Unfolding the Curriculum: Physical Computing, Computational Thinking and Computational Experiment in STEM's Transdisciplinary Approach

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Abstract—The aim of the present article is to analyze the relation of physical computing with the computational thinking dimensions and the transdisciplinary approach of STEM epistemology in inquiry-based learning environments, when the methodology of the computational experiment is implemented. We argue that computational science and computational experiment can be applied in connection with STEM epistemology, when physical computing activities are embedded in the curriculum for Higher Education students. In order to implement this connection, we present software applications that combine algorithms and physical computing. We believe that engaging students through their existing STEM courses in physical computing - in the form of the computational experiment methodology- is a strategy that is much more likely to succeed in increasing the interest and appeal of STEM epistemology. Different learning modules were designed, which covered the combination of easy java simulations (Ejs) with Arduino and Raspberry pi.

Index Terms—Computational Experiment; Computational Thinking; STEM Epistemology; Physical Computing.

I. INTRODUCTION

A. Computational Science (CS)

Computational Science (CS) is the integration of Mathematics, Computer Science and any other discipline to explore “real world” problems. It is defined as a multidisciplinary activity, which brings together concepts from a variety of cognitive subjects [12] and is considered to be part of the Computational Science-Engineering (CSE) community. CS helps learners solve a STEM problem using computational models and this includes tasks like: formulating the problem in a way proper for development of models of simulations, selecting an efficient algorithm; collecting numerical data; analyzing the data obtained; discovering the solution of the problem. One of the essential components of CS is the transformation of a real phenomenon to an abstract model and its execution as a computational model. This leads us to the notion of the computational experiment (CE), where the model and its

corresponding simulation “substitute” the “hands-on” experiment [18], [19]. According to Landau et.al. [12], CS suggests the following steps for problem-solving a. Definition of the Problem (from science/real world); b. Modeling the problem (introduction of the mathematical relations between selected variables); c. Selection of the Simulation Method (determination of time dependence of the state variables, selection of discrete, continuous or stochastic processes); d. Creation of the algorithm based on selected numerical analysis methods; e. Implementation of the algorithm in source code (using computer languages); and f. Evaluation of the results and comparison with real data.. Later on, when we will discuss computational thinking (CT), it will be quite apparent that CS shares many commonalities with CT and may serve as the background platform to implement didactic models that include the dimensions of CT and STEM epistemology.

B. Computational Thinking (CT)

Jeanette Wing [24] introduced the term 'computational thinking' (CT) in an article published in Communications of the ACM. CT involves solving authentic problems, designing systems and understanding human behavior by drawing on the concepts fundamental to computer science. Despite this extensive interest, successful CT integration in education still faces unresolved issues and challenges [9]. According to the literature, CT includes: abstraction, algorithmic thinking, decomposition, debugging, pattern recognition and generalization [1], [3].

C. The inquiry-based teaching and learning approach

Inquiry-based learning is considered as a didactic model for improving the teaching and learning of STEM disciplines [6] and can be defined as the process of identifying problems, reviewing experiments, selecting alternatives, designing investigations, developing conjectures, searching for data, developing models, communicating with peers and constructing consistent arguments [5]. Bell et al. [4], identified nine main science inquiry processes, that could be used in inquiry-based STEM disciplines, namely: orienting and asking questions; generating hypotheses; planning; investigating; analyzing and interpreting; exploring and creating models; evaluating and concluding; communicating; predicting. The nine inquiry tools of Bell et al. [4] are connected to the essential features of Inquiry [2], namely: Question (Learner engages in scientifically oriented questions); Evidence (Learner gives priority to data collection); Analysis (Learner analyses the data to form evidence); Explain (Learner develops

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explanations from evidence); Connect (Learner connects explanations to scientific knowledge); Communicate (Learner communicates and justifies explanations); and Reflection (Learner engages in metacognitive experiences).

D. The Computational Experiment (CE) approach combined with Inquiry-Based teaching and learning approach

In order to effectively implement the inquiry-based learning as a didactic model, Klahr & Dunbar [11], introduced two “spaces”, the hypothesis and the experimental spaces. Psycharis [20] added one more space, the “prediction space”, in order to introduce the process of modeling and the comparison of data produced by the model with real data taken from a simulation or from a physical computing activity. In the “prediction space”, the CS methodology is implemented through the development of models of simulations that include all or some of the dimensions of the “Computational Thinking (CT)”. According to Psycharis [18],[19]), the three spaces of the CS methodology should include dimensions from CT, namely: logically collecting, organizing and analyzing data; representation of data in forms suitable for analysis and exploration, development of abstract models, creation of simulations; and algorithmic thinking (a series of ordered steps) as they are also suggested by the International Society for Technology in Education (ISTE) and the Computer Science Teachers Association (CTSA) (<http://www.iste.org/docs/ct-documents/computational-thinking-operational-definition-flyer.pdf?sfvrsn=2>, Last Access, 31 May, 2016).

In this context, the three spaces of the CS methodology include:

- 1) The hypotheses space, where the students –usually under the guidance of the teacher–state the hypotheses of the problem to be studied, as well as the variables included in the problem and the possible relations between the variables.
- 2) The experimental space, which includes the “numerical” model and the method of simulation for the problems under study. In this space, the learners are engaged in the scientific method writing their models, according to the variables selected and the interaction laws (e.g. from Physics) that govern the phenomenon. In this space, students collect the data from their model and analyze them; while they attempt to connect their explanations with the theory they have been taught.
- 3) The prediction space, where the results, conclusions or solutions formulated in the experimental space, are compared with the analytical (Mathematical) solution, as well as with data from the real world. Students would also make logical arguments about the generalization of their results and whether the results have been impacted by their hypothesis and the variables they have chosen. Generalization is closely linked to one of the dimensions of CT.

In Table II, we propose an interrelation between the spaces of the CE and the features and the tools of inquiry.

E. STEM epistemology

STEM methodology follows the so-called

transdisciplinary approach, which focus on the “integrated” approach to teach the four disciplines included in the STEM cognitive areas. According to Kelley & Knowles [10], STEM methodology includes: Situated Learning; the Engineering Design and Making; the Scientific Inquiry and the Mathematical Thinking and Logical Thinking, as an integrated system. A pedagogy referred to as “Purposeful Design and Inquiry” (PD&I), is considered as an important component of integrative STEM education. PD&I pedagogy combines technological design and making with the inquiry based learning, engaging students in inquiry, situated in the context of the problem-solving process [22].

TABLE I: THE INTERRELATION OF THE CE SPACES, THE INQUIRY-METHOD FEATURES AND THE INQUIRY TOOLS

Spaces of the Computational Experiment [20]	Essential Features of Inquiry [2])	Inquiry tools [4]
Hypotheses space	Question	Orienting and asking questions; generating hypotheses Planning-Investigating
Experimental space	Evidence Analyze Explain	Analysis and interpretation Modeling
Prediction Space	Connect Communicate	Conclusion-Evaluation-Prediction

F. Physical Computing

Recently, education researchers have adapted the term physical computing and they are now using it in a wider meaning. Specifically, they consider physical computing as a way to use computers to collect data received by the physical/real world [13]. Physical computing can be implemented in computer science by using it in order to teach computer science concepts [16]. Physical computing is considered as a proper tool in order to combine digital elements with the real world, as it develops a communication between the physical world and the digital world of the computer [23]. Physical computing takes the computational concepts into the real phenomenon so that the student can use them in an authentic environment Physical computing activities are strongly connected to the dimensions of CT, namely: abstraction; algorithmic thinking; automation; decomposition; debugging; and generalization.

G. Physical Computing: unplugged, making, tinkering and remixing

According to Namukasa et al. [14], there are four pedagogical stages of learning in order to think computationally when learners are engaged in physical computing, namely: (1) unplugged; (2) making; (3) tinkering; and (4) remixing (or “hacking”). Unplugged activities can be implemented without the use of computers and can be used to engage in CT dimensions (e.g. abstraction), as well as to enhance subject knowledge, often embedding and augmenting computer science concepts into the curriculum [8]. These constructivist activities are often kinesthetic in nature and make abstract concepts both tangible and visible [8].

Making is a technical term used to refer to activities of

individuals or groups of people who, inspired by technology, “work” with things, make things, take things apart and want to develop things that solve problems. In making, they engage in practices, such as prototyping and testing products, methodologies used by engineers. Digital making can be used to engage students in CT dimensions, such as sequencing, recursion, decomposition and debugging [17].

When mentioning about tinkering, Papert [15] described learning as consisting of building up a set of materials and tools that one can handle and manipulate. The main idea of tinkering is to encourage students to use materials as tools to represent/implement the dimensions of CT. Commonly and widely used and known computer programming software for children and novices, useful for tinkering, are: the Scratch (<https://scratch.mit.edu/>), Scratch for Arduino (<http://s4a.cat/>), Ardublock (<http://blog.ardublock.com/>) and Easy Java Simulations (Ejs). Arduino and Raspberry pi platforms are also considered as essential tools to implement tinkering. These can enable students to easily see the connection between changes in the program and the corresponding changes in the data received from the physical model/real world. Activities can be created that need the implementation of an algorithm and the development of programming in order to guide a robot through an obstacle course or programming the Arduino or Raspberry pi to reveal specific patterns.

TABLE II: A MODEL FOR THE CONNECTION BETWEEN CT, CE AND PHYSICAL COMPUTING

Spaces of the Computational Experiment	Essential Features of Inquiry – Physical Computing-Dimensions of CT	Inquiry tools
Hypotheses space	Essential Features of Inquiry Question Physical Computing Unplugged activities Dimensions of CT Abstraction, decomposition	Orienting and asking questions; generating hypotheses

Lastly, Remixing involves proficiency in examining a source code with a critical eye, as well as modifying, debugging and manipulating the code to adjust it to new situations. When students are engaged in coding, they develop their creative thinking by proposing new solutions and alternatives. Scratch can be used for remixing, since, according to Resnick et al. [21], community members are constantly borrowing, adapting and building on one another's ideas, images, and software programs. Physical computing covers the design, making and implementation of interactive objects and allows students to develop concrete products and artefacts of the real world, which are in alignment with the dimensions of CT. Physical computing can be used in STEM education as an educational activity, grounded in students' interests and creativity.

H. Computational Science, Inquiry-based approach, Computational Thinking and Physical Computing in STEM epistemology. An integrated model

We will now propose an integration of the CE, the physical computing, the STEM epistemology and the

dimensions of CT and present our results in a form of a Table (Table II).

II. MATERIALS AND DIDACTIC ACTIVITIES

A. Software and Materials used

Here, we will present some experiments-activities that connect the CE, CT and Physical computing using in some examples the software Ejs (<http://www.um.es/fem/EjsWiki/>). Easy Java simulation (Ejs) software does not demand knowledge of the programming language Java and its interface is not difficult for use, since it resembles the interface the students have met in traditional lectures embedded with specific tools to write down mathematical expressions. Arduino (<https://www.arduino.cc/>) is an open hardware platform that is becoming increasingly popular within the education community. The creators of Arduino designed a very easy-to-use platform and due to its open-source nature, it is supported by a massive user community who share their ideas, projects and solutions. Raspberry pi is an open hardware platform that can be used to control physical objects, while it has the advantage to operate as computer and not only as controller (as Arduino does).

B. Didactic Activities

1) Visualization of Sorting algorithms (Activity 1)

Given that students face difficulties with the concepts of the “variable” and the algorithm, researchers have turned their focus on the “use” of CT to resolve such problems. CT poses an important question to researchers: *What are the proper ways to teach fundamental computing concepts to students?* Visualization is suggested as one way of supporting student learning [7]. In this activity, we will use Ejs to help students understand the sort algorithms using the visualization capacity provided by the “view” element of Ejs. You can visit the link (<http://www.opendiscoveryspace.eu/edu-object/algorithmos-taxinomis-fysalidas-me-ti-hrisi-ejss-848384>, Last Access 15 June 2017) to explore and download the algorithm and the source code for the visualization of the bubble sort algorithm. This application was developed by one of the authors (Psycharis) and an MSc student (Mastorodimos Dimitrios). Initially, we presented the video to students (as an unplugged activity) about Hungarian dance and its connection to bubble sort algorithms in order for them to make hypotheses about the way the sorting algorithms work. This activity also enhances the abstraction dimension of students. At the next phase (the experimental phase), we developed the source code in Ejs, in order to connect Ejs with Arduino. The algorithm and part of the source code developed are presented below. The reader can find the algorithm and the source code at this link: <http://www.opendiscoveryspace.eu/en/edu-object/algorithmos-taxinomis-fysalidas-me-ti-hrisi-ejss-848384>.

During the experimental phase of the CE, students used the essentials features of inquiry-based teaching approach (evidence, analysis, explanation), the algorithmic thinking of CT and they participated in the development of the source code. For the physical computing part, they had to classify

in order 20 CDs and they tried to reproduce the steps of the algorithm, in order to sort the CDs according to the algorithm. At the prediction phase, they communicated their result and they tried to find examples to generalize their code. They proposed examples of sorting from real life, like the Hungarian dance (Fig. 1).

Fig. 1. The running of the model. During the running colors were changed according to the comparison between them

2) Control of LED using Ejs and Arduino (Activity 2)

In this activity, students controlled a LED using Ejs (Fig. 2).

Fig. 2. Connection of Ejs with Arduino

In this activity, students were engaged in many dimensions of physical computing (i.e. design/making) and in almost all dimensions of CT. For example, they used the CT concept of abstraction when they thought about the possibility to switch on a LED remotely, the design of the circuit; the algorithmic thinking and the generalization (for example, how we can extend this simple example in order to control traffic lights). We also presented the same application using the Scratch for Arduino, where the control of the LED is done from the keyboard (Fig. 3).

1) Activity 3

In this application, we used the Raspberry pi in order to control the motion of four graphical elements using Scratch (Fig. 4).

2) Activity 4

This activity is an unplugged activity. Students were asked to construct (design and make) the following robotic arm (Fig. 5).

Fig. 3. Control of the LED from the keyboard using Scratch4A(<http://s4a.cat/>)

Fig. 4. A simple video game using Raspberry pi

Fig. 5. An unplugged activity

During the activity, students had to be engaged in the features of the inquiry-based teaching and learning approach and the physical computing activities (design/make). Students also had the chance to be engaged in CT dimensions, as they had to think in abstraction for the different parts of the arm, to decompose the system and use logical reasoning to explain its motion.

III. PRELIMINARY RESULTS -DISCUSSION

We focused on physical computing, which involves building interactive physical systems, which can sense and respond to the measurements received from the Analog world. We then developed applications created by Raspberry Pi and Arduino and controlled by Ejs or Scratch. This work proposes a model that combines the phases of the CE with the dimensions of CT and the dimensions of physical computing. We implemented –as a preliminary work- the above activities to postgraduate students, who study for their MSc degree in STEM, and prospective trainee teachers. We followed the qualitative approach and in the future, we aim to extend our research to a bigger sample with quantitative tools like a questionnaire for CT. After the instructional intervention, eight students were selected for semi-structured interviews. The results showed that the intervention based on the visualization method resulted in significantly better acquisition of sorting concepts. The qualitative data analysis indicated that

students constructed proper abstractions through their engagement in visualization algorithmic activities, mainly due to Activity 1. All students expressed the view that framing the activities in the three phases of the computational experiment and organizing the tasks in each phase for CT and physical computing, made them more organized and they considered that this connection was also helpful in their preparation for organizing a lesson plan. Students felt that in the experimental phase of the CE, they had a lot of degrees of freedom to develop the dimensions of CT (mainly the logical reasoning, the development of algorithm and decomposition) and also that they could propose the design of artefacts. Some students expressed the view that sometimes unplugged activities can form a good guideline to understand the physical process before they try to transfer the problem in computing. All students considered the above activities as a good starting point and they continued their work developing new applications connecting Scratch or Ejs with Arduino and Raspberry. For example, one such activity can be found at: <http://portal.opendiscovery.space.eu/edu-object/heat-transfer-conduction-monitoring-tool-844601>, which studies the transfer of heat using Arduino and Ejs. Another artifact was based on the Balak Ram theorem (http://page.mi.fu-berlin.de/bhrnds/publ_papers/behrends_humble.pdf).

The authors of this study argue that students' active engagement in inquiry-based activities that combine the CT and physical computing dimensions in a CE setting, could help them increase their self-efficacy and internal motives for STEM epistemology (work in progress). Another research in progress is related to a quantitative research of: "What effects does physical computing have on the dimensions of computational thinking, when the transdisciplinary approach is implemented in inquiry based learning environments?"

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