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LEARNING WITH COMPUTER SIMULATIONS: A CASE STUDY ON RESERVOIR TEMPERATURES IN CARNOT CYCLES

Aprendizagem com Simulações Computacionais: um estudo de caso sobre temperaturas de reservatório em ciclos de Carnot

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Abstract

Computer simulations have played a significant role in the development of physics, and in physics education as well. Researchers have addressed whether simulations promote learning, but few studies have investigated how simulations actually participate in learning processes. This study seeks to describe how simulations participate in conceptual learning. A case study is carried out using videotaped interviews with three groups of undergraduate students as they address a problem-solving task on thermodynamics (Carnot cycles). Students use a specifically developed simulation for support. The analysis is based on Coordination Class Theory (CCT). Results indicate that students not only use the simulation to think; it is actually a part of what they think. Students were found to engage in three different interaction dynamics with the simulation. Attuned with CCT, these were coded as either Extractive/Inferential/Articulative interactions. In each case, the substance of how these interactions input conceptual learning is described. Implications for future research and for teaching are given.

Keywords: Carnot cycles; Computer simulation; Learning; Reservoir temperature.

Resumo

As simulações computacionais desempenharam um papel significativo no desenvolvimento da física e também na educação em física. Pesquisadores têm se perguntado se as simulações promovem a aprendizagem, mas poucos estudos investigaram como as simulações realmente participam dos processos de aprendizagem. Este estudo busca descrever como as simulações participam da aprendizagem conceitual. Foi realizado um estudo de caso utilizando entrevistas gravadas em vídeo com três grupos de estudantes de graduação enquanto eles resolvem uma tarefa sobre termodinâmica (ciclos de Carnot). Os estudantes utilizam uma simulação especificamente desenvolvida para dar suporte à tarefa. A análise é baseada na Teoria das Classes de Coordenação (TCC). Os resultados indicam que os estudantes não apenas utilizam a simulação para pensar; ela é, na verdade, parte do que eles pensam. Foi observado que os estudantes se engajam em três dinâmicas diferentes de interação com a simulação. De acordo com a TCC, essas interações foram codificadas como interações *Extrativa/Inferencial/Articulada*. Em cada caso, descreve-se como a substância dessas interações contribui para a aprendizagem conceitual. São apresentadas implicações para futuras pesquisas e para o ensino.

Keywords: Ciclos de Carnot; Simulação computacional; Aprendizagem; Temperatura do reservatório.

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. These have the potential to make instruction more interactive and to foster the learning of abstract concepts (Ramasundaram, Grunwald, Mangeot, Comerford, & Bliss, 2005). They allow students to confront their own beliefs by working with, and receiving immediate feedback about, original and/or real data and making personalized problem-solving decisions (Berners-Lee, 1999; Hargrave & Kenton, 2000; Rose & Meyer, 2002).

For over four decades, much research has found positive effects of simulations on students' learning, as reported by reviews on the literature (Smetana & Bell, 2012; Velasco & Buteler, 2017; Vlachopoulos & Makri, 2017). For example, Krajcik and Mun (2014), examine research done on the use of simulations in a variety of disciplinary areas (Chemistry, Biology, Physics). They show how simulations allow students to participate in science practices that they would not otherwise be able to. These include testing dynamic models, using interactive visualizations of unseen phenomena, viewing instantiations of scientific principles that they cannot experience firsthand and analyzing and visualizing complex (and extended) data sets. Ronen and Eliahu (2000) study the performance of teenage students learning contents related to electric circuits either with or without the aid of simulations. They find significant differences between the two groups. Simulations help students bridge the gap between theory and practice. They are a source of constructive feedback that helps students identify and correct misconceptions. Lally and Forbes (2019) study the performance of students on hydrology content in an introductory water course taught in a revised condition compared to the regular version of the course. The revised condition includes the use of a computer-based water model to complete a project. They obtained data from a pre/post-course assessment, student assignments, and student interviews. Results of quantitative and qualitative data analyses show that students in the revised version of the course increased their understanding of core hydrology concepts and performed better on their evaluation of a computer-based water model.

Some researchers have taken a step further in analyzing the positive impact of simulations on learning, by addressing the instructional decisions that can make the best out of the possibilities that simulations offer for learning. Basu, Sengupta and Biswas (2015) describe a study in which middle school students used a multi-agent-based computational model (MABM) to investigate and learn about a desert ecosystem. They identify the different types of scaffolds needed to support inquiry learning activities in that simulation environment and propose a comprehensive theoretical framework to describe how MABMs can help students develop a deep understanding of complex ecological systems. In a pilot study, Colella (2000) explored the instructional potential of participatory simulations to address dynamic biological systems. By wearing small, communicating computers called Thinking Tags, students become agents in a simulated microworld. As they interact among themselves and the computer simulation via the Thinking Tags, they take part in simulating the spread of a virus and decide what steps to take in order to survive. As the simulation develops, the authors focus on the specific ways that the simulation can support collaborative learning. As part of their results, they point out that the simulation allows the inclusion of students' prior knowledge, attitudes, habits, and interests. As they participate in the experience, students not only draw on their own knowledge and imagination, but also on the simulation framework. Both these cases go beyond establishing a positive correlation between learning and the use of simulations. In the first case, Basu and colleagues focus on ways of scaffolding instruction in order to foster the positive impact on learning. In the second case, Collela describes affordances that a participatory simulation can have for learning.

The studies mentioned so far either establish evidence as to the benefit of using simulations during instruction or go a bit further providing a better view of how instructional strategies can be tailored to increase the chances of obtaining those benefits. Other studies have taken a finer focus on the conceptual learning that can be fostered by the use of simulations. Those studies are more closely related to the present study due to the in-depth approach they take, and therefore will be described in detail below

Conceptual Learning and Simulations

Conceptual change, how conceptual understanding is transformed, has been investigated extensively since the 1970s. The field has now grown into a multifaceted, interdisciplinary effort with strands of research in cognitive and developmental psychology, education, educational psychology, and the learning sciences. The literature on student conceptions and their change is vast, as evidenced by a periodically updated bibliography containing thousands of publications (Amin & Levrini 2017; Amin, Smith, & Wiser, 2014; Vosniadou, 2008). No single review can do justice to it all. This literature shows a wide variety of approaches to conceptual change that reflect both convergences and disagreements. However, there is a broad consensus in the field of physics education research that conceptual change implies a transformation of students' previous knowledge towards the physics canon. This process involves questioning that previous knowledge either to refine them, to develop them or to reformulate them to some degree. Many attributes of computer simulations are potentially useful for promoting such cognitive processes. Simulations offer students the opportunity to visualize objects and processes that are normally inaccessible to them. Also, they allow students to manipulate variables that are not subject to user control in the real world. Given these traits, some authors claim that computer simulations have the potential to promote conceptual learning more effectively than direct experience (Koneman, Allen, Janda, Schreckenberger, & Winn, 2006). This claim holds particularly for scientific concepts that are counterintuitive, abstract, and/or not easily accessed through direct observation (Allessi & Trollip, 1991).

Given the potential that simulations have for the promotion of conceptual learning, different authors have studied how they can actually impact learning in different environments. Windschitl (2001), for example, examined the effectiveness of a simulation-based approach to promote students' conceptual learning about the cardiovascular system. The simulation was used along with a descriptive guidebook by different pairs of students to solve a series of cases dealing with cardiovascular health problems. A significant improvement was reported in overall mean scores on a content assessment. However, no significant gains were found on questions targeting more persistent intuitive ideas. Baser (2006) draws on the value of discrepant events to foster learning of direct current electricity concepts. In this paper, the author recommends caution in the use of computer simulations since, as they argue, simulations alone will not confront all of students' prevailing ideas. Gorsky and Finegold (1992), for instance, explored whether a computer simulation could tension students' intuitive ideas. Students were actually able to simulate the behavior of physical systems that followed those ideas about force and motion. They found that the effectiveness of the simulation to tension students' ideas was only moderate. However, for those students who did experience it, this actually opened a path for them to eventually achieve scientific conceptions. In other words, a sensible use of simulations should include, at the same time, other instructional approaches.

Other authors have addressed the effectiveness of simulations, combined with different pedagogical settings, to promote conceptual learning. Bell and Trundle (2008) as well as Trundle and Bell (2010) described the impact of computer simulations together with inquiry instruction on pre-service teachers' conceptual understanding of lunar concepts. In the latter quasi- experimental investigation, the researchers compared the effectiveness of three inquiry-based instructional approaches, using moon observation data collected from: (1) a planetarium simulation program, (2) a combination of nature observations and simulated observations, or (3) nature observations alone. Non-parametric tests of significance revealed that the substantial pre- to post-instruction gains were significant for the three treatments across all targeted concepts. The authors concluded that the three treatments were equally and highly effective in helping students achieve desired conceptual learning. Furthermore, the ability to make more consistent and accurate observations and measurements of the moon were cited as specific beneficial features of the computer simulation.

Thus far, the literature suggests that simulations can promote learning, and that their effectiveness to do so depends on the pedagogy they are combined with. Therefore, to study the impact that teaching with simulations can have on students' learning, different pedagogy should be combined with any given simulation and the differential learning outcomes assessed. This would call for a systematic combination of any given simulation with a set of pedagogical devices, and the assessment of different outcomes. However, we believe that an exhaustive combination of simulation-pedagogy pairs is not the most efficient way of approaching this question. First, finding out which pair "works better" might leave us just as uninformed as to which could be the best next choice. Rather, we claim that deciding which pedagogy can be combined with any particular simulation device can be better informed by focusing on the conceptual aspects of students' thinking as they use simulations, in contexts not connected to any particular instructional agenda. This requires the analysis of the connections between simulation traits and conceptual development at a fine-grain level.

Several authors have addressed the conceptual analysis of students' thinking while using simulations by using Coordination Class Theory (CCT, diSessa & Sherin, 1998) as a theoretical lens (Kluge, 2019; Parnafes, 2007; Sengupta, Krinks & Clark, 2015). These authors made progress in describing how the representations provided by simulations participate in the process of conceptual learning. 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. 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 all the studies just mentioned, the use of a theoretical framework capable of providing details of conceptual learning at such a fine-grain level proved to be very useful. This supported our choice of CCT to address the understanding of how simulations could participate in the process of conceptual understanding. We believed that the substance of that learning, resulting from the interaction between simulations and students' thinking, is located at such a fine-grain level.

In spite of the valuable contributions of previous research to the understanding of how simulations can participate in the process of conceptual learning, there are good reasons to go deeper into this question. 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 found. In fact, the literature on conceptual learning described through CCT does not include examples of reservoir temperatures in the context of Carnot cycles. Students actually show difficulties with the temperature of those reservoirs, which are conceptual in nature.

Learning Difficulties on Reservoir Temperature

Some studies have addressed the issue of how students can learn to model physical systems with the aid of computer simulations The work of Greca, Seoane and Arriassecq (2014) and Devalaki (2019) analyze methodological and epistemological issues involved in modeling and the role that simulations can play in that process. They provide a set of considerations on the benefits that simulations can bring to learning from a NOS perspective. Modeling the physical system in problems involving Carnot Engines implies modeling the "hot" and "cold" reservoirs connected to it. Thermal reservoirs play a central role in the functioning of Carnot engines. The heat delivered from and to reservoirs allow for all the transformations that, via work done either on or by the system, turn the ensemble into either an engine or a heat pump. Thermal reservoirs are very often idealized as very large subsystems, consisting of, for example, water, which is an acceptable assumption for most of the problems that students solve. Textbooks often refer to thermal reservoirs as sources or deposits at a constant temperature, which is consistent with the assumption just mentioned. (Ingard & Kraushaar, 1984; Resnick, Halliday & Krane, 2010; Sears & Salinger, 1980; Serway & Jewett 2018). However, modeling ideal infinite-capacity thermal reservoirs that remain at a constant temperature regardless of heat exchanges with any system, is far from trivial. To begin with, for a real system (such as water) to have an infinite heat capacity, the volume/mass of water must, in fact, be infinite. Another way to consider this idealization is to require that the mass of the reservoir (water) be large enough so that, given the amounts of heat to be exchanged, its temperature variations will be negligible. So, in fact, idealizing a thermal reservoir implies assuming that the heat exchanged with the reservoir is finite, but at the same time, it produces a negligible variation of its temperature. In operational terms this means that the temperature of the reservoirs is to be considered constant throughout the process, which is actually impossible. Smith, Christensen, Mountcastle & Thompson (2015) report that students very often lack the ability to consider such hypothetical and impossible situations. Bing and Redish (2012) regard the use of imagined (and impossible) situations as a trait of expertise, and point out that many advanced undergraduate students may not have developed the capacity necessary for this kind of reasoning. Other authors have addressed the issue of how

The problem task that will be discussed later (Figure 2) was part of a previous study (first author's doctoral thesis) in which students' ideas about Entropy were studied in the context of Carnot cycles. Students' ideas on thermal reservoirs were also collected. On one hand, students assumed that the heat received (by the reservoir) in each cycle would either go to an increase of its internal energy (and therefore, temperature) or in work done by the reservoir onto some other subsystem. At the same time, since reservoir temperatures are ideally assumed to remain constant (just as textbooks indicate), students believed that the reservoir receiving heat was either doing work on some unseen subsystem or transferring heat out of the reservoir by interacting with another, also unseen, medium. All these ideas that students' express support the claim of Smith et al (2015) and Bing & Redish (2012).

In sum, although not very extensive, the existing literature on students' ideas on reservoir temperatures shows that in order to assume that reservoirs are the "constant-temperature deposits" that textbooks define, students must imagine ideal processes that could well be beyond their non-expert abilities.

Given the difficulties involved in the idealization of thermal reservoirs, and the affordances of simulations to support conceptual learning, the goal of our research is to unveil the potentialities of computer simulations for specific stages of conceptual learning during problem solving. We will address this analysis through the lens of CCT. In particular, we analyze the case of a problem situation involving consecutive Carnot cycles, addressed by undergraduate students. The analysis is focused on the temperature of the hot and cold reservoirs.

Thus far, we have described previous research in which simulations are used in instructional settings in order to assess their efficacy to promote students' learning. The present research differs from those in two basic characteristics: First, it focuses on the fine-grain details of students' understanding. Also, it is carried out in a non-instructional setting; in this way, we believe that our results will not be pedagogically biased. The goal of this research is to develop a detailed description of the traits of students' thinking as they advance their conceptual understanding while interacting with a simulation. Therefore, we will address our research in an interview setting, which is not connected to any particular teaching agenda.

So, our Research Question is: Ho*w do computer simulations participate in the learning of the reservoir temperature concept while solving a problem dealing with Carnot cycles?*

The Theoretical Framework section presents the CCT (diSessa, Sherin & Levin, 2016) that will guide the interpretation of the data. The Methodology section describes the case study carried out using videotaped interviews with three groups of undergraduate students as they address a problem-solving task on thermodynamics (Carnot cycles). Students use a specifically developed simulation for support. Also included in this section is the coding scheme developed to interpret the data. In the Results section we present the findings: students not only use the simulation to think; it is actually a part of what they think. Students engage in three different interaction dynamics with the simulation. Attuned with CCT, these were coded as either Extractive/Inferential/Articulative interactions. This is followed by a discussion of the results, our conclusions and the educational and research implications of the study. Finally, the limitations of the findings and future perspectives are explained.

THEORETICAL FRAMEWORK

Coordination Class Theory (CCT) constitutes a particularly significant contribution to the field of research on conceptual development. Unlike other theoretical proposals to describe conceptual change, CCT explicitly discusses what a concept is and how it comes up in students' reasoning, which is particularly helpful for keeping track of its changes. Used to study problem solving situations, it can provide information at a sufficiently fine-grained level which can afford tracing changes in conceptual knowledge. This theory has been successfully implemented to describe processes of conceptual development for some particular concepts. Several papers have presented valuable contributions for the learning of physics concepts: force (diSessa & Sherin, 1998), frequency and velocity (Parnafes, 2007), motion (Dufresne, Mestre, Thaden-Koch, Gerace & Leonard, 2005), buoyancy (Buteler & Coleoni, 2016), mechanical waves (Wittman, 2002), proper time (Levrini & diSessa, 2008), energy (Barth-Cohen & Wittman, 2017), heat (Kluge, 2019), and entropy (Velasco, Buteler, Briozzo & Coleoni, 2022). Other work has also addressed contexts such as computer science (Lewis, 2012) and algebra (Levin, 2012).

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 et al., 2016). Extractions allow people to focus their attention on and read out certain information from 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 a more thorough description, please refer to the work of diSessa *et al*. (2016).

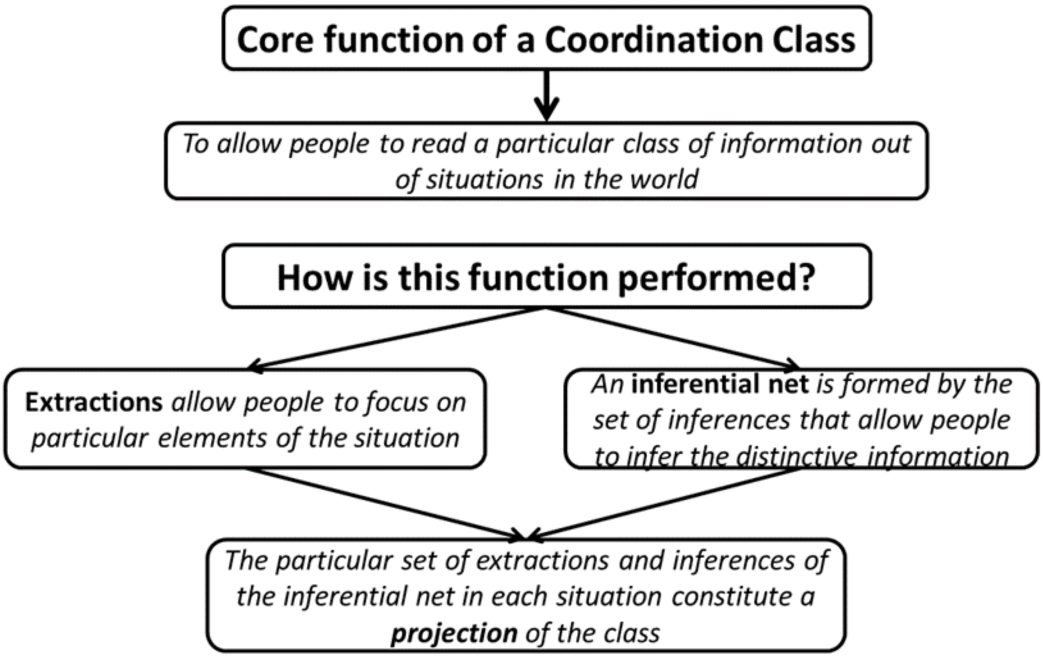


Figure 1. Schematic Representation of Theoretical Elements That Constitute a Coordination Class (Adapted from Buteler & Coleoni, 2016)

METHODOLOGY

Research Design

Our interest was to unveil the fine-grain details of students’ idiosyncratic thinking processes as they solved a problem using a computer simulation. For this reason, our research setting was taken out of the instructional context, far from instructions connected to any particular teaching agenda. Thus our decision to set up small-group discussions in a collaborative environment. We believed that this constituted the simplest possible setting in which we could analyze, in detail, participants' interaction with each other and with the computer program. Prior instances of similar studies using the same methodological approach proved to be assertive to unveil fine-grain details of conceptual learning (Buteler & Coleoni, 2016; Velasco et al., 2022).

We implemented a qualitative method for the study of learning: microgenetic learning analysis (MLA) (Parnafes & diSessa, 2013). This methodology is aligned with the purpose of our research and frames the type of study we seek to conduct. MLA has three fundamental characteristics:

1) Theory-focused: one of its objectives is to generate and/or improve theories concerning learning. In our case, the theory that informs our study, and which results will potentially feed back into, is CCT.

2) Fine-grained: the analysis seeks to account for as many incorporations, connections, inferences, and displacements of participants' elementary knowledge elements as possible. In the results section we will interpret data in such fine-grained terms, identifying the corresponding extractions, elements of inferential nets, and projections

3) Open consideration of relevant aspects of data: any characteristic of the learning event can be potentially relevant. Verbal and non-verbal language can be equally informative, as they can all suggest meaning that students construct. Thus, the complete information provided by video registries is a minimum requirement for the analysis.

As our interests fit MLA features, we adopt this methodology to set the case and carry out the qualitative analysis of the data. In this way, we develop a two-hour interview with three groups of two students who are presented with a problem-solving situation and asked to solve it together.

Sample

Participants are all full-time university students with an average socioeconomic background. They had passed a thermal physics course (second year of a career in physics) three months before the interview. A call was made for volunteers to participate in the study in the semester following that course, and out of those who signed up, only the ones who had passed the course with similar grades were selected. A total of 6 participants volunteered for the study and they were allowed to pair up by themselves; thus, they were the ones who decided who they would work with during the interview. they did this by themselves into the tree groups interviewed. They had no academic relation to the researcher who conducted the interview. In this way, the conditions in which students would solve a problem during the interview setting was quite similar to those under which students spontaneously work in peer study groups. We believe that it is safe to assume that the thinking processes observed in these groups are consistent with what can occur with students studying in natural environments.

As mentioned above, students' participation was voluntary. They were aware of the purposes of the study and the use that would be made of the audio/video registries and agreed to participate in those terms.

The problem they solved during the interview is described in Figure 2, and the simulation they could work with is described in Figure 3.

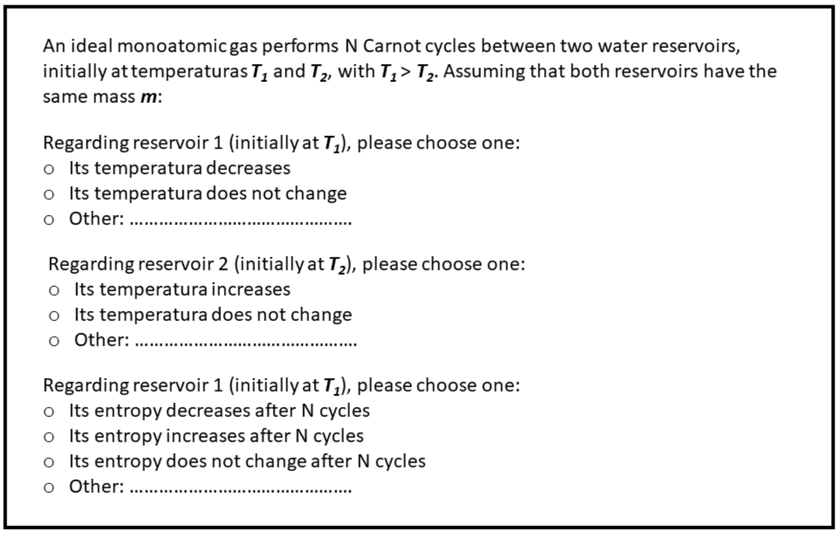
The Problem Solving Task

The problem that students were given presents a thermal engine that works between two real (as opposed to ideal) water reservoirs. This trait was meant to generate conflict with the ideas associated with ideal reservoirs, of extended use in the common treatment of heat engines.

A few minutes into the problem solving task, and after some discussion, it became clear that students had encountered difficulties associated with the reservoirs that exchange heat with the system. There seems to be a discrepancy between what they understand will happen to those reservoirs, as thermodynamic sub-systems, and the thermal properties that those reservoirs, regarded as ideal entities, should have.

Once conflicting ideas or doubts were detected by the interviewer, students were offered the simulation. They were the ones 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.

We will address students' knowledge production in relation to reservoir temperatures only (first two questions of the problem). Their subsequent considerations on entropy will not be part of our analysis. The problem is shown in its full version for the sake of completeness.



An ideal monoatomic gas performs N Carnot cycles between two water reservoirs, initially at temperaturas T_1 and T_2, with $T_1 > T_2$. Assuming that both reservoirs have the same mass ***m***:

Regarding reservoir 1 (initially at T_1), please choose one:
- ○ Its temperatura decreases
- ○ Its temperatura does not change
- ○ Other: ……………………………………….

Regarding reservoir 2 (initially at T_2), please choose one:
- ○ Its temperatura increases
- ○ Its temperatura does not change
- ○ Other: ……………………………………….

Regarding reservoir 1 (initially at T_1), please choose one:
- ○ Its entropy decreases after N cycles
- ○ Its entropy increases after N cycles
- ○ Its entropy does not change after N cycles
- ○ Other: ……………………………………….

Figure 2. Problem Task. Extracted from Velasco, Buteler & Coleoni (2021) p. 53.

The Simulation

When designing the simulation, different results from previous research were considered. First, as reported by Adams et al. (2008) simulations that offer greater opportunities for the user to change parameters and manipulate the model are potentially more useful to foster conceptual advancement. Thus, the simulation was designed to allow adjustment of (initial) reservoir temperatures and masses (figure 3, upper left). Also, we took into account the fact that realistic schemes favor the connection between models and phenomena (Martinez, Naranjo, Perez, Suero & Pardo, 2011) and offer opportunities for students to activate the most intuitive reasonings about the phenomenon (Lowe, 2004). Consequently, an animation of a device operating as a Carnot machine was included (Figure 3, bottom left).

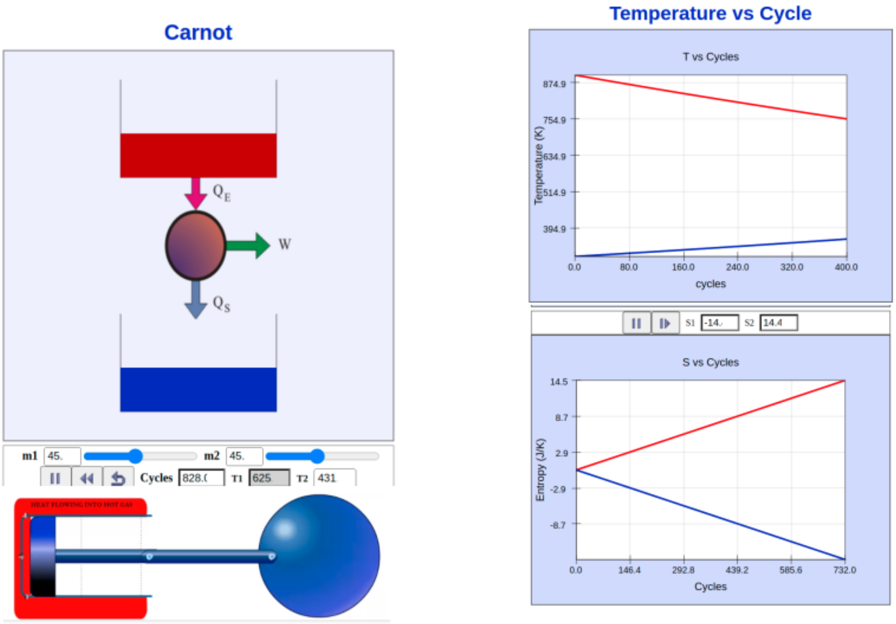


Figure 3. Screenshot of the Simulation Designed (Please visit https://entropycarnot.wordpress.com/ and follow the instructions described in"_ejs_README.txt", contained in the zip file). Extracted from Velasco et al. (2021) p. 532.

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. 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 during a cycle. Finally, since simulations that represent temporal events by means of spatial representations have a better chance of fostering users' conceptual understanding (Parnafes, 2007), two x-y plots of both Temperature and Entropy vs cycle (for both reservoirs) were included (figure 3, top and bottom right).

Figure 3 shows snapshots of the actual simulation. In order to see it perform dynamically, the reader is kindly invited to visit https://entropycarnot.wordpress.com and follow the instructions contained in the file "_ejs_README.txt". Furthermore, on the basis of preliminary interviews that involved the problem task of figure 2, we conjectured that students participating in the study would encounter difficulties regarding reservoir temperatures. Therefore, the simulation was tailored to help them address those difficulties in particular. The simulation was designed with the Easy Java Simulation platform in html language.

Data Collection

Problem solving sessions were video-recorded. During the interview students discussed their decisions, opinions and changes of mind. The interviews lasted slightly over 120 minutes. They were conducted by a researcher (first author) who was not the students' instructor. Elements proposed by Halldén, Haglund & Strömdahl (2007) were considered during the interview: 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' reasoning.

The analysis was carried out on the audio-video data obtained during the interviews. It involved two distinct methodological instances. A first stage consisted of an individual (one single researcher) revision of the videos as they were transcribed. Each researcher's individual interpretations are made explicit. In a second instance, all differences are put up for consideration by the whole group. In this second stage, coding schemes were reviewed by a research team (in our case the authors) as proposed by Jordan and Henderson (1995). 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. Collaborative viewing is an effective antidote to what Hutchins (1991) refers to as "confirmation bias," and explains it as the propensity to affirm prior interpretations while discounting or even ignoring counterevidence. Collaborative video analysis allows us to revisit them and question a given interpretation, regardless of whether or not it is the predominant one within the group. When this work is iterative and continues until a consensus is reached, results are more reliable than, for example, those obtained by reaching high percentages of agreement between individual researchers' interpretations (high Inter Rater Reliability, IRR). Some authors argue that high IRR does not necessarily mean validity (Hammer & Berland, 2013). Coding schemes presented in this paper emerged from the process described above.

Coding Scheme

Our coding scheme was the result of two separate rounds of analysis in which the authors worked on the audio-video records (~360 minutes of footage), as described above. During the first round, each author watched the videos and their transcripts focusing on the details of how the simulation interacted with students' reasoning during the episodes of conceptual development. In a second, collaborative, stage, records were analyzed by the group of researchers (authors).

The forms of interaction that we were able to code were theoretically informed by CCT. This theoretical lens anticipates that when faced with a problem situation, students extract pieces of information that they find relevant. From these extracted pieces of information, they make inferences that enable the construction of new knowledge elements. The coordinated set of knowledge elements that end up instantiating the concept in the particular situation is given the name of projection. Since the extractions and inferences that lead to a projection are not unique, students can actually make more than a single projection. In these cases, they need to set forth a process called articulation, by means of which they seek coherence between different projections. Thus, the categories described below correspond to ways of interaction between simulation and students' ideas that match with extractive, inferential, or articulative functions (operational definitions and examples are shown in Table I).

Extractive interactions are more common when students start working with the simulation. They are named this way because the interaction with the simulation basically serves the purpose of extracting (in terms of the Theory described) information from the situation (See Figure 1).

After these initial moments, ***Inferential*** interactions appear over a wider time-span. Their name responds to the fact that these interactions help students to develop an inferential net for the Coordination of the class. (Figure 1).

Finally, ***Articulative*** interactions with the simulations help students undertake a stronger form of alignment that the theory refers to as 'articulation'. These kinds of interactions occur after they have been working with the simulation (and the problem) for quite some time.

Table 1 - Operational Definitions for Extractive, Inferential and Articulative Interactions.

Interaction type	**Operational criteria**	**Some examples**
Extractive	- involve specific traits of objects in the simulation - are directly read from the simulation plots/animations	*Here in the animation* [as they point to the red coloured part of the piston surroundings] *you can see the heat flows...* *Look what's going on there. I think I can see the process now. There* [compression] *the temperature increases*
Inferential	- elements provided by the simulation are entangled with the inferences students make as they project the class. - usually expressed in the form of if-then statement	*If when I come back here the temperature is less so this cylinder is not going to go there* [they indicate the ends of the piston range] *... it is going to get here* [pointing to the piston of the simulation]
Articulative	- Involves matching different projections using simulation outcomes.	[They run the simulation using different values for reservoirs' initial temperatures] *Again, this isn't working* [simulation equilibrium temperature is less than average] *... wait...we are not considering* [in the computation] *that the gas is doing work.*

RESULTS

We will describe our results using three different fragments. These were chosen because they were found to be the clearest and most representative examples available from the data.

Interaction Type 1: Extractive Interaction

This fragment corresponds to the first minutes in which students were solving the problem (Fig. 2). They explain the process of a Carnot cycle on a PV diagram, such as those typically depicted in textbooks. However, they cannot associate this diagram with an actual physical process. That is, even though they refer correctly to the cycle on the P-V diagram, they are unable to acknowledge what is actually happening to the gas and the reservoirs. They recall a few conditions ideal reservoirs need to meet, like constant temperature, but they make almost no comments about their nature. Therefore, they cannot choose any of the answers proposed. After that, the interviewer offers them the simulation:

Fragment 1

1. Int: *I get the feeling that you could use a visual of what an actual machine does when doing a Carnot cycle, right? to understand what happens with these two reservoirs that you drew here* [they had drawn the well-known P-V diagram, as found in textbooks]... *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 compression/expansion and the heat flows:

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

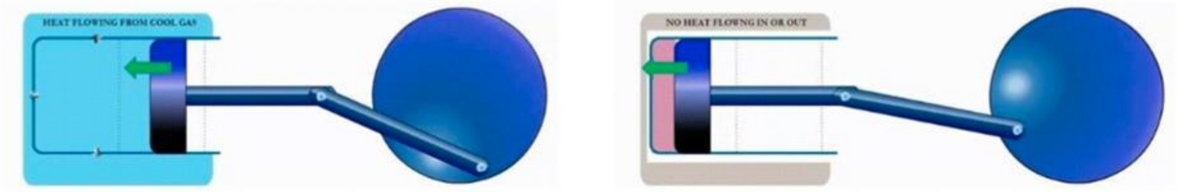
3. F: *I don't know if that's showing you the temperature... Here in the animation you can see the heat flows...*

4. N: *Well... there the heat flows out* [of the gas] ... *there the temperature* [of the reservoir] *increases... That* [the colored area surrounding the piston] *would be like the two reservoirs*.

The simulation actually offers new representations that were not present in the statement of the problem, and enables students to extract new information: what is the process about (turn 2) and the specific moment of heat exchange and its direction (turns 3 and 4). Figure 4 shows snapshots that illustrate specific times of the simulation associated to those extractions: a) Isothermal expansion → heat flows into the gas as it expands; b) Adiabatic expansion → the piston continues to increase gas volume but no heat is exchanged, and the temperature drops; c) Isothermal compression → the volume decreases as heat flows out of the gas and into the low-thermal reservoir, and d) Adiabatic compression → gas volume continues to increase, with no heat exchange involved, and gas reaches the same temperature as the “hot” reservoir.

Thus, students have an opportunity to make extractions that were not enabled at the beginning, before visualizing the animation. Up to that point (before interacting with the simulation) they were stuck in their effort to connect their knowledge with the problem and the questions posed.

a) Heat flowing into gas from hot reservoir **b) No heat flowing in or out**



c) Heat flowing from gas to cool reservoir **d) No heat flowing in or out**

Figure 4 - Snapshots from 4 Different Times During the Simulation. a) Isothermal Expansion, b) Adiabatic Expansion, c) Isothermal Compression, d) Adiabatic Compression (Green arrows are not part of the simulation and were added in the figure to indicate piston direction of movement)

We define this type of interaction as ***Extractive*** due to the fact that the simulation offers new representations that become a source for new extractions. These new extractions are inputs for the development of new projections, as will be detailed in the next section (see Figure 6). By means of these interactions, students are able to produce an augmented number of extractions. This increased amount of extractions enables the possibility of a larger number of inferences and projections. In other words, extractive interactions contribute to setting forth a starting point for the coordination of a class that affords a wider and richer variety of projections.

Interaction Type 2: Inferential Interaction

The type of interaction we will discuss in this section is related to the inferences students make as they project the [reservoir temperature] class. The following excerpt was chosen to illustrate this type of interaction as students make inferences with the simulation about the physical system under consideration.

Fragment 2

1. P: *Then the reservoirs are going to maintain their temperature...the idea is that they maintain their temperature so that the cycles can go on and on...*

2. E: *Of course that's what I think because if the temperature decreases...*

3. P: *It would not complete the cycle...*

4. E: *Of course if we have the reservoirs and this* [the reservoir at T_1] *has to make the cylinder go and return, doesn't it? If when I come back here the temperature is less so 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. P: *Well I think the initial cycle has this graph* (see figure 5). *Suppose you don't have a constant* [he points to a reservoir]. *Start with a* T_1*, 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* T_1 *but stop 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*.

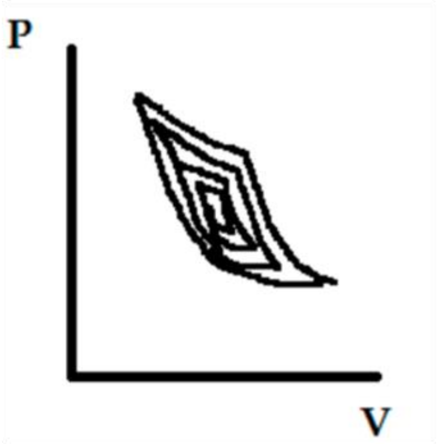


Figure 5 - Students' Depiction of "Realistic" Cycles in Which Reservoirs Alter Their Temperature.

In turns 2 and 3, they make a "what-if" kind of inference: what would happen if the (hot) reservoir temperature could decrease. This is an inference they make about the system *with* the simulation[1]. They infer that if reservoir temperature decreases, the cycle cannot be completed as in the animation : the piston will not

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[1] The reader should keep in mind that the animation of the piston expanding and compressing the gas is the endless repetition of a single cycle.

reach its initial position after consecutive cycles. Therefore, as the piston goes back and forth in each cycle the hot/cold reservoir's temperature goes down/up (turn 4 and 5). The temperature of the reservoirs is modified in each cycle (the hot one cools down and the cold one heats up) and the limiting values of the volume of the gas also become closer to each other. Students represent these ideas by means of a modified, more realistic depiction of the cycles on the PV diagram for Carnot cycles in which reservoirs can modify their temperature (figure 5). We define this type of interaction as ***Inferential***, given that the simulation becomes an essential part of the inferential net of the projection that is taking place.

Students' extractive and inferential interactions with the simulation are a characterization of the way that they advance their conceptual understanding. They are, in brief, extracting information about the Carnot machine operating between two reservoirs, making inferences about the relationship between system variables, and finally arriving at a conclusion: reservoir temperatures, in this particular case, cannot remain unaltered after each cycle (this is in fact the projection of the class in this particular case). A schematic diagram of this projection is offered in figure 6.

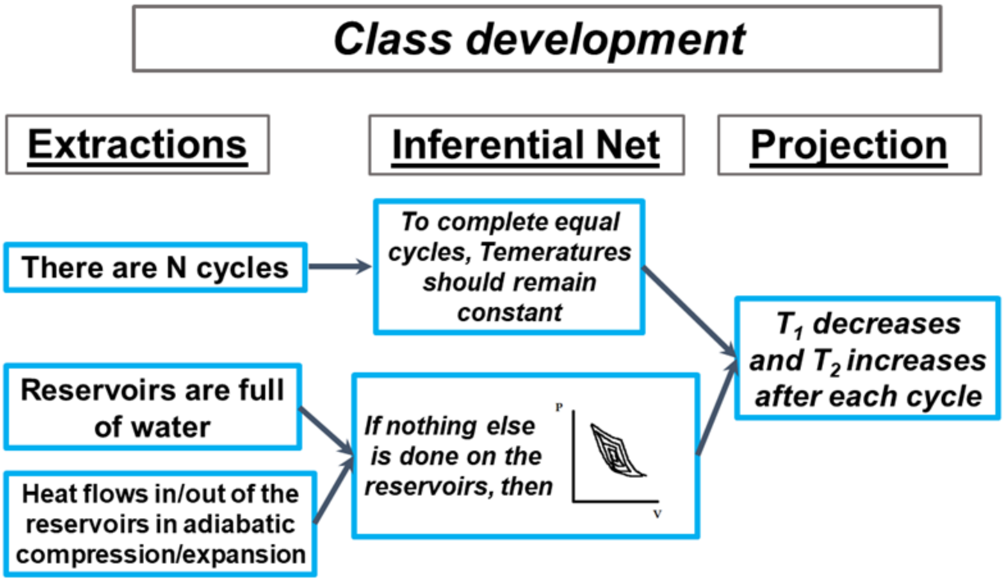

Figure 6 - Class Development During an Inferential Interaction.

Interaction Type 3: Articulative Interaction

In the following excerpt, students are invited by the interviewer to estimate an equilibrium temperature for the reservoirs. In their first attempt, they recognize heat transfers out of the hot reservoir and into the cool one. Therefore, they find it sensible to proceed as in many other heat transfer processes: they use the heat-balance equation. Since both reservoirs have the same mass, they infer that the final (equilibrium) temperature will be the average between the two initial temperatures. They will eventually question this result.

Fragment 3

1. N: *I think it is the average*

2. F: *The average?... Well I think that the heat flows at a constant rate… It is the same* [mass for each reservoir], *so the average makes sense...*

3. N: *If you still doubt, compute it… You know the masses, assume a coefficient* [specific heat]...

\\They take the pencil and they write down the heat-balance equation...

4. F: *Well as you can see, it is the average*

5. N: *Yes. You're right*

6. Int: *Do you all agree that it's* [final temperature] *the average?*

7. N-F: *Yes, we do…*

8. N: [that average is] *250 K…*

\\They run the simulation

9. F: *The result is 245K … Well, hold on… The problem is that we are not considering energy loss, isn't it? The temperatures are going to be the same but there is a loss of energy*.

10. Int: *Is the simulation considering energy loss?*

11. N: *No, I don't think so…*

\\They run the simulation several times, using different values for reservoir masses and initial temperatures. In every run the simulation yields values below their estimate using the heat balance equation temperatures.

12. F: *Again, this isn't working. Wait...We are not considering [in the computation] that the gas is doing work. That there is energy going out, so the temperatures are not going to be the average. They will end up at a value less than the average.*

13. N: *Yes, and that is not because of energy loss. It is because of work.*

One of the students' projection of the equilibrium reservoir temperatures is based on the use of the heat-balance equation, according to which its value will be 250 K (turn 8). Simulation also offers the opportunity to observe the evolution of reservoir temperature as a function of the number of cycles. This enables a different projection, according to which the final equilibrium value is 245 K. Students acknowledge this discrepancy, and they need to figure out where it comes from. These two projections are clearly non-aligned: they deliver different distinctive information.

In order to address the misalignment between these projections, students manipulate the parameters in the simulation to seek for the possible sources of discrepancies. After a few runs they realize that the work done by the machine will necessarily bring the equilibrium temperature to a value lower than the average of the initial temperatures (turn 12 and 13). They also realize that this work is not taken into account anywhere in the heat-balance equation. In this sense, by working with the simulation, an articulation process was enabled. According to CCT, an articulation can occur when two projections deliver different distinctive information, as in this case. By articulating these projections, students revisit them both, and realize that one of them fails to account for the work done by the machine. This is why this type of interaction is defined as ***Articulative***.

DISCUSSION

In this work we focus on the study of conceptual development in the particular case of students learning with simulations. Guided by Coordination Class Theory, we focus on students' conceptual development with the simulation during a problem solving session. We address the following research question: How do computer simulations participate in conceptual development throughout a problem-solving task on thermodynamics?

When addressing the paper and pencil problem, students found obstacles that were hindering their progress toward a solution of the problem. By solving the problem with the simulation, students are able to find a way to overcome their difficulties. In fact, they are able to think about the problem in new, more productive, ways. Other studies have previously pointed out the value of simulations for thinking. Segnupta et al. (2015) reported that representations function as bootstrap for students' reasoning. Parnafes (2007) showed how multiple representations offer students the opportunity to make conceptual inconsistencies explicit. Other authors have reported that computer simulations can promote conceptual learning even more effectively than direct experience, in particular for concepts that are abstract, counterintuitive or not accessible to direct observation. In this work, we probed into the actual thinking processes that occur when thinking with the simulation. We were able to describe strategies for conceptual learning that occur within those processes at a fine-grain level.

During the first stage of the problem solving session, as students were thinking with the simulation, they made extractions that became an important starting point for their reasoning. We call these interactions extractive. Extractive interactions contribute to setting forth a starting point for the coordination of a class that affords a wider and richer variety of projections.

We were able to unveil another form of students' thinking-with-the-simulation. Students imagine a modified animation in which the piston compressing the gas starts every new cycle at a slightly different position (as opposed to the animation provided, in which every cycle is an exact repetition of the previous one). This imagined, modified, animation allows them to infer that the corresponding cycles on the PV diagram are actually more like the ones in figure 5. Since they reason with simulation to produce those inferences, we named this type of interaction inferential.

Ultimately, students think-with-the simulation to articulate different projections, and thus the name articulative for this third type of interaction. They compare two different, non-aligned projections. They are not aligned because one of them actually corresponds to a process in which the two reservoirs are put in thermal contact (and no work is obtained). Students try to find the source of this discrepancy by changing the parameters in different runs of the simulation. In doing this, they find that the final temperature predicted by the simulation is systematically lower than the temperature computed using the heat balance equation. This lets them realize that the source of the discrepancy is that the use of the heat-balance equation does not account for the work done by the Carnot machine.

The simulation our participants used was not connected to any particular pedagogy. It was, in that sense, not connected to any teaching agenda. However, it had been tailored to address the difficulties that we believed our participants would run into. Therefore, it was connected to students' learning difficulties. In this sense, our results do not contradict Trundle and Bell's (2010) report that computer simulations used in isolation have shown to be ineffective. Our results support the idea that when connected to students' learning process, the simulation can actually promote students' conceptual development, even in isolation from any teaching agenda. Extractive, inferential and articulative interactions are good examples of this.

CONCLUSIONS

This work studies the interactions that students have with a simulation device when solving a problem on the thermodynamics of thermal reservoirs in a Carnot engine. The analysis of these interactions support our claim that the simulation does more than just assist students' thinking: it is a part of what they think. Extractive interactions set forth a starting point for the coordination of a Class that affords a wider and richer variety of projections. Inferential interactions produce knowledge that is the entanglement between students' previous knowledge and salient features of the simulation. A clear example of this is students' depiction of realistic Carnot cycles, shown in figure 5. Students are able to intertwine the idea of a cycle with the effects of heat transfer and modify those ideal Carnot cycles accordingly. Finally, articulative interactions also show how simulations can play a central role in students' learning. Simulation offers the possibility of being run as many times as desired, and with any initial value configuration. This affords the possibility for students to encounter a systematic result: equilibrium temperature of the reservoirs is always lower than the one resulting from the heat-balance equation. This allows them to realize that by using the heat-balance equation they are failing to account for the work done by the thermal machine.

As mentioned in the Introduction, previous research has already shown that simulations can have a positive impact on learning. In this paper we advance our comprehension of how this can take place. Adopting a theoretical framework such as CCT, we have been able to identify how a particular simulation device can become a part of students' learning. Also, as mentioned in the Results Section, the methodology adopted (MLA) allows for its results to feed back into the theoretical framework that supports the analysis. In this case, our results make a contribution to CCT, since it allows us to expand the functions of extractions, inferences, projections and articulations beyond the realm of individuals or groups of individuals, to the collective of humans-with-media (Villarreal & Borba, 2010). Our results are in line with the idea that cognition includes the tools, devices and media with which it is produced. Students not only use the simulation to think; it is actually a part of what they think.

RECOMMENDATIONS

From a theoretical point of view, CCT provides a very fine detail of the cognitive processes that make up students' ideas. However, it falls short in allocating the specific role of an external device, such as a simulation. Therefore, these results call for possible dialogues between CCT and other theoretical contributions stemming from distributed cognition perspectives. In a similar vein, we have already complemented CCT with ideas from the Community of Practice perspective to understand the learning of Entropy among peers (Velasco et al., 2022).

As for teaching, this research could have important implications. We developed a simulation aimed at addressing a learning difficulty reported in the literature. Smith et al. (2015) report that undergraduate students very often lack the ability to consider hypothetical and impossible situations such as a reservoir keeping a constant temperature despite heat exchanges. Bing and Redish (2012) regard the use of imagined (and impossible) situations as a trait of expertise, and point out that many advanced undergraduate students may not have developed the capacity necessary for this kind of reasoning. Our results feed into the possible ways of addressing those difficulties.

LIMITATIONS

As for any case study, direct generalizations are not afforded. Since participants constitute an incidental sample, there is no statistical support to infer that other subjects would replicate these results. In the same vein, one cannot assume that other simulations, related to other conceptual content, would yield the same interaction categories. However, these limitations do not undermine the value of the present work in contributing to the understanding of how students carry on their thinking processes in interaction with simulations.

Ethics Statements. Students' participation was voluntary and consent was given for video recording, and ulterior use of registries for research.

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