of interaction is *projective*. From CCT, we can identify that students compare their projections with simulation outcomes. When they find disagreements, they begin an articulation process, by means of which they identify differences and similarities between projections. This is similar to that reported by Parnafes (2007) who mentions that different representations make conceptual inconsistencies explicit. In this sense, we saw that students assign a value to simulation very similar to that of experimentation, as if the program were actually the phenomenon.

In addition to having a positive impact on learning, it has been shown that computational simulations correspond to a very useful tool as a scaffolding for processes of conceptual change. This line of work has made it possible to identify in greater detail how this tool intervenes in the learning process. We have been able to show that it does so in different ways at different stages of conceptual development and according to the need for learning at each time. The contextual factor is key to understanding this tool in action. This line of research calls for further development, so that the community can not only acknowledge the potential of these tools but, above all, understand the best ways to make use of them.

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