Physics Conceptual Understanding in a Computational Science Course

Rivka Taub
Department of Education
Hevel-Yavne Regional Council
Israel
rivka.t@hevel-yavne.org.il

Michal Armoni
Science Teaching Department
Weizmann Institute of Science
234 Herzl. St. Rehovot 7610001
Israel
michal.armoni@weizmann.ac.il

Mordechai (Moti) Ben-Ari
Science Teaching Department
Weizmann Institute of Science
234 Herzl. St. Rehovot 7610001
Israel
moti.ben-ari@weizmann.ac.il

ABSTRACT

Students[1] face many difficulties dealing with physics principles and concepts during physics problem solving. For example, they lack the understanding of the components of formulas, as well as of the physical relationships between the two sides of a formula. To overcome these difficulties some educators have suggested integrating simulations design into physics learning. They claim that the programming process necessarily fosters understanding of the physics underlying the simulations. We investigated physics learning in a high-school course on computational science. The course focused on the development of computational models of physics phenomena and programming corresponding simulations. The study described in this paper deals with the development of students' conceptual physics knowledge throughout the course. Employing a qualitative approach, we used concept maps to evaluate students' physics conceptual knowledge at the beginning and the end of the model development process, and at different stages in between. We found that the students gained physics knowledge that has been reported to be difficult for high-school and even undergraduate students. We use two case studies to demonstrate our method of analysis and its outcomes. We do that by presenting a detailed analysis of two projects in which computational models and simulations of physics phenomena were developed.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**; *Redundancy*; Robotics • **Networks** → Network reliability

DOI: https://doi.org/10.22369/issn.2153-4136/9/2/1

KEYWORDS

Computational science, conceptual understanding, concept maps

ACM Reference format:

R. Taub, M. Armoni, M. Ben-Ari. 2018. Physics Conceptual Understanding in a Computational Science Course. In *Journal of Computational Science Education*, 14 pages. https://doi.org/10.1145/123 4

1 INTRODUCTION

Students face many difficulties while trying to understand physics principles, concepts and formulas [15, 19, 26]. These misconceptions exist in physics areas that are strongly related to everyday experiences such as mechanics [28], as well as in other areas that are less related to everyday experiences such as electromagnetism [17].

Widespread instructional methods aiming at overcoming these difficulties involve computer simulations—programs that model systems or processes [10]—in physics teaching. One approach for such involvement is by students' use of simulations, with or without controlling some of their variables [37]. Another approach is by programming simulations of physics phenomena [4]. Programming physics simulations has the potential to promote physics conceptual understanding in two ways. First, it enables dealing with real-life problems [35], a possible opportunity for conceptual change of misconceptions that are related to real-life experiences. Second, programming the physics phenomena may unfold students' physics knowledge, leaving no "black boxes" [4].

The research presented in this paper aims at investigating the physics learning taking place while programming physics simulations. Moreover, it investigates physics learning in a unique context, a computational-science course where the physics learning is not one of the direct goals of the course. Instead, the course's goal is to expose the students to different computational methods, while the physics content is addressed mainly through examples demonstrating how to apply these methods.

Here we report on the evolution of the students' physics conceptual knowledge taking place during the course. This knowledge was evaluated at the beginning and at the end of the process of developing computational models, and at different stages in between. The students' knowledge in each stage was compared to that of physics experts. To represent the experts' and students' knowledge we relied on the framework of concept maps [29], a powerful tool for knowledge representation, while making several modifications to this tool.

Originally, concept maps were intended to be used by students to express their own knowledge as a learning tool or as assessment tool. In Section 2, we elaborate on various ways for using concept maps as an assessment tool. In this study concept maps were used in the following manner: We asked physics experts to represent as concept maps the physics knowledge the students were supposed. We then followed the evolution of students' physics knowledge, represented as concept maps at various points during the learning process, and compared these concept maps with those of the experts.

This paper opens with a review of the relevant literature, continues with a description of the research context—the computational-science course—and the research methodology, presents the findings and summarizes them.

2 LITERATURE REVIEW

This section reviews literature on the difficulties students experience while learning physics, on the knowledge area of computational science and on concept maps as tools for assessing the evolution of knowledge.

2.1 Difficulties in Physics Understanding

Research on difficulties and alternative conceptions that students have when dealing with mechanics shows that students' intuitive knowledge differs from the formal knowledge. McDermott [28] reviewed studies that explored mechanics-related difficulties. Populations in these studies ranged over different age groups, from middle- and high-schools to universities, and included students who studied physics less than a year to those who studied for several years. Interestingly, the results obtained were very similar, pointing to the persistence of difficulties and misconceptions in mechanics. For example, Gunstone and White [18] discovered that when dealing with questions related to gravity, students tend to mix velocity and acceleration, and mass and weight. Similar results regarding the confusion between velocity and acceleration were found by Trowbridge and McDermott [46].

Bagno, Berger, and Eylon [2] found that high-school physics students provided a vague description of the components of a formula. For instance, when referring to the formula $\sum\vec{F} = m\vec{a}$, students related only to one force $\vec{F}$ and ignored the net force. As another example, the students explained the meaning of the variable t in a formula as 'time', while an accurate explanation should have been 'the time elapsed since $t = 0$,. Another difficulty described by Bagno et al. [2] is that many students were unable to explain the conditions under which a formula can be applied. For instance, in the formula $x = x_0 + at + \frac{1}{2}at^2$, 80% of the students did not mention the fact that the formula applies only for objects moving with constant acceleration. Another study reported by Shaffer and McDermott [40], examined whether 20,000 college and university students were able to associate the direction of the acceleration and the net force denoted by the formula $\sum\vec{F} = m\vec{a}$. They found that when asked about the direction and magnitude of the acceleration of a ball moving on a ramp, only 20% of the students answered correctly. The others thought that the direction of the acceleration is toward the bottom because 'gravity causes the motion'. The authors explained that some of the students did not associate the direction of the acceleration with that of the net force.

Research on students' learning geometrical optics, in particular light propagation, also uncovered difficulties. Galili and Hazan [15] reported on a conception students hold that claims that a single ray is emitted from each point of the light source. The authors explained that this conception is not incorrect but incomplete from a scientific view: the complete conception should be that multiple rays emanate from each point of the light source in all directions. Chang, Chen, Guo, Chen, Chang, Lin et al. [7] examined conceptions of elementary, middle-school and high-school students regarding different topics in classical physics. One of their findings was related to the images created by lenses and mirrors, showing that the students tended to use point-by-point conception to describe the refraction of lens and perceived light as a kind of material. When asked what would happen to the image of an object standing in front of a partially covered convex lens of a camera, most students answered that a part of the image would disappear. This is in contrast to the scientifically correct answer stating that the size of the image would stay the same, although it would look darker. Similar results were found by other researchers such as Galili [14].

Studies point to difficulties that students face regarding temperature and heat. For example, Thomaz, Malaquias, Valente, and Antunes [45] suggested five common students' misconceptions that students: (a) believe that heat is a kind of substance; (b) cannot differentiate between heat and temperature; (c) confuse temperature and the 'feel' of an object; (d) believe that application of heat to a body always results in a rise in temperature; and (e) misunderstand the temperature of a phase transition. Jasien and Oberem [22] reported on the following three difficulties physics students, and pre- and in-service teachers face: (a) the meaning of thermal equilibrium; (b) the physical basis for heat transfer and temperature change; and (c) the relationships between specific heat, heat capacity, and temperature change.

Difficulties students face when dealing with physics topics, such as mechanics, geometrical optics and heat are closely related to conceptions stemming from everyday experiences. Some topics, however, have no obvious parallel experience in everyday life. Electromagnetism is one such example [17]. While learning electromagnetism students were found to (a) be unable to link electrostatics and electrodynamics [13]; (b) be unable to connect between macro and micro relationships in electric circuits [5]; (c) confuse related concepts such as current, voltage, energy and power [40]; (d) incorrectly determine the direction of the induced magnetic field; and (e) claim that the path of an electric charge in a magnetic field is always circular [3].

2.2 Computational Science

Computational science is a field that deals with different aspects of the construction of computational models. The Journal of Computational Science [42] describes it as an interdisciplinary field that uses advanced computing and data analysis to understand and solve complex problems. It claims that computational science has reached predictive capabilities that join the traditional experimentation and theory.

Yasar and Landau [47] explain that computational science is a field that integrates natural sciences, applied mathematics and computer science (CS), and uses the common elements of these disciplines to develop models of scientific systems; they add that computational science is not only the intersection between the three domains but also has content of its own (Fig. 1).

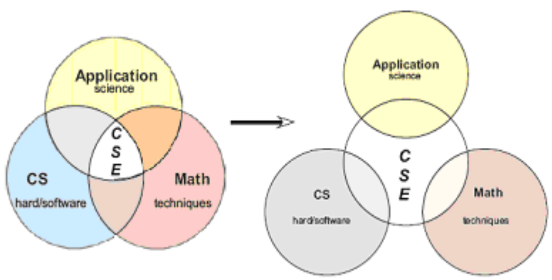

Figure 1: Left: Early view of CSE (Computational Science and Engineering) as the intersection between science, applied mathematics and computer-science. Right: Current view of CSE as sharing common concerns with these disciplines and also having content of its own [from 47].

Computational modeling is perceived to provide opportunities to promote students' conceptual knowledge. One of the most influential views regarding programming as a way to enhance scientific learning is described by Papert [31]. Learning by programming is claimed to be significantly better than learning by watching television or even reading. Programming a computer is an active learning process that empowers the learner due to the active creation of knowledge. Papert [31] explains that programming provides a tool to concretize formal and abstract knowledge. Since programming is about teaching the computer how to think, programming requires the learner to think about thinking. For example, children tend to think that in learning, they either get a right or wrong answer. But when programming a computer, solution is rarely right the first time the program is run.

Physics instructors suggest combining programming computational models as a way to improve physics learning [4, 38]. The rationale behind this suggestion is that such a combination requires that physics knowledge be organized and represented as computational models of physical systems, that is, computer programs. Abelson, Sussman, and Sussman [1] explain that computer programs are more than just sets of instructions for a computer to perform tasks. They also serve as frameworks for organizing ideas about processes. They deal with *data* that represent objects in a given system, and *procedures* that represent the rules for manipulating the data. These attributes of computer programs enable computational-science students to organize their ideas about physical objects and processes.

Research on combining computational-science elements in physics introductory courses shows positive effects. Redish and Wilson [35] developed an introductory physics course that was based on the computerized M.U.P.P.E.T environment. The authors introduced programming at the beginning of the traditional calculus-based introductory physics course at the University of Maryland. They found several benefits for teaching physics in a computer-based environment, among them are: (a) using the environment to overcome a lack of intensive mathematical knowledge; (b) exposing students to research methods that professional physicists use, and (c) being able to discuss real-world problems such as projectile motion with air resistance.

Chabay & Sherwood [4] list the pros and cons of learning physics while programming. One benefit is that when programming the physics phenomena, there are no "black boxes" of the physics knowledge at the basis of the simulation. Another benefit is the link generated between different representations of the same physics idea: an algebraic equation and programming code. Among the negative aspects of using programming for learning physics, they mention that a large portion of the students have no background in programming and therefore teaching programming takes up a lot of time needed for physics learning.

Sherin [41] compared between what he termed *algebraic physics* and *programming physics*. Two groups of his students solved physics problems. One group solved ordinary textbooks problems (algebraic physics) and the other (programming physics) was asked to develop simulations on phenomena similar to those underlying the problems solved by the algebraic physics group. He concluded that the algebraic notation of the physics formulas does not naturally displays causal relationships between variables; therefore students tend to infer the existence of equilibrium between the two sides of an equation instead of causal relationships. In contrast, programming physics leads more naturally to understanding processes and causality, stemming from the importance of the order of the lines in the program.

2.3 Concept Maps

Researchers use different methods to assess learners' conceptual knowledge, among which are open-ended and multiple-choice questionnaires. In order to use such questionnaires as research tools, they are designed by the researchers before the teaching and learning process, and they require the students to express their conceptual knowledge, as answers to the pre-defined questionnaire. In the current research, however, the situation was somewhat different. First, the physics topics that the students' projects were dealing with were not defined in advance. Instead, the students decided on these while already working on the projects and learning the related physics material. In some cases, the students even changed the subject of the project after working on it for a few lessons. In addition, each project dealt with a different subject. Therefore, we could not prepare in advance a questionnaire for determining the students' conceptual knowledge before and after working on their projects. Second, we wished to capture and assess several stages in the development of the students' knowledge, not only pre- and post-working on the projects. It seemed that the students would find it too exhausting to answer assessment questions several times during their projects. Moreover, we could not know in advance exactly when these stages would occur. For these reasons, we looked for a method of using the students' discourse in order to assess stages in the development of their knowledge. Concept maps were our choice.

As noted by Novak and Cañas [29] concept maps were first proposed by Novak in 1972. Novak and Gowin [30] described them as spatial arrays that represent elements of knowledge as nodes together with links among them. Here we follow Ruiz-primo[36] and define a concept map as a graph consisting of nodes and labeled lines and/or arrows.[2] The nodes denote the important concepts in a domain. The lines and arrows denote relations between pairs of concepts (nodes). The labels on the lines or the arrows tell how the two concepts are related. The combination of two nodes and a labeled line or arrow is called a *proposition*. A proposition is the basic unit of meaning in a concept map.

The psychological foundations of concept maps lie in the attempts to characterize the knowledge of experts, and to assess the distance of learners' knowledge from it. Research on the cognitive aspects of science learning suggests that the knowledge of experts, apart from being more extensive than that of novices, is organized in a cognitive structure, a *schema* [8, 11, 32].

Novak and Cañas [29] explained how to construct a good concept map, emphasizing that "a concept map is never finished" (p. 12): (a) create a context by identifying a segment of a text, a laboratory or field activity, or a particular problem or question that one is trying to understand; (b) identify the key concepts that apply to this context and construct a preliminary map; (c) seek links between the concepts; and (d) revise the map, by repositioning the concepts or refining the links in ways that lead to more clarity and a better over-all structure.

Originally, concept maps were intended to be used by students to express their own knowledge as a learning tool or as assessment tool. As an assessment tool, concept maps are effective in identifying both valid and invalid ideas held by students. They can be as effective as other, more time-consuming, assessment tools for identifying the relevant knowledge a learner possesses before or after instruction [27, 29, 36]. Concepts maps are being extensively used to assess knowledge structures [21, 43]. For example, Jacobs-Lawson and Hershey [21] used concept maps to evaluate students' knowledge in psychology courses. They, too, concluded that concept maps are effective in such assessments.

There are various strategies for using concept maps for assessment which differ on several dimensions: The phase of the teaching process in which concept maps are used, the methods used for analyzing and evaluating the concept maps (direct evaluation or by comparison to a target concept map), and the manner in which concept maps are drawn (by the students, by the teachers, or by the researchers). For example, Hasemann and Mansfield [20] used concept maps drawn by 4th-grade students to assess their mathematics knowledge before the teaching process, right after it, and two years later. Ghaffar, Iqbal, and Hashmi [16] used concept maps to represent a learning objective through a concept map describing the knowledge of an expert. Novak and Gowin [30] suggested evaluating students' concept maps by comparing them to a criterion map (representing sufficient knowledge, which may be partial, compared to an expert's knowledge). McClure et al. [27] used concept maps to take a snapshot of students' knowledge and examined various assessment methods, some of which used a direct scoring method and some used master maps. Peterson and Treagust [33, 34] used concept maps in a pre-post research setting. Lomask, Baron, Greig, and Harrison [25] used concept maps that were developed by teachers from students' essays.

Our use of concept maps was a combination of several of the strategies described above. We used them as a qualitative assessment tool to analyze the development of conceptual understanding. Hence, the students' knowledge was monitored at various points during the learning process. We followed the strategy used by Lomask et al. [25] in which concept maps were developed from students' essays. Thus, our concept maps were not created by the students; rather, we created the concept maps, using them to reflect the students' knowledge. However, unlike Lomask et al. who relied on written essays, our concept maps were based on students' audio-recorded discourse. Finally, we evaluated students' knowledge as reflected in the concept maps by comparison to an expert's map. To this end, we asked physics experts to represent as concept maps the physics knowledge the students were supposed to acquire.

3 METHODOLOGY

3.1 The Research Question

How does students' conceptual physics knowledge change when developing computational models in the context of a computational-science course?

3.2 The Research Setting

The research was conducted in a 3-year computational-science course intended for talented high-school students (10th to 12th grades). This was an elective course, for which the students earned credit that was reflected in their matriculation diploma. During the course the students learned about different models such as static, mechanistic and stochastic, and used them to

[2] Although Ruiz-Primo and Araceli (2000) use only lines, we sometimes use arrows to demonstrate the direction of the connection between two nodes.

represent scientific phenomena, mainly physics phenomena. Learning about these models required the combination of physics, mathematics and computer science (CS).

Most of the learning during the course was done independently by pairs of students under the guidance of a textbook, while the teacher served as a mentor. All the classes took place once a week for 3 hours in the afternoon after regular school hours. In each of three years, the students developed (in pairs) mid and final projects of their choice, most of which dealt with physics material they had not learned before.

This research was carried out among 10th- and 11th-grade students (during the first and second year of data collection, respectively). During the course these students learned programming concepts, the Java language, kinematics, dynamics and optics. The researchers were not involved in the teaching of this course. The software the students used in these classes was Easy Java Simulations[3] (10th-11th grades) and Maxima[4] (11th grade).

Easy Java Simulation (EJS) is a software package created by Francisco Esquembre [9, 12]. It enables the construction of computational models by providing a user-friendly environment for Java. The intended users are science students, teachers and researchers who want to avoid putting too much effort into programming and more emphasis on the scientific content. To achieve that the user interface can be created without any programming knowledge on the part of the simulation's designer. Therefore she/he may focus on the algorithmic component when designing the scientific model. This software breaks the modeling process into three activities that are selected by the user: (a) documentation, (b) modeling, (c) interface design. In the modeling activity the designer represents the physical solution as an algorithm implemented in Java.

Maxima is a Computer Algebraic System (CAS), for manipulating symbolic and numerical expressions, including differentiation, integration, ordinary differential equations, systems of linear equations, polynomials, and more. In the computational-science course, 11th-grade students used Maxima for studying random models in a CAS environment, studying differential equations, finding analytic and numeric solutions of differential equations, writing a program to solve linear equations, and more.

During the research we observed and recorded the work on seven final projects. Five of them were designed and implemented by pairs of 10th-grade students and the other two by pairs of 11th-grade students. All students volunteered to participate in the research, and the research, including its methodology of data collection, was approved by the Ministry of Education. Of the volunteers we chose all the girls (three) since we wanted to have both genders represented in the research population. All together during the research we analyzed the work of 12 students, since one pair of students was observed working on two projects, in both 10th grade and 11th grade, respectively. The work on each project lasted approximately 10 hours (four lessons).

The choice of which physics phenomena to simulate was done independently by the students and it ranged over many topics. Four projects dealt with mechanics (a circular motion of a car, an anti-missile system, collision of two balls on an inclined plane, and a Frisbee game) one dealt with optics (lenses and mirrors), one with electricity and magnetism (the Lorentz force – an electric charge moving in a magnetic field), and one with thermodynamics (the diffusion equation – air heated by fire).

3.3 Research Tools

Two types of research tools were used to collect data in this study.

1. The work of the six pairs of students on the seven final projects was documented in detailed using the Debut screen-capture software.[5] It recorded their computer screens, including the work on the programming files, the mouse actions, and the students' voices while talking to each other during their work.
2. Observations of the students' work while taking field notes. One researcher (the first author) joined each lesson one to three pairs, observing their work and taking field notes. This enabled her to notice non-auditory gestures that could not be recorded and to get an impression of the students' working style, for example, how the work was divided between the two students.

As noted above, students' participation was voluntary and they were aware of the data collection process.

3.4 Analysis

Analysis of the students' discourse was conducted using concept maps [30] aimed at assessing evolution of the students' physics conceptual knowledge.

To express the students' conceptual knowledge in physics, we relied on excerpts from the students' discourse taken from the students' work on the computational models (approximately ten hours per project). Based on the excerpts we created concept maps. The students were not involved in the creation of the concept maps. For each episode in the students' discourse we drew several maps that represented the evolution in their understanding of physics concepts that were relevant to their project, and of the relationships among them. This was done by:

1. Identifying the main physics concepts discussed by the students in a specific episode.
2. Linking between the physics concepts according to the physics formulas and principles. Almost all the physics phenomena that the students modeled evolve in time, such as circular motion or a flying discus. For this reason, some of the links between concepts express time evolution. For example, the link $\vec{v} \rightarrow \vec{x}$ shows that a

[3] http://fem.um.es/Ejs/
[4] http://maxima.sourceforge.net/
[5] www.nchsoftware.com

change in velocity of an object yields a change in its position over time. Other links, however, stem from physics definitions. For example, the link $\vec{v} = \frac{d\vec{y}}{dt}$ shows that the velocity **is** the derivative of the position with respect to the time.

3. Drawing an expert's concept map expressing the concepts and links in (1) and (2).
4. Drawing concept maps that represent the students' knowledge of these concepts in several points along of the learning process: initial, final, and at least one point in between.
5. Comparing between the students' initial and final concept maps to evaluate the evolution in their conceptual knowledge (relevant to their project).
6. Comparing between the expert's concept map and the students' final concept map to evaluate the level of the students' conceptual knowledge (relevant to their project).

Actions (1)-(6) were applied twice (for validation purposes) by the third researcher, by a physics educator and by a physicist who is also a computer scientist. Disagreements were discussed and resolved, and the maps were changed accordingly.

4 FINDINGS

The choice of which physics phenomena to simulate was done independently by the students and ranged over many topics. Still, it was possible to identify some general findings that repeated themselves in several different projects. This section opens with two case studies (two projects) exemplifying in detail the analysis process and its outcomes. Then we presents the general findings of our overall analysis of all seven projects.

4.1 Case Studies

This section focuses on two projects, describing their analysis in detail and presenting its results. These case studies enable a deeper insight of the concept-map-based analysis process and its rationale. The first project was developed by two 11th-students simulating a Frisbee game. The second was developed by two 10th-grade students, simulating an electric charge moving in a magnetic field.

4.1.1 Case Study 1. Students S5 and S6 (11th grade) decided to develop a simulation of a discus thrown at a specific initial velocity and moving in the air, affected by the wind. The physics description of the motion relates to:

1. Projectile motion of the discus under the effect of the forces exerted by gravity, aerodynamic lift, aerodynamic drag (air resistance), and the wind.
2. Spinning of the discus due to an angular momentum provided by the thrower.

Developing such a simulation is challenging for high-school students since the high-school physics syllabus that they study is limited to motion primarily under the effect of a constant force such as $m\vec{g}$. Varying forces that the students encounter are the harmonic force, inverse square forces (such as the electrostatic force), and the magnetic force ($\sum \vec{F} = q\vec{v}\times\vec{B}$). The syllabus does not, however, treat motion under other varying forces that are exerted, for example, by the air on a moving object. Moreover, the syllabus does not include the physics of spinning objects. Accordingly, the teacher advised the students to first simulate the projectile motion of the discus under the effect of the constant and varying forces, and only later on to add its spinning. As it turned out, developing the simulation of projectile motion was challenging enough for them and lasted five lessons (approximately twelve hours), leaving no time for the spinning force. For this reason, the new physics material that the students had to study was dealing with the effect of the forces mentioned in item (1) above on the motion of the discus.

The conceptual knowledge required in order to develop such a simulation appears in Fig. 2 represented as a (high-level) expert's concept map.

The discus is being thrown at an initial velocity $\vec{v_0}$. Four forces affect the motion of the discus: gravitation (assumed to be constant), aerodynamic lift and drag, and the wind. The students assumed the wind to have a constant velocity. The net of these forces generate an acceleration as expressed by Newton's second law $\sum \vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt}$. Since the velocity is a vector, it is represented by magnitude and angle (v, α). The velocity is defined as the derivative of $\vec{x}$, the position of the discus. For each Δt , the drag and lift forces are being changed because of change in the velocity, leading to a new net force, changing the velocity and accordingly the position of the discus.

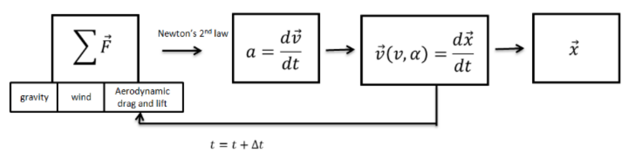

Figure 2: Expert's concept map representing the conceptual knowledge of the physics involved in the project of S5 and S6.

Here we focus on an example demonstrating the development of a subset of the physics involved, relying on data taken from several episodes scattered along the full work on this project, which lasted about 12 hours.

The example deals with the interrelationships between the net force and the velocity of the discus, repeatedly calculated every Δt. Figure 3 presents the relevant parts of the expert's concept map. This map is more detailed than the previous one. It shows, as previously, the effect of the net force on the velocity. In addition, it shows that the observed velocity of the discus ($\vec{v}$) is the sum of the discus' velocity relative to the air and the velocity of the wind (assumed by the students to be constant and in the direction of the x axis). The speed of the discus relative to the air changes the forces of aerodynamic lift and drag.

Since this example focuses on this aspect of the project, the students' evolving concept maps will be compared to the expert map in Fig. 3, and not to the wider map of Fig. 2.

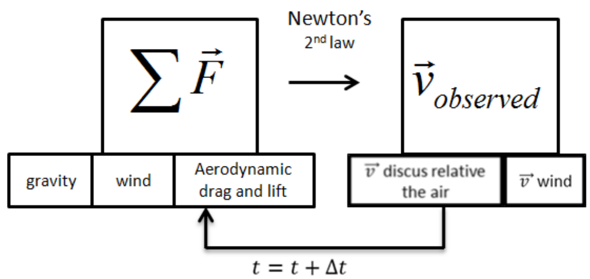

Figure 3: Expert's concept map of the interrelationships between the net force and the velocity of the discus.

The students started the project by studying the relevant physics principles and formulas from a scientific paper the teacher gave them. The relevant material that was explained in this paper includes: (a) the observed velocity of the discus is the sum of the velocity of the discus relative to the air and of the velocity of the wind; (b) the calculations of the discus' velocity and position are time dependent; and (c) the velocity of the discus relative to the air affects the aerodynamic forces of drag and lift.

In what follows we describe three learning episodes. We will see that the students did not understand these issues very well, and that their understanding evolved while developing the simulation.

Episode 1: After reading the paper given to them by the teacher, the students said:

S5: I don't understand the meaning of *Vrel* [velocity of the discus relative to the air].

S6: I want to start programming; we'll figure it out later.

S5 and S6 began with declaring the program variables corresponding to the physics variables. They started with *Vd* and *Rd,* the variables corresponding to the magnitude and angle of the velocity of the discus **relative** to the air. They continued by declaring *Vrel* and *R,* corresponding to the magnitude and angle of the **observed** velocity of the discus. The reason they chose to name the variable *Vrel* and not *Vobserved* was that they referred to this velocity as **relative to the ground**. Choosing such variable names was the first step in confusing between the two kinds of velocities of the discus.

The students wrote the programming segment corresponding to the physics formulas that appeared in the scientific paper (Fig. 4). It started with calculating *Vrel,* the observed velocity of the discus by summing the wind velocity and the discus velocity relative to the air. It continued with calculating the x and y components of the acceleration.

Two logical errors exist in this segment. First, it is written just once, thus it will be executed only once and will not cause a change in velocity over time. Second, the calculation of the contribution of the aerodynamic drag and lift forces to the acceleration (based on Newton's second law) is affected by *Vrel*, which is the sum of the velocity relative to the air *and* the wind velocity. Instead, it was supposed to be affected only by the discus' velocity relative to the air.

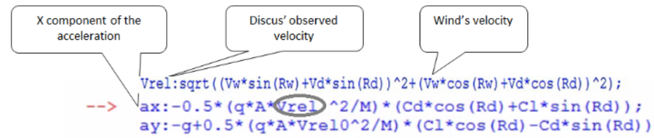

Figure 4: Code of the calculation of the discus' *observed* velocity and of the x and y components of the acceleration.

We conclude that the students correctly perceived the observed velocity of the discus as including its velocity relative to the air and the wind velocity. They incorrectly thought that the discus *observed* velocity affects the forces and thus the acceleration and they did not see the dependence of the velocity on time.

The concept map that describes the students' understanding appears at Fig. 5. It shows the students' perception of the effect of the sum of the velocities on the aerodynamic forces. However, it does not contain a time loop, indicating the students' lack of understanding of the time dependency of the process.

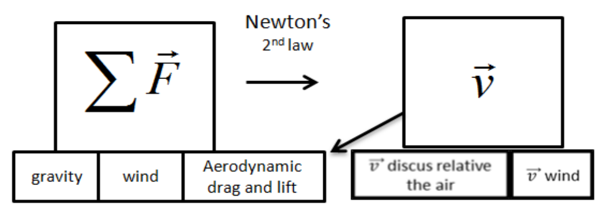

Figure 5: First concept map of the students S5 and S6.

Episode 2: Executing the simulation led S6 to understand that there are problems in the program they wrote. She re-checked it several times, reflecting on what they wanted to achieve:

S6: In order to calculate the velocity I need to first calculate the acceleration and then calculate its anti-derivative.

She then suddenly said:

S6: Wait, does that mean that I need to calculate it *every time*?

S5: Hmmm… I don't know.

S6: Do I actually need to calculate all the previous values and use them for calculating the velocity repeating it again and again?

The above excerpt indicates that S6 gained a new insight, regarding the time dependency of the calculation of the velocity (proving that she did not understand it in the previous episode). These desired repetitions are the algorithmic description of a programing loop which calculates the physical change in the acceleration and consequently in the velocity of the discus.

After several more discussions, the students programmed a for-loop (Fig. 6) representing the progress of time (t=0 to t=10). It includes a repetitive calculation of the: acceleration of the discus (as was explained for Fig. 5), the discus velocity relative to the air, and the observed discus velocity including the wind. Although here the students understood the dependency of the calculation on time, they were still in error in that they calculated the acceleration according to the discus observed velocity and not the relative velocity.

The concept map that describes the students' conceptual knowledge at this stage appears at Figure 7. Again, it shows the students' perception on the effect of the sum of the velocities on the aerodynamic forces. It differs from the previous map, however, in that it contains a time loop, indicating an understanding of the time dependency of the calculations.

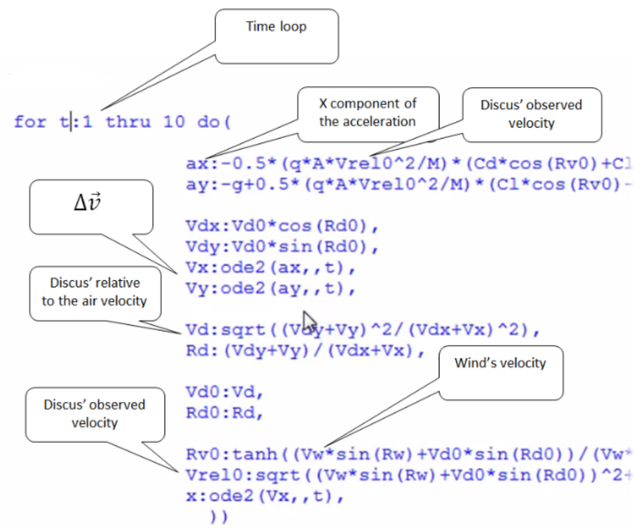

Figure 6: The for-loop written by the students.

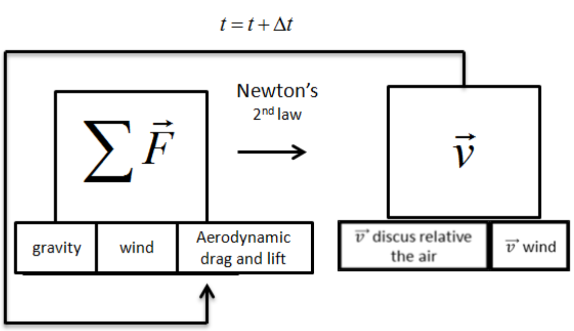

Figure 7: The second concept map of the students S5 and S6.

Episode 3: S5 and S6 faced many difficulties when trying to execute their program, debug and understand it. Significant effort was invested trying to understand the meaning of each of the velocities:

S6: There are the wind's velocity, the discus velocity, and *Vrel*.

S5: Wait, what was our meaning here [pointing on the segment of calculating the anti-derivative of the acceleration]? Which velocity is it?

S6: I can't remember.

At this point the students consulted their teacher for help in writing a correct program. Since they still did not understand the meaning of each velocity, they tried to copy the components of the formulas into the program without understanding them. This led to long sessions of correcting the code, the students trying again and again to understand the variables. Eventually, S6 said:

S6: Oh! *Vrel* is equal to *Vdiscus* **minus** *Vwind*.

In this excerpt S6 means that *Vrel* is not what they previously thought— the observed discus velocity, summing the velocity relative to the air and the wind velocity. Instead, it is the velocity relative to the air, that is, the observed velocity minus the velocity of the wind. The following method was generated (Fig. 8):

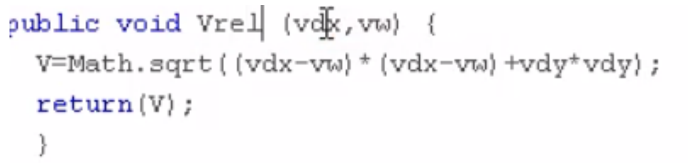

Figure 8: Code of calculation of relative to the air discus' velocity.

The relevant concept map describing the students' current conceptual knowledge is now equivalent to the expert's one (Fig. 9).

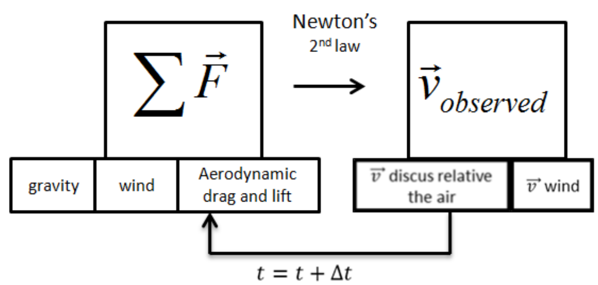

Figure 9: Third concept map of the students S5 and S6.

To summarize this case study, S5 and S6 achieved three main insights:

1. The dependence of the calculation of the discus velocity on time. The students understood the need to repeatedly calculate the velocity based on its previous values.
2. The difference between the variables of the observed velocity of the discus and one the relative to the air. After confusing the two variables for three lessons, the students finally understood which of the discus velocities is the observed and which is relative to the air.
3. The cause and effect relationships between the discus velocity relative to the air and the aerodynamic forces. After achieving the second insight of the difference between the two discus' velocities, the students correctly understood that only the discus *relative* velocity affects the aerodynamic forces and hence the acceleration.

Many factors affected the development in the students' conceptual understanding: the computational environment, the scientific paper, the teacher, the conversations between the students and more. It is not clear which one of these affected each one of the described episodes. Still, during observations, we noticed the following:

The students did not understand the physics formulas well enough before programming them; they simply copied parts of the formulas. The statement of S6 in the first lesson clearly demonstrates this point: "I want to start programming; we'll figure it [the meaning of the variables in the formula] out later." The reason may be that the students preferred implementing the formulas as programming segments instead of properly understanding them. Or, they may have thought that programming the formulas will assist them in understanding them. Either way, it seems reasonable to conclude that the need to program prevented the student from achieving understanding, at least initially.

The students used names of programming variables that were very hard to distinguish from each other. For example, they used *Vd, Vx, Vy,* and *Vrel* to represent different kinds of velocities. Since programming the simulation was a long process that lasted around twelve hours, the students could not remember the meaning of each variable. This made the process of debugging the code quite challenging. For example, when debugging, S5 asked: "Which velocity is it?" We believe that using more meaningful names may have assisted the processes of understanding both the physics and the programming.

On the other hand, it was clear that the students have gone through deep learning processes. The relevant physics material was challenging. The need to represent it in a program forced the students to explore the meaning of each concept and the interrelationships among the physics concepts. Moreover, the fact that the simulation was time dependent encouraged the students to understand the time dependency of the process. An analysis of the learning processes that occurred during the course and the interrelations between CS and physics during these learning processes was the focus of another publication (removed for anonymity) in which we used the perspective of Knowledge Integration [23, 24].

Another interesting observation concerns the students' strong motivation to accomplish their mission and develop a correct simulation. This motivation was expressed, for example, in their use of several sources for learning the relevant physics material, among which are the scientific paper, the teacher and the internet. Most of their time was used for independent learning and very little irrelevant activities such as chatting with friends. We believe that the type of the mission the students confronted yielded both enthusiasm and obligation. However, the interrelations between students' motivation and learning are not at the focus of this paper.

4.1.2 Case Study 2. S7 and S8 (10th grade) simulated an electric charge entering a force-free region and then moving into a constant magnetic field. The students decided that the charge would start moving along a straight line in the force-free region and then circulate in the magnetic field. The physics equations the students relied on were $x = vt$ for the force-free region and $\vec{F} = q\vec{v}\times\vec{B}$ for the magnetic field. They programmed the two motions of the charge. When executing the simulation they discovered that the circular motion did not appear as they expected. They tried various ways to solve this problem, but after two more lessons (approx. 5 hours) the students reached a dead end and decided to abandon the project. Despite their lack of success, they did gain physics knowledge while working on the project.

Fig. 10 presents the expert's concept-map of the formula $\vec{F} = q\vec{v}\times\vec{B}$, underlying the mechanism of the motion of an electric charge in a magnetic field.

It contains three vectors, each with direction and magnitude: $\vec{v}$, the velocity of the electric charge, $\vec{B}$the magnetic field, and $\vec{F}$, the magnetic force acting on the electric charge. The fourth concept is q, the charge of the particle, which has magnitude and a sign (plus or minus).

The velocity $\vec{v}$ and the charge q of the electric charge entering a magnetic field, jointly with the magnetic field $\vec{B}$, set the size and direction of the force $\vec{F}$. The force, (which is the net force in this case), in turn (according to Newton's second law) changes the velocity of the charge and consequently its location. For each Δt the force repeatedly changes the velocity causing the process to repeat itself as long as the charge moves in the magnetic field.

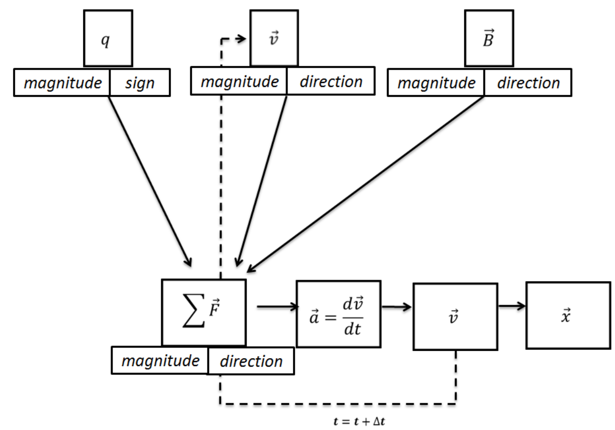

Figure 10: Expert's concept map representing the conceptual knowledge of the physics involved in the project of S7 and S8.

At the beginning of the episode taken from the second lesson of the project, the students demonstrated a vague understanding of the equation $\vec{F} = q\vec{v}\times\vec{B}$, but they did not understand the meaning of the concepts denoted by the equation nor the relationships among them. At the end of this episode they were able to explain the meaning of the concepts, and the casual relationships among them. Three concept maps representing the evolution in the students' understanding during this episode are presented.

This description starts at the stage when the students discovered that the circular phase of the motion is wrong, that is, the charge entered the magnetic field, "jumped" upwards, moved down and only then started the circle. The students debugged the simulation, but did not succeed in correcting it.

At this stage they consulted the teacher and clarified the physical meaning of the equations they wrote as programming code:

S7: What do we have here? *v*? What is *v*? [...] *B* is the magnetic field.

Teacher: What is the direction of the field?

S7: I don't care, we haven't decided yet.

According to the formula, the direction of the magnetic field affects the direction of the circular motion of the charge; therefore, in order to present this motion the direction of the field should be pre-set, though S7 did not think that this was necessary.

Fig. 11 presents the concept map representing the students' knowledge at this stage.

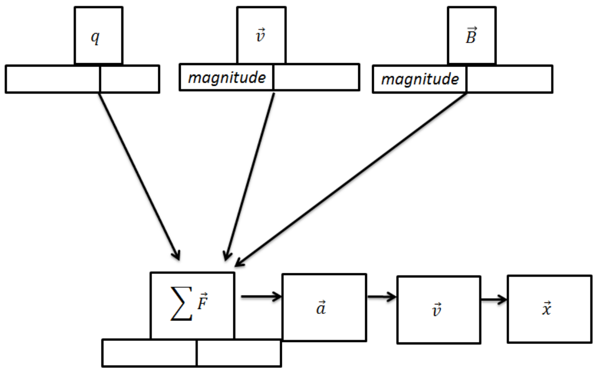

Figure 11: First concept map of the students S7 and S8.

This map shows that the students did not know the meaning of some of the concepts denoted in the equation. Moreover, although they knew that $\vec{B}$ is the magnetic field, they did not understand that its direction affects the direction of the force, thus affecting the direction of the charge's motion. Having to concretely represent the direction of the charge's motion in the visual simulation led the students to discuss the factors that influence it. They arrived at the following conclusion:

S7: The simulation is two dimensional; therefore, the charge cannot circulate inward. The magnetic field, therefore, has to be directed outward. It affects the direction of the force which in turn changes v every time, resulting in a circle.

The above understanding is expressed in the following concept map (Fig. 12):

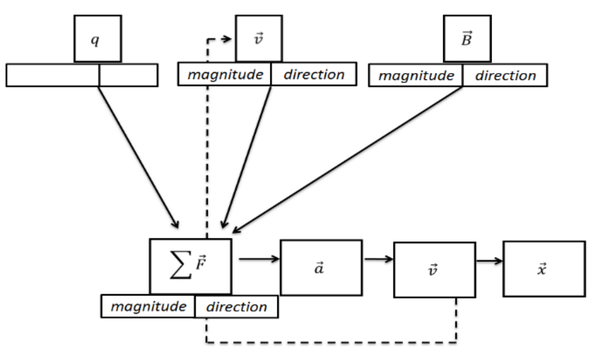

Figure 12: Second concept map of the students S7 and S8.

This map shows that the students understood the meaning of the variables and the relationships among them. Still, it is not complete, since q is missing. After discussing it some more with the teacher, S8 stated the following:

S8: The sign of the charge [the sign of q] affects the direction of the circle, as well.

The concept map representing the students' current understanding (Fig. 13) is similar to the expert's map (Fig. 10) with one exception. The expert's map includes $\vec{a} = \frac{d\vec{v}}{dt}$ but the students' map does not. This is because 10th-grade students have not yet learned derivatives.

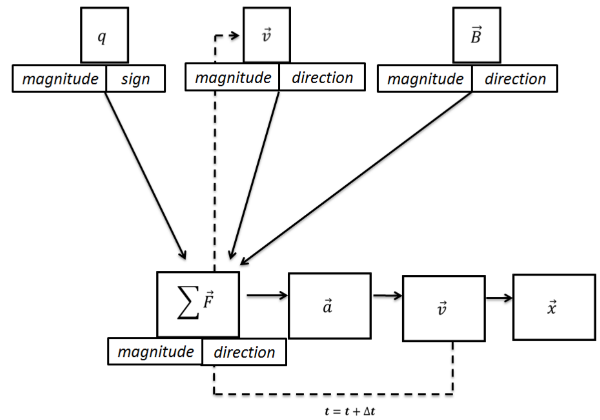

Figure 13: Third concept map of the students S7 and S8.

Although gaining a better understanding of the meaning of the equation, the students did not solve the problem of the charge "jumping" before circling in the magnetic field region. Their error was in another equation used for the circular motion inside the magnetic field: $\theta = \omega t$, where θ is the angle, ω is the angular velocity, t is the time. The variable t is assumed to be equal to zero when starting the circular motion. In their simulation, on the other hand, the time was greater than zero, since the charge was moving in the force-free region first.

The students kept making minor changes to the program and executed the simulation to check whether the problem was solved. After two more lessons they decided to abandon the subject and develop a new simulation.

4.2 General Findings

The other five projects were analyzed in a manner similar to that of the two case studies. In all projects a development of students' conceptual knowledge was evident. As the work on the projects progressed, students' concept maps improved and became more similar to the corresponding expert map. Our findings indicated that this development was fostered by the need to program a physics phenomenon and represent it as a simulation. In particular, the following patterns, which were demonstrated in the two case studies above, were also found in other projects:

Understanding the time dependency of physical processes. In both case studies, the students' initial concept map did not contain a link representing time dependency, but such a link was present in the consequent maps. This was the also case for other projects. Most of the simulations designed by the students represented physical processes that progress in time. For this reason, simulations' design demands an explicit use of the time variable and loops. The loops may be implicit in the software (as in EJS) or explicitly written by the students (as in Maxima). In both cases, recognizing the need for such loops is related to students' better understanding of time dependency, an understanding that is known to be hard for physics students [2].

*Understanding the meaning of the components in a formula***.** In both case studies, the students' concept maps depicted a misunderstanding or a partial understanding of the meaning of a certain variable (which represents a component in the formula that corresponds to the simulation) that was later resolved. This was also evident in the other projects. All the students worked with formal physics formulas that they later translated into programming statements. One of the initial phases in program design is declaring the variables that represent the physics variables, and deciding on their type (integer or float). Even this simple action forced the students to try and understand the meaning of the programming variables and consequently the physics ones.

Understanding the cause and effect relationships in the formula. In both case studies an understanding of the cause and effect relationships in the formula developed during the work on the project. In the first case study these were cause and effect relationships between the discus velocity relative to the air and the aerodynamic forces. In the second case study these were the cause and effect relationships between the direction of the magnetic field, the direction of the force, and the direction of the charge's motion. Many times students started the projects with a vague understanding of the physics formulas, as also reported in the literature [2]. The "step by step" nature of the algorithm and the resulting program, in which a single-line physics equation needs to be implemented in several program lines, forces the students to decide what is the cause in the formula and what is the effect. This is in contrast with the mathematical notation that uses the equality sign and does not indicate the direction of the causality.

5 DISCUSSION

This research focused on gifted high-school students who participated after regular school hours in an elective 3-year computational-science course (for which they earned credit reflected in their matriculation diploma). They combined physics, mathematics, and computer science in order to learn computational models and computational methods. We investigated the relationships between the computational environment, CS and the physics conceptual knowledge that the students gained.

Programming physical phenomena is a complex activity. On the one hand, it puts an extra load on the students. It may confuse the students and prevent them from focusing on aspects of physics. Evidence for this claim was included in the descriptions of both case studies presented in the paper and was found in other cases that we analyzed. Using improper names for programming variables, lack of debugging skills, and more were found to prevent the students from achieving some physical insights.

On the other hand, programming forces the students to unfold the physical meanings and relationships expressed in the formulas. It motivates students to deal with difficult physics knowledge and causes them to feel obligated to design correct simulations. Moreover, programming simulations provides context-rich problems similar to real-life situations. Students' conceptual knowledge in physics was found to develop even regarding concepts that are known in the literature to be difficult. Within the limitations of an exploratory qualitative study, it is reasonable to attribute this learning to the computational science course and the unique learning scenarios it has enabled.

Physics and computational-science instructors face a dilemma when considering the inclusion of programming sessions in physics classes. Our observations lead us to hypothesize that one of the major problems students face when combining these three disciplines is related to cognitive load [6]. Three types of cognitive load are described in the literature: intrinsic, extraneous [6], and germane [44]. Intrinsic load is the level of difficulty inherent to the learning task, extraneous load is generated by the manner in which the information is presented to the learner, and germane load is the load devoted to the processing, construction and automation of schemata. Thus, intrinsic and extraneous are the "bad" loads and germane is the "good" one, since instructional effort should be put in creating schemata of information to make the learning efficient.

Learning within multiple disciplines (CS, physics and mathematics) may cause intrinsic load, since each discipline is difficult by itself. Moreover, it may cause extraneous load as well, due to the instruction of three different disciplines at the same time.

One of the possible ways to reduce the extraneous load would be to provide the students with more intensive physics training. Some of the training may take place apart from programming, so that students would have a chance to understand the physics aspects before they mix it with programming. This recommendation is compatible with the teacher's claim that the students lacked proper physics knowledge when programming the simulations. Similarly, the students should be taught CS strategies separately, possibly after learning some of the physics content.

The research presented in this paper explored the evolution of conceptual knowledge in physics during the programming of computational models. Other studies explored *what* elements in the computational-science environment affected this evolution (removed for anonymity). We did not, however, refer to other factors that may have been related to the students' learning. Further research is needed to explore the possible relationships among other factors and the students' learning, such as them being gifted or learning in pairs.

Another important aspect that was not addressed here is the evolution of the students' CS learning. A large portion of the class time was spent on learning programming aspects. The question of the influence of the physics context on CS learning is one that would definitely interest CS educators and may affect the instruction of the discipline.

REFERENCES

[1] Abelson, Harold, Sussman, Gerald Jay, and Sussman, Julie. 1996. *Structure and interpretation of computer programs* (2^{nd} Ed.). Cambridge, MA: MIT Press, Cambridge, MA, USA.

[2] Bagno, Esther, Berger, Hana, and Eylon, Bat Sheva. 2008. Meeting the challenge of students' understanding of formulae in high-school physics: a

learning tool. *Physics Education,* 43, 1 (Jan. 2008), 75-82.
[3] Bagno, Esther, and Eylon, Bat Sheva. 1997. From problem solving to a knowledge structure: An example from the domain of electromagnetism. *American Journal of Physics,* 65, 8 (Aug. 1997), 726-736.
[4] Chabay, Ruth, & Sherwood, Bruce. 2008. Computational physics in the introductory calculus-based course. *American Journal of Physics*, 76, 4 (Apr. 2008), 307–313.
[5] Chabay, Ruth. W., and Sherwood, Bruce. A. 1994. *Electric and magnetic interactions*. Wiley, New York.
[6] Chandler, Paul, and Sweller, John. 1991. Cognitive load theory and the format of instruction. *Cognition and Instruction,* 8, 4, 293–332.
[7] Chang, Huey-Por, Chen, Jun-Yi, Guo, Chorng-Jee, Chen, Chung-Chih, Chang, Ching-Yi, Lin, Shean-Huey, . . . Tseng, Yaw-Teng. 2007. Investigating primary and secondary students' learning of physics concepts in Taiwan. *International Journal of Science Education,* 29, 4, 465-482.
[8] Chi, Michelene T. H., Feltovich, Paul J., and Glaser, Robert. 1981. Categorization and representation of physics problems by experts and novices. *Cognitive Science,* 5, (Apr.-Jun. 1981), 121-152.
[9] Christian, Wolfgang, and Esquembre, Francisco. 2007. Modeling physics with easy Java simulations. *The Physics Teacher,* 45, 8 (Nov. 2007), 475-480.
[10] De Jong, Ton, and Van Joolingen, Wouter R. 1998. Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, 68, 2 (Jun. 1998), 179–201.
[11] Détienne, Françoise. 1990. Expert programming knowledge: a schema-based approach. In J-M Hoc, T.R.G. Green, R. Samurcay, and D. Gilmore (Eds.), *Psychology of Programming*. Academic press, London, 205-222.
[12] Esquembre, Francisco. 2004. Easy Java Simulations: A software tool to create scientific simulations in Java. *Computer Physics Communications,* 156, 2 (Jan. 2004), 199-204.
[13] Eylon, Bat Sheva, and Ganiel, Uri. 1990. Macro- micro relationships: the missing link between electrostatics and electrodynamics in students' reasoning. *International Journal of Science Education,* 12, 1, 79-94.
[14] Galili, Igal. 1996. Students' conceptual change in geometrical optics. *International Journal of Science Education,* 18, 7, 847-868.
[15] Galili, Igal, and Hazan, Amnon. 2000. Learners' knowledge in optics: interpretation, structure and analysis. *International Journal of Science Education*, 22, 1, 57–88.
[16] Ghaffar, Munazzah Abdul., Iqbal, M. Ashraf., and Hashmi, Yasser. 2007. Meaningful learning of problem transformations for a grid graph. In *Proceedings of the International Conference on Engineering Education (*ICEE 2007).
[17] Guisasola, Jenaro, Almudi, Jose M., and Zuza, Kristina. 2013. University students' understanding of electromagnetic induction. *International Journal of Science Education*, 35, 16, 2692–2717.
[18] Gunstone, Richard F., and White, Richard. T. 1981. Understanding of gravity. *Science Education,* 65, 3 (Jul.. 1981), 291-299.
[19] Halloun, Ibrahim Abou, and Hestenes, David. 1985. The initial knowledge state of college physics students. *American Journal of Physics*, 53, 11 (Nov. 1985), 1043–1055.
[20] Hasemann, Klaus, and Mansfield, Helen. 1995. Concept mapping in research on mathematical knowledge development: backgrounds, methods, findings and conclusions. *Educational Studies in Mathematics* 29 (Jul.. 1995), 45-72.
[21] Jacobs-Lawson, Joy M. and Hershey, Douglas. A. 2002. Concept maps as an assessment tool in psychology courses. *Teaching of Psychology,* 29, 1 (Jan. 2002), 25-29.
[22] Jasien, Paul. G., and Oberem, Graham. E. 2002. Understanding of elementary concepts in heat and temperature among college students and K-12 teachers. *Journal of Chemical Education,* 79, 7 (Jul. 2002), 889.
[23] Linn, Marcia C., and Eylon, Bat Sheva. 2006. Science education: integrating views of learning and instruction. In *Handbook in Educational Psychology*, Patricia. A. Alexander and Philip. H. Winne (Eds.). Lawrence Erlbaum Associates, Mahwah, NJ, USA, 511-544.
[24] Linn, Marcia C., and Eylon, Bat Sheva. 2011. Science Learning and Instruction: Taking Advantage of Technology to Promote Knowledge Integration. Routledge, New York.
[25] Lomask, M., Baron, J.B., Greig, J., and Harrison, C. 1992. ConnMap: Connecticut's use of concept mapping to assess the structure of students' knowledge of science. Presented at the Annual Meeting of the National Association of Research in Teaching (March, 1992, Cambridge, MA, USA).
[26] McCloskey, Michael. 1983. Naive theories of motion. In *Mental models*, Dedre Gentner and Albert L. Stevens (Eds.). Lawrence Erlbaum Associates, Hillsdale, NJ, USA, 299–324.
[27] McClure, John R., Sonak, Brian, and Suen, Hoy. K. 1999. Concept map assessment of classroom learning: Reliability, validity, and logistical practicality. *Journal of Research in Science Teaching,* 36, 4 (Mar. 1999), 475-492.
[28] McDermott, Lillian. C. 1984. Research on conceptual understanding in mechanics. *Physics Today*, 37, 7 (Jul. 1984), 24–32.
[29] Novak, Joseph D., and Cañas, Alberto. J. 2008. The theory underlying concept maps and how to construct and use them. *Florida Institute for Human and Machine Cognition Pensacola.* Retreived August 29, 2017, from http://cmap.ihmc.us/docs/theory-of-concept-maps.
[30] Novak, Joseph D., and Gowin, D. Bob. 1984. *Learning how to learn*. Cambridge University, Cambridge, UK.
[31] Papert, Seymour. 1981. Mindstorms: children, computers, and powerful ideas. Basic Books, New York.
[32] Pearsall, N. Renne, Skipper, Jo. El J., and Mintzes, Joel. J. 1997. Knowledge restructuring in the life sciences: A longitudinal study of conceptual change in biology. *Science Education,* 81, 2 (Apr., 1997), 193-215.
[33] Peterson, Ray, and Treagust, David, F. 1995. Developing preservice teachers' pedagogical reasoning ability. *Research in Science Education,* 25 (Sep. 1995), 291-305.
[34] Peterson, Ray, and Treagust, David, F. 1998. Learning to teach primary science through problem-based learning. *Science Education,* 82, 2 (Dec. 1998), 215-237.
[35] Redish, Edward F., and Wilson, Jack M. 1993. Student programming in the introductory physics course: MUPPET. *American Journal of Physics*, 61, 3 (Mar. 1993), 222-232.
[36] Ruiz-Primo, Maria. 2000. On the use of concept maps as an assessment tool in science: What we have learned so far. *Revista Electrónica de Investigación Educativa,* 2, 1, 1-24.
[37] Rutten, Nico, van Joolingen, Wouter R., and van der Veen, Jan T. 2012. The learning effects of computer simulations in science education. *Computers & Education,* 58, 1 (Jan. 2012), 136-153.
[38] Savinainen, Antti, Mäkynen, Asko, Nieminen, Pasi, and Viiri, Jouni. 2012. An intervention using an Interaction Diagram for teaching Newton's third law in upper secondary school. In *Physics Alive. Proceedings of the GIREP-EPEC 2011 Conference*. (Aug., 2012), 123-128.
[39] Shaffer, Peter. S., and McDermott, Lillian. C. 1992. Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies. *American Journal of Physics,* 60, 11 (Nov. 1992), 1003-1013.
[40] Shaffer, Peter S., and McDermott, Lillian C. 2005. A research-based approach to improving student understanding of the vector nature of kinematical concepts. *American Journal of Physics,* 73, 10 (Oct. 2005), 921-931.
[41] Sherin, Bruce. L. 2001. A comparison of programming languages and algebraic notation as expressive languages for physics. *International Journal of Computers for Mathematical Learning,* 6, 1 (May. 2001), 1-61.
[42] Sloot, Peter. (n.d.). Aims & scope of the Journal of Computational Science. Retreived August 29, 2017, from http://www.elsevier.com/wps/find/journaldescription.cws_home/721195/description.
[43] Stoddart, Trish, Abrams, Robert, Gasper, Erika, and Canaday, Dana. 2000. Concept maps as assessment in science inquiry learning - a report of methodology. *International Journal of Science Education,* 22, 12 (Dec. 2000), 1221-1246.
[44] Sweller, John, van Merriënboer, Jeroen J. G., and Paas, Fred. 1998 Cognitive architecture and instructional design. *Educational Psychology Review* 10, 3 (Sep. 1998), 251-296.
[45] Thomaz, Marília F., Malaquias, I. M., Valente, M. C., and Antunes, M. J. 1995. An attempt to overcome alternative conceptions related to heat and temperature. *Physics Education,* 30, 1 (Jan. 1995), 19-26.
[46] Trowbridge, David E., and McDermott, Lillian C. 1980. Investigation of student understanding of the concept of velocity in one dimension. *American Journal of Physics,* 48, 12 (Dec. 1980), 1020-1028.
[47] Yasar, Osman, and Landau, Rubin. 2003. Elements of computational science & engineering education. *SIAM Review* 45, 4, 787-805.