

DOI: 10.5281/zenodo.1214565

# STEAM IN EDUCATION: A LITERATURE REVIEW ON THE ROLE OF COMPUTATIONAL THINKING, ENGINEERING EPISTEMOLOGY AND COMPUTATIONAL SCIENCE. COMPUTATIONAL STEAM PEDAGOGY (CSP)

Sarantos Psycharis

*Department of Education, School of Pedagogical & Technological Education (ASPETE)  
Heraklion Attikis, 141 21 Athens, Greece  
(spsycharis@gmail.com)*

Received: 03/03/2018

Accepted: 05/04/2018

---

## ABSTRACT

Here we discuss the role of Computational Thinking (CT), Engineering Education Epistemology (EEE) , Computational Science Education (CSE) and the integration of Arts with STEM in education and more generally in learning and teaching approaches and learning objectives. We present arguments from research articles and we propose activities that support our model for Computational STEAM Pedagogy. The purpose of the literature review is to outline research studies in the different forms of STEAM integration and to highlight how CT, EEE, CSE and Arts can be used in this integration and what epistemology can support this holistic approach . The main objective is to summarise what is currently known about the STEAM approaches and to add to the existing literature with a primary model which connects EEE with the Computational pedagogical knowledge mode. The bibliography presents materials covering theoretical considerations around Computational Thinking, Engineering Epistemology, STEM Epistemology, Computational Science in Education and Arts in STEAM. Literature review was conducted using several web-based search engine tools like Web of Science, Google Scholar and open Google searches.

---

**KEYWORDS:** STEM epistemology, Computational pedagogy, Epistemology, Engineering epistemology, CSP, Computational thinking, Computational experiment, Engineering education, Arts, STEAM

---

## 1. INTRODUCTION

There is a debate in education for the STEM to STEAM movement and the impetus to include the arts in science, technology, engineering, and math learning (Maeda, 2013).

Research also suggests that (Ghanbari, 2015) “the arts are well-suited to be combined with science, technology, engineering, and math disciplines making the STEM acronym STEAM”. The STEAM paradigm also emphasizes the importance of STEM education, but argues that the arts have the ability to open up new ways of seeing, thinking, and learning”.

Studies have also suggested that “learning through the arts has the ability to transcend across different disciplines and enrich learning in disciplines beyond the arts’ (e.g. Hetland, 2013).

STEAM can be considered as an educational teaching and learning approach that can integrate in a transdisciplinary epistemology STEM disciplines with Art that can enhances students’ inquiry skills, problem solving skills and creative thinking while the STEM to STEAM movement can offer news insights and new “vocabulary” in transdisciplinary thinking. This transdisciplinary coupling of broad STEM disciplines with Culture and Arts – is unfolded below in the form of literature review.

## 2. COMPUTATIONAL THINKING

### 2.1 Computational Thinking in general

In 2006, Wing published an article which coined the term Computational Thinking, in the Journal of the Association for Computing Machinery (ACM). Wing suggested that computational thinking involves solving problems, designing systems, and understanding human behaviour, by drawing on the concepts fundamental to computer science while later (Wing, 2008). She argued that “CT is a universal skill and attitude that complements thinking in mathematics and engineering with a focus on designing systems that help to solve complex problems humans face” (Wing 2008).

Lu & Fletscher (2009) argue that “teaching CT should focus on establishing vocabularies and symbols that can be used to annotate and describe computation and abstraction, suggest information and execution, and provide notation around which mental models of processes can be built”.

The concept that CT is a universal skill, attitude, competency practice and problem solving approach that impacts nearly all disciplines was suggested by many researchers in the field.

Bundy (2007) stated that “the ability to think computationally is essential to conceptual understanding in every field, through the processes of

problem solving and algorithmic thinking”. He also spoke about “the e-Science and he stated that researchers are using computational metaphors to enrich diverse theories while computing leads to new kinds of questions and the acceptance of new kinds of answers, for instance, questions that require the processing of huge amounts of data”. The emphasis on “big data” appears in many research papers and currently there is a lot of research for big data and learner analytics in education.

As we will present later, collection and analysis of data is a fundamental skill in CT and can be used in every discipline and is related to STEM.

Glass (2006), consider that “CT is not problem solving, since computers rarely compute but do manipulate information and computer science concepts can certainly be part of such a course, but problem solving is a universal activity, and many disciplines are capable of teaching it”.

There is a lot of discussion about the skills, attitudes, competences and practices that they should be included in CT, while there is also a discussion if CT is a problem-solving process. NRC (2010) suggested “20 high-level skills and practices that computational thinking might include, like problem abstraction and decomposition, reasoning, optimization, association reuse or sharing (from the engineering design), coding, and knowledge of computer science concepts like parallel processing, machine learning, systematic processing of information, symbol systems and representations, debugging and error detection, and recursion”. NRC (2010) speaks about concepts from Computer Science, while many researchers put an emphasis on the fact that “Despite the obvious relevance of CT to computer science, scholars argue that CT needs to be taught in disciplines outside of computer science beginning in kindergarten” (Kotsopoulos et al. 2017; Barr & Stephenson 2011; Yadav et al. 2011)

### 2.2 Computational Thinking. The concepts of Computing, Computation and Computational

There is a lot of research about CT and computing and computation. Research papers use sometimes these concepts as they are similar while some others differentiate them (implicitly or explicitly).

We will try to delineate these terms, since their concise definitions will help us to proceed towards the Computational Science Education.

According to Wing (2008) “computing” is the field that encompasses computer science, computer engineering, communications, information science and information technology. Wing (2006) also stated that the advances in computing would allow researchers

to envision new problem-solving strategies and to test new solutions in both the virtual and real world.

Bundy (2007) does not define computing but he states that “Computing has enabled researchers to ask new kinds of questions and to accept new kinds of answers, for instance, questions that require the processing of huge amounts of data”.

Katehi et al. (2009) include “computing” in the framework of engineering design, applications for the mathematics (e.g., plotting signals, computing Cartesian coordinates).

The report “Computing at School Working Group (2012), report endorsed by BCS, Microsoft, Google and Intellect, March, 2012 Retrieved from: <https://www.computingschool.org.uk/data/uploads/ComputingCurric.pdf>”, states that “The Computing at School Working Group recognizes that Computer Science (CS) and Information Technology (IT) are disciplines within Computing that, like maths or history, every pupil should meet at school.” At this seminal report we notice that computing includes Computer Science and Information Technology.

In the report “After the reboot: computing education in UK schools Issued: November 2017 DES4633 ISBN: 978-1-78252-297-3”, computing is a subject that covers the areas of computer science, digital literacy and information technology (IT). In the same report there is a very precise terminology for Information Technology, as “the assembly, deployment and configuration of digital systems to meet user needs for particular purposes, Digital Literacy, as the basic skill or ability to use a computer confidently, effectively and safely, including the ability to use office software such as word processors, email and presentation software, and the ability to use a web browser and internet search engines, and Computer science, covering principles such as algorithms, data structures, programming, systems architecture, design and problem-solving”.

We observe that there is, yet, no widely agreed definition of computing, and there is also no agreed definition for the Computer Science too. Denning (2003) posited that “computer science consists of mechanics (computation, communication, coordination, automation, and recollection), design principles (simplicity, performance, reliability and security) and practices (programming, engineering systems, modeling and validation, innovating, and applying)”.

However, according to Tucker et al. (2003), “Computer Science is neither programming nor computer literacy, but it is the study of computers and algorithmic processes including their principles, their hardware and software design, their applications, and their impact on society”.

Kallia (2017) states that “evaluation of students’ knowledge and learning in computing courses is challenging where there is a notice about the computing curriculum”.

According to (ACM Pathways 2013), “by 2020, one of every two jobs in the “STEM” fields will be in computing”.

The term computation appears also in research papers. For example, Jona et al. (2014) state that “Computation is an indispensable component of STEM disciplines as they are practiced in the professional world. In the last twenty years, nearly every STEM field has seen the birth or reconceptualization of a computational counterpart, from Computational Engineering and Bioinformatics to Chemo metrics and Neuroinformatics. In this article we notice that computation is related to computational”.

According to Weintrop et al. (2015), “bringing computational tools and practices into mathematics and science classrooms gives learners a more realistic view of what these fields are, better prepares students for pursuing careers in these disciplines” and from a pedagogical perspective, the thoughtful use of computational tools and skill sets can deepen learning of mathematics and science content (e.g. National Research Council 2011a, b).

As stated in Barr & Stephenson (2011), Computer Science is related to computational processes and “scientists can promote understanding of how to bring computational processes to bear on problems in other fields and on problems that lie at the intersection of disciplines. For example, bioinformatics and computational biology are different, but both benefit from the combination of biology and computer science. The former involves collecting and analyzing biological information. The latter involves simulating biological systems and processes”.

The concepts of computing and computational appear in Yasar et al. (2016). Authors state that “Computational pedagogy is an inherent outcome of computing, math, science and technology integration”. In the same article computing is related to algorithmic and programming. They also suggest that computational modeling and simulation technology (CMST) can be used to improve technological pedagogical content knowledge (TPACK) of teachers.

According to Landau (2006), deep learning is based on problem solving and computational skills and many science departments have created new interdisciplinary courses, concentrations, and tracks to prepare their majors for computing jobs while there is a demand for computationally competent STEM workers leading to the necessity “for a pipeline between Higher education and school (K-12) education” (Yasar, 2013). There is a need to educate in USA future computational scientists

(www.itr.nsf.gov). Jona et al. (2014) state that one of the fundamental research questions in the STEM agenda is “with the STEM approach, how can we increase computational competencies for all students and build interest in computing as a field in its own right?”. Chande (2015) states that “the science that scientists and researchers developed drawing inspirations from natural processes now looks to be taking the center stage and reversely motivating them to decipher natural processes as computational activities”. Zandler & Spannagel (2008), following a cluster analysis research study, state that computer science includes “the following central concepts: problem, data, computer, test, algorithm, process, system, information, language, communication, software, program, computation, structure, and model”.

Bienkowski et al. (2015), state that “Projects with an orientation to computational science tend to emphasize data, modeling, and systems thinking”. In this article there is a strong link between Computational Science: and Computational Thinking. Aho (2012) defined CT as the “thought processes involved in formulating problems so their solutions can be represented as computational steps and algorithms”.

Finally, we will discuss briefly the relation of CT with programming. According to Voogt et al. (2015) “the concepts of Computational Thinking (CT) and the practice of programming are difficult to delineate in the literature because many CT studies or discussions of theory use programming as their context. This can lead to the impression that CT is the same as programming or that CT requires the use of programming. Instead, research supports that CT focuses on developing thinking skills while within subjects beyond computer science”. The same authors provide a nice taxonomy about CT, Computer Science and programming: “Programming, Computer Science, and Computational Thinking are not equivalent concepts, yet are intertwined. Programming is but one context for the practice of Computer Science and Computational Thinking. Computer Science is the field and practice from which Computational Thinking skills arose, however is not the only discipline in which these skills can be found or applied”. In the same spirit, Yadav et al. (2011) state that “computational thinking is an approach that does not necessarily need programming of computers, but rather is an approach to problem solving that uses strategies such as algorithms and abstraction”.

From the brief analysis presented above, it is evident that the terms computing, computation, computational are used sometimes with the same meaning (i.e. algorithms, make calculations etc) and in other cases computational means something wider than computing.

When we will discuss the Computational Science Education epistemology we will present the cognitive are of CSE and we will justify that the concept of “Computational” is wider than that of “Computing and Computation”.

### 2.3 Computational Thinking and Science-Mathematics-Engineering

According to Weintrop et al. (2015), Science and Mathematics are becoming computational endeavors. Next Generation Science Standards (NGSS, 2013) also suggest that “computational thinking” is a core scientific practice and due to the increased presence of computation in mathematics and scientific contexts, a new urgency has come to the challenge of defining computational thinking and providing a theoretical grounding for what form it should take in Science and Mathematics. Authors introduced a taxonomy consisting of four main categories: data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices. We notice that modeling and computational practices are included leading to a more tangible approach to introduce CT in the classroom teaching and learning models. As we will see later, modelling, simulation and computational practices will be the core of our proposal for the Computational Experiment (CE) approach. There is a lot of discussion about the mapping of CT skills and attitudes onto school subjects. Barr & Stephenson (2011), mapped a list of CT skills/concepts on conventional school subjects.

The issue of the relation of Computer Science and Computational Thinking has been at the core of many research papers. According to Zandler & Spannagel (2008), “design of computer science curricula should rely on central concepts of the discipline rather than on technical short-term developments”. In contrast, Barr & Stephenson (2011), state the objective is to articulate a set of key concepts within computation that can be mapped across school subjects. They proposed a set of CT concepts across different disciplines. Authors made very important and operational specific mappings to schools subjects but they did not map CT concepts to STEM epistemology as content, something that will be presented below, when epistemologies of STEM will be discussed and analyzed.

According to Common Core State Standards (National Governors Association, 2010) it should be a direct reference of computational thinking practices in mathematics, and more specifically to problem solving and abstraction

Other approaches to CT practices include the use of CT to teach mathematics (Bienkowski et al. 2015;

Bootstrap Materials: Curriculum and Software, 2015).

### 3. ENGINEERING EDUCATION

Katehi et al. (2009) report that the Committee on K-12 Engineering Education in USA- under the auspices of the National Academy of Engineering (NAE) and the Board on Science Education at the Center for Education of the National Research Council (NRC)- determined the scope and nature of efforts to teach engineering to the elementary and secondary students. One of the major questions addressed was “How does engineering education “interact” with science, technology, and mathematics?”.

The same committee believes that engineering education “may even act as a catalyst for a more interconnected and effective K-12 STEM education system in the USA and achieving the latter outcome will require significant rethinking of what STEM education can and should be”. This report faces another very important objective about the description of the ways in which K-12 engineering content has incorporated science, technology, and mathematics concepts, as context, to explore engineering concepts, or how engineering is used as context to explore science, technology, and mathematics concepts. This reciprocal relationship will be discussed a lot in this review and is of fundamental importance in order to define the STEM epistemology.

According to Shirey (2017), the discipline of engineering can be divided into engineering content and engineering design. “Engineering content arises from the intersection of science, mathematics, and encompasses a collection of tools, which engineers can use to design solutions to specific problems based on criteria and constraints”. Rugarcia et al. (2000) described engineering education “as the development of engineering knowledge (facts and concepts), skills (design, computation, and analysis), and attitudes (values, concerns and preferences)”. Berland et al. (2013) “consider that engineering in high schools can influence students’ deep learning and teach students the engineering design process”.

Katehi et al. (2009) state that “perhaps the most important for engineering is design, the basic engineering approach to solving problems and when students are engaged in the design process, they can integrate various skills and types of thinking—analytical and synthetic thinking and detailed understanding”. They also state that the engineering design process is “(1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) provides a meaningful context for learning scientific, mathematical, and technological concepts; and (4) provides stimulus to systems thinking, modeling, and analysis while engineering design is a po-

tentially useful pedagogical strategy”. We comment on the emphasis given from the report for the modelling concept/process and the types of thinking that are closely related to the skills included in CT.

Engineering design has been also treated as a “pedagogical strategy to bridge science and mathematics concepts in use of solving ill-defined (open-ended) problems by developing creative thinking, formulating solutions and making decisions, and considering alternative solutions using scientific and mathematical concepts” (Sheppard et al., 2009; Shahali et al., 2017)

According to (Dym et al. 2005) “engineering design is a systematic, intelligent process in which designers generate, evaluate and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs, while satisfying a specified set of constraints”. According to National Research Council (2012a, b), there are engineering practices, which, at school level, involve “defining problems, developing and using models, planning and carrying out investigations, analyzing data, using mathematics and computational thinking, designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information”. These practices are related to design process as they provide students with opportunities to purposefully follow a design process for solving engineering problems or challenges.

According to Denning (2003), the “principles of computing include: computation, communication, coordination, recollection, automation, evaluation, and design and we can easily recognize that computing is connected to engineering design”. According to NRC (2012, a, b) CT is closely connected to Engineering Education Epistemology (EEE). The term “practices” appear also in Guzey et al. (2016) where authors state that “recent reform efforts in the USA call for teachers to integrate scientific and engineering practices into science teaching; for example, science teachers are asked to provide learning experiences for students that apply crosscutting concepts (e.g., patterns, scale) and increase understanding of disciplinary core ideas (e.g., physical science, earth science)”.

In the same article there is a reference that distinguishes “practices” from “engineering design” and a statement that engineering practices and engineering design are essential elements of this new vision of science teaching and learning. In this article we notice a concrete relationship between engineering practices and design with science and Mathematics. Authors make also a significant observation, namely that we need a reformed science education that can help students to be successful because solving the complex problems that we face in the world today,

this requires the use of multiple disciplines (e.g., science, engineering) and application of nonroutine problem solving skills [e.g., communicating effectively, recognizing patterns, examining a broad span of information; National Academies of Engineering (Guzey et al., 2016; NAE & NRC, 2014). “While in the past an engineering design-based activity was viewed as a design or model construction activity, the new science education standards in USA require students to engage in engineering design and engineering practices as they learn and apply crosscutting concepts and disciplinary core ideas (NGSS 2013; NRC 2012a, b)”. We notice that emphasis is given to crosscutting effects that later will be connected to the interdisciplinary and transdisciplinary approach for STEM education.

Moore et al. (2014) distinguish two teaching approaches for engineering design and practices in K-12 science classrooms. One approach is to use engineering as a context to learn science (e.g. Kolodner et al. 2003; NRC 2012; NGSS 2013). In this approach students apply science laws and concepts to solve design challenges. The iterative process mentioned previously by Katehi et al. (2009) is implemented by the design/redesign process in which students first “design a prototype (e.g., a modestly working vehicle), experiment with the variables to discover ways to design a better prototype (e.g., resistance forces act on the car), and redesign (e.g., a car that travels farther by reducing the friction or by changing the shape/material of the car)”. We consider this approach a highly inductive approach and we will use this in our approach where the development of the model will be the basic instructional unit. A second approach to integrate engineering” is to use engineering as a culminating or end of science unit project (Moore et al., 2014)”. In this approach engineering is again used as a context, but “ultimately engineering is used as an add-on to science instruction”. This approach is not considered – pedagogically-very helpful as would not help students see the connections between science and engineering, and at the end of unit design challenge turns to a craft activity in which students do not apply targeted science concepts.

Pedaste & Palts (2017) analyzed 31 articles where CT models were implemented. Authors stated that these models were not directly included in the further analysis because none of these approaches to CT has been used in more than one article found by the systematic search.

On the contrary, authors suggested three approaches to form a model of CT which were found in several articles: “ i) Interaction between a Human and Computer, ii) Conceptual Model and iii) Engineering Design (evidence found in 3 articles)”.

Pedaste & Palts (2017) include, in the first approach, the concept of computational learning “as suggested by Cooper et al. (2010) as an iterative and interactive process between the student and the model of computation)”.

They explicitly present their considerations with Figures that connect Computational Science, Computational Thinking and Engineering epistemology (through the iterative process of engineering discussed above). We consider that considerations discussed and present in this paper (not only for the first approach but for all the three) are very fundamentals for the connection of CT with EEE and CSE. The reader should also look especially at Figure 1 of this article which summarizes concisely all the ideas about this connection.

## 4. STEM EPISTEMOLOGY

### 4.1 Epistemology in general

Generally, epistemology is defined as the ways that people acquire, justify, and use knowledge. According to Chandler et al. (2011) “epistemology is a way of reasoning and understanding the things we encounter in the world. Education epistemology is considered as the epistemology made up of experiences, formal and informal instruction, and assumptions about education. Engineering epistemology is made up of lived experiences, formal and informal knowledge and assumptions about the discipline of engineering”. Epistemology is also considered as a branch of philosophy concerned with the nature and justification of human knowledge. Educational psychologists study epistemological development and beliefs to determine how students come to know, what beliefs they have about knowledge and how epistemological beliefs affect cognitive processes and critical thinking (Psycharis et al. 2017; Hofer et al. 1997, King et al. 2009). “Epistemology is usually defined as the way an individual value and understands knowledge and is related to the nature of knowledge, its possibility, scope, general basis, and justification of belief” (Honderich, 1995). Researchers have also introduced the concept of practical epistemology, which is based upon the work of Wittgenstein and draws upon sociocultural theories and approaches, linking learning with talk, action and habits (Wickman, 2004). Practical epistemology “does not view knowledge as a matter of getting reality right, but as a matter of acquiring habits of action for coping with reality” (Rotry,1991). Practical epistemology does not insist that truth is not important, but only put emphasis that to question truth is only one of several ways that help people proceed with practice (Habermas, 2001). The practical epistemology mainly concerns students’ ways of engaging with

laboratory work and implement their practical epistemologies, i.e., what they count as knowledge and how they get knowledge as acting participants in the laboratory practice. Psycharis et al. (2017) consider that practical epistemology aligns to engineering education epistemology (EEE), as students are involved in the design and make, which are considered essential characteristics of engineering pedagogy.

According to Borrego & Newswander (2008;2010), (EEE) “involves the cooperation of many scientist form various disciplines (engineers, psychologists, social scientists etc) and research suggests that the way an individual understands and appreciates the nature of knowledge affects the way he or she collaborates with colleagues in different academic disciplines, especially when the disciplines are fundamentally different”.

Alongside with this important remark, and accepting that epistemology varies across academic disciplines, “a truly interdisciplinary collaboration must necessarily be able to change his or her epistemic “lens” to suit various contexts” (Borrego & Newswander, 2008; 2010). Authors connect this necessity for change with the ideas of Spiro et al. (1987) of cognitive flexibility which emphasizes “cognitive training as the main facilitator of a researcher’s ability to accommodate or shift epistemologies according to context”.

According to research, acquisition of new knowledge depends on “personal epistemological beliefs and research papers have reported students’ beliefs about knowledge on their learning and problem-solving in math, science, and physics but the research on epistemological beliefs in engineering is limited” (Yu et al., 2012).

Yu & Strobel (2011) state that “engineering epistemology is a topic of philosophy and engineering, whose object is the construct ‘engineering knowledge’ concerning the concept of ‘truth’, the logical structure of justification, and the relationship of engineering knowledge to ‘reality’. Epistemological engineering beliefs mean ‘how we know what we know in engineering’, whereas ontological engineering beliefs mean ‘what we believe is reality that engineering deal with”.

#### **4.2 The Interdisciplinary and the Transdisciplinary approach**

There are different concepts and views about these terms and we will try not to present all the views but rather we will present some views that are closer to our purpose to connect epistemology with STEAM. According to Toomey et al. (2015) “Multi-disciplinarity draws on knowledge from different disciplines but stays within their boundaries. Inter-

disciplinarity analyzes, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole”. “Inter-disciplinarity is not just research in two or more different disciplines, nor is it adding methodologies from other disciplines to an already discrete project; rather, it is an integrated approach to answering a question that recognizes the limitations inherent in the compartmentalized system of academic research”. “Trans-disciplinary work moves beyond the bridging of divides within academia to engaging directly with the production and use of knowledge outside of the academy”. Mittelstarss (2011) makes an interesting remark that “subjects and disciplines have grown through the history of science, and that their boundaries are thus determined neither by their objects themselves, nor by theory, but by historical growth. Furthermore, their identity is determined by certain objects of research, theories, methods, and aims of research, which often do not correspond univocally to the definitions of subjects or disciplines, but which instead overlap these disciplines. This does not just become apparent in the fact that disciplines are being guided by methodical and theoretical ideas which, as with the concepts of a law of nature, of causality, and of explanation, are not determined to belong to anyone discipline. It is also evident in the fact that the problems to find solutions for science serves, often do not fit straightforwardly into a disciplinary framework”. Mittelstarss (2011) believes that “not the objects define the discipline, but our manner of dealing with them in theory and this is equivalent with the statement that certain problems cannot be captured by a single discipline”. Transdisciplinarity was introduced to the world in 1972 at a Parisian seminar held by the Organization for Economic Cooperation and Development (OECD).

Balsiger (2004) states that “the concept of Transdisciplinarity is deduced from the principle that Transdisciplinarity is a scientific approach with a strong orientation towards societal problems and successful Transdisciplinarity practice is based on great flexibility. According to him appropriate description of the methodology of a transdisciplinary research approach is given by the concept of “guide and supply” based on the research programs of Lakatos”.

In a very good report by Glyn (2009), interdisciplinary endeavors from the social sciences, natural sciences and engineering are described. In this report, Balsiger(2004) proposes “Supra-disciplinarity as a generic term for all cross-disciplinary work and proposes that Supra-disciplinarity is problem-oriented. He then goes on to outline somewhat usual distinctions between multi- and interdisciplinary

(multi is not problem oriented, inter- is a more active collaboration)".

Zscheischler et al. (2017) discuss transdisciplinary research projects. Authors consider that "transdisciplinary research (TDR) as a collaborative process of knowledge production that involves scientists from different disciplines and societal actors and is aimed at addressing highly complex, real-world problems and can be viewed as a research-guiding principle that integrates different knowledge types and incorporates processes of co-design and co-production. As described here, TDR shows many commonalities with action-research approaches, such as community-based action research (CBPAR) (e.g., Horowitz et al., 2009) and transdisciplinary action research (TDAR) (e.g. Stokols, 2011)". A very interesting find, related to our approach for STEM epistemology, is the need to integrate knowledge, perspectives and interests not only from different disciplines but also from related societal actors when the research project is designed. We consider that this issue as very important for a real STEAM epistemology implementation as societal factors should inspire STEM research in school settings and in Higher Education new curricula as well as for the creative industry. One of the main conclusions of this report is that TDR was not clearly defined and it was described as encompassing interdisciplinary collaboration between academics and the integration of knowledge (interdisciplinarity), in particular to join "nature scientific-technological sciences with the economic and social sciences disciplines".

Another interesting aspect related to transdisciplinarity is pointed in (Després et al., 2004). Authors argue that "disciplines are the result of a methodological reduction of reality to manageable units for knowing and transdisciplinary work could not function without regular physical meetings; geographical distance and cyber-contact would not work. They link transdisciplinary research closely with the notions of inter subjectivity and collaborative planning".

Lawrence & Després (2004) believe that "transdisciplinary endeavors should emerge more easily from more 'multidisciplinary' disciplines such as architecture and planning, before outlining four key characteristics of Transdisciplinarity, namely: tackling knowledge complexity and challenging its fragmentation; context-specificity; Intercommunicative action, requiring close and continuous collaboration, and action-orientedness, connecting with wider society, although they emphasize that it should not be seen as being entirely and always action-oriented". Nowotny (2003) argues that "knowledge and expertise are inherently transgressive, and that transdisciplinary research is inherently about transgressing

boundaries; disciplines still exist, but new ones continue to arise and can be actively produced from interdisciplinary work".

Antola et al. (2013) provide definitions about the different terms, based on the work of McGregor (2006). "Monodisciplinary seeks for solutions to a problem through the lens of a single discipline, in Multidisciplinary professionals from two or more disciplines contribute their separate areas of expertise to a solution, in Interdisciplinary we transfer methods from one discipline to another to address a problem and in Transdisciplinary new approaches are created and integrated while considering complex social issues.

In the distinction between interdisciplinary and transdisciplinary teaching reveals additional possibilities for new approaches to solving social issues". In transdisciplinary there are chances for generating new knowledge which lies in between disciplinary boundaries (McGregor, 2006; Negre, 1999).

According to (Nicolescu, 2002; McGregor, 2015), transdisciplinarity is concerned with "creating new, integrative knowledge to address the complex problems of the world". Antola et al. (2013) demonstrate examples of pedagogy and learning using "transdisciplinary approaches which involve multiple disciplines and the space between the disciplines with the possibility of new perspectives 'beyond' those disciplines".

In the report of Glyn (2009) there are many concise definitions about the terms we will use. We present only the term "transdisciplinary" as it is closely related to STEM epistemology. "Transdisciplinary is defined as the more common referent for work beyond consideration of disciplinary boundaries. Transdisciplinarity is variously referred to "as being based on but going beyond or transcending disciplinary practices (Ramadier, 2004), or being research more concerned to transcend academic enclaves to engage with real-world problems and there by involvement different concerned publics in the research process (Lawrence & Després, 2004)".

There are mainly two approaches to transdisciplinarity. The first one -the "Nicolescuian Transdisciplinarity", was introduced by Nicolescu (1985) and Morin (1992). They view "Transdisciplinarity as a new methodology to create knowledge, with attendant axioms for what counts as reality, logic, and knowledge" (McGregor, 2015). The other approach (frequently referred to as the Swiss, Zurichor German school) conceptualizes transdisciplinarity (McGregor, 2015) "as a new type of research, called Mode 2 research informed by the post-normal science perspective (Nowotny 2003). This approach is "not the express intent, nor does it advocate axioms



for knowledge generation, as does the Nicolescuian methodological approach”.

Transdisciplinarity is the term used by Nowotny (2003) in defining “Mode 2 knowledge production (knowledge production is carried out within its context of application; it is transdisciplinary, heterogeneous, transient, socially accountable and reflexive)”. Transdisciplinary “supports” Mode-2 where we see the emergence of loose organizational structures, flat hierarchies, and open-ended chains of command.

In Mode-1 system, “the focus of intellectual endeavor, the source of the intellectually challenging problems, arises largely within disciplines but other frameworks of intellectual activity are emerging which may not always be reducible to elements of the disciplinary structure” (Nowotny, 2003).

Hughes (1998) has stated the “change in ethos amongst engineers, particularly in the area concerned with finding solutions to complex problems and we consider this issue as very fundamental to the STEM epistemology, as engineering is a core component of STEM”. According to Max-Neef (2005), “Transdisciplinarity leads us deeper into the realms of reality and epistemologically is based “on three fundamental pillars: a) levels of reality, b) the principle of the included middle and, c) complexity”.

In addition, “it recognizes as simultaneous modes of reasoning, the rational and the relational representing a clear challenge to the binary and lineal logic of Aristotelian tradition”. For a detail analysis of the three pillars, reader should consult the classical paper of Nicolescu (2000).

The “concept” of complexity is something that scientists will face and it will be the new revolution in Science, while we believe it represents a content epistemology between many sciences. Complexity is relevant to STEAM epistemology as it develops a kind of recursive thinking, i.e. a thinking capable of establishing feedback loops in terms of concepts such as “whole/part, order/disorder, observer/observed, system/ecosystem, in such a way that they remain simultaneously complementary and antagonistic “(Max-Neef, 2005; Morin, 1992).

### 4.3 The STEM Epistemology

We presented some of the views related to the terms interdisciplinary and transdisciplinary. This “ambiguity” continues the different approaches applied in the delineation of the STEAM epistemology since there is a lot of discussion about STEM epistemology.

Approaches to STEM epistemology are related to the so called “Integrated STEM Education”. Curriculum integration was based in constructivism theories of learning. Satchwell & Loepp (2002) describe an integrated curriculum “as one with an explicit assim-

ilation of concepts from more than one discipline”. The idea of curriculum integration is derived from educators’ awareness that authentic problems cannot be faced using discrete disciplines that are taught in schools (Czerniak et al., 1999) and quite often students cannot be involved in the problem based learning process because they cannot be engaged in the context in which the problems are embedded (Frykholm & Glasson, 2005; Shahali et al., 2017). Stohlmann, Moore & Roehrig (2012) found “that integrated lessons allow for a more authentic treatment of mathematics and science content”.

Wilber (2001) presented the idea that “integral refers to things that are required to ensure completeness of the whole”. “The word integral means comprehensive, inclusive, non-marginalizing, embracing” (Wilber, 2003). Integrated Curriculum is connected with different epistemologies, like the interdisciplinary and the Transdisciplinary approach.

According to (Borrego & Newswander, 2008) “cross-disciplinary” is a general term to “describe collaborations involving multiple disciplines”, and Cross-disciplinary collaborations can be enacted through either (1) multidisciplinary approaches or (2) truly interdisciplinary approaches. Based on this definition, they seem to talk about an interdisciplinary engineering education epistemology.

According to (Glyn, 2009), cross-disciplinary is most commonly used as a catch-all or generic referent for work employing more than one discipline, thus covering all of the terms like Interdisciplinary, Mono-disciplinary, multidisciplinary, Pluri-disciplinary, Transdisciplinary. We can easily observe that these definitions cannot converge.

According to (Shahali et al. 2017; Wang et al., 2011) “STEM integration in the classroom is a type of curriculum integration. STEM integration is a curricular approach that combines the concepts of STEM in an interdisciplinary teaching approach. The goal of integrated STEM education is to be “a holistic approach that links the disciplines, so the learning becomes connected, focused, meaningful, and relevant to learners”.

Sanders (2009) argued that “the focuses of STEM education should apply knowledge of mathematics, science and engineering, design and conduct experiments, analyze and interpret data, and communicate and cooperate with multidisciplinary teams”.

According to English (2016), one of the problematic issues for researchers and curriculum developers lies in the different interpretations of STEM education and STEM integration. As indicated in numerous articles, STEM education has been defined variously ranging from disciplinary through to transdisciplinary approaches. In acknowledging the lack of an agreed-upon definition, the California Depart-

ment of Education (2014) provides a broad perspective on STEM education, namely, “[STEM]... is used to identify individual subjects, a stand-alone course, a sequence of courses, activities involving any of the four areas, a STEM-related course, or an interconnected or integrated program of study”.

Vasquez et al. (2013) define concisely different forms of boundary crossing along a continuum of increasing levels of integration, with progression along the continuum involving greater interconnection and interdependence among the STEM disciplines. According to the authors interdisciplinary refers to “closely linked concepts and skills are learned from two or more disciplines with the aim of deepening knowledge and skills” and transdisciplinarity refers to “knowledge and skills learned from two or more disciplines are applied to real-world problems and projects, thus helping to shape the learning experience”.

According to (Morrison 2006; Tsupros et al., 2009), “the interdisciplinary bridging among discrete disciplines is treated as an entity, known as STEM. STEM education offers students one of the best opportunities to make sense of the world holistically, rather than in bits and pieces. STEM education removes the traditional barriers erected between the four disciplines, by integrating them into one cohesive teaching and learning paradigm”. Authors state that “STEM education is an interdisciplinary approach to learning where rigorous academic concepts are coupled with real world lessons as students apply science, technology, engineering, and mathematics in contexts that make connections between school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new economy”.

According to (Morrison, 2006) STEM education often has been called a meta-discipline, the “creation of a discipline based on the integration of other disciplinary knowledge into a new whole”.

According to (Roehrig et al., 2012; Moore, 2008) STEM integration is necessary for”

1. deepening student understanding of each discipline by contextualizing concepts;
2. broadening student understanding of STEM disciplines through exposure to socially and culturally relevant STEM contexts; and
3. increasing interest in STEM disciplines to broaden the pathways for students to enter STEM fields”

There are two approaches for STEM education integration: the content integration and the context integration. These different approaches allow teachers flexibility on how they integrate STEM in their classrooms.

Content integration (Moore, 2008) “focuses on the merging of the content fields into a single curricular activity or unit to highlight “big ideas” from multiple content areas”. Consider for example the operation of wind turbines to illustrate the power and possibilities of teaching within a fully integrated STEM context. “The wind turbine design lessons utilize robust hands-on wind turbine kits that allow teachers and students to explore the variables that impact electricity generation”. Teachers had direct experiences with engineering design by considering a model construction (or they can ask students to create the model) selecting the variables of the phenomenon and the relation between the variables.

Engineering design is included by designing a prototype according to the scientific concepts included and by asking questions about the material, shape, and length etc of the blades. A full understanding of an optimal wind turbine design also involves developing and applying physics concepts related to electricity generation, the mathematical concepts (related to trigonometry, rotation, and gear system).

This STEM curriculum activity needs a series of lectures to be implemented and faces a problem of real life. It is usual this problem to be faced as a whole and not in separate issues (i.e. first discussing issues form physics, next move to mathematics etc).

A unit such this allows a teacher to teach concepts from each discipline and highlight how these disciplines are all needed to solve a problem in this area. In this example students can design and make their artifact, test this against the experimental data and reframe their considerations about the prototype. This process can be implemented either by using the computational experiment (see next section) using physical computing (e.g. Arduino construction), or without using computers, i.e. unplugged computing. You can find also a very interesting example in the article of Schnittka et al. (2010).

In the context STEM integration approach, the focus is on the content of one discipline and next contexts from other disciplines are “used to make the content more relevant.” For example, a mathematics teacher might choose a unit from probability about Bayes theorem and then he can ask students to analyse samples from a biochemistry lab in order to examine the probability for diseases using conditional probabilities.

In another example, teacher teaches algorithms and then ask engineering students to visit different networks and register the response time in a network with different number of nodes.

In unplugged computing (unplugged CT) students are taught about the buoyancy force and then

they make small submarines to test their hypothesis and their artifact.

We have observed a lot of confuse about the terms that describe STEM epistemology which led to different integrations in school education and can be extended in Higher Education.

This is also stated in NAE and NRC report (2014) where it is stated that “in educational practice and in research, the term integrated is used loosely and is typically not carefully distinguished from related terms such as connected, unified, interdisciplinary, multidisciplinary, cross-disciplinary, or transdisciplinary”.

We consider that the above-mentioned approaches to STEM should be also connected to the approaches of Mode-2 and “Nicolescuian” methodological approach.

We claim that STEM epistemology is closely related to Mode-2 system as it faces problems that emerge from different disciplines and loose organizational structures, flat hierarchies, and open-ended chains of command are dominant.

STEM integration even shares some issues alongside with the Nicolescuian methodological approach. Realities of Nicolescuian methodological approach can appear in personal epistemology when students create their own model (see below for the use of models in STEM education).

Complexity also, according to Nicolescuian methodological approach, could be related to STEM content epistemology. According to (Nicolescu, 2004), complexity “is a modern form of the ancient principle of universal interdependence, in that everything is dependent on everything else, everything is connected, and nothing is separate”. This definition of complexity, alongside with current research efforts to define complexity, raise awareness about issues like emerging behavior, connection of scales etc that could be related to STEM content, as STEM faces complex problems.

Issues like the relationship between the interdependence of the constituents of a complex system, the structure of a complex system which spans several scales etc can only be confronted through the STEM contact approach.

As a conclusion, we consider that STEM epistemology should follow the Mode-2 Transdisciplinarity as it faces problems that emerge not only from one cognitive area. However, we cannot ignore the different levels of reality and complexity of the “Nicolescuian” methodological approach.

Our suggestion is based on the consideration that the “whole” is qualitatively different from its parts and this “panoramic” view sometimes focuses on specific discipline (STEM context approach) but in general moves with a holistic way between the dis-

ciplines. This approach put an emphasis on the “whole” and on the correlation of concepts and phenomena and not on the separate phenomena enhancing the abstraction skills as well as the modelling practices of the CT.

We conclude by a general reference to the integration of Art with STEM. This is a rather general reference, but we hope it will highlight the reason for the integration of Arts with STEM. It is well known that art skills are often associated to STEM skills (Daugherty, 2013). People working in creative industries have realized that creativity is related to the design and creation of new products and services. In the STEAM epistemology, the arts can establish a dual relationship with engineering (think for example many interesting phenomena related to visual arts).

Art can be integrated in STEM content from the primary school. Optics, Chemistry and basic algebra and trigonometry can be in in photography, and students can be involved in the development of artifacts associated with films.

According to Watson & Watson (2013) “In the commercial world, there are many fields where the line between art and engineering has been blurred for years. For instance, both architecture and industrial design require the knowledge of an engineer but are driven by aesthetics. With the onset of digital media, the commercial publishing and advertising worlds now require engineers to have art skills and artists to have engineering skills. This blending of engineering and the arts had been adopted by companies such as Apple and Disney (where design engineers are titled “imagineers”).”

Computers graphics use algorithms and their effectiveness needs the engagement of mathematician, engineers and “imagineers”. Serious games use STEM disciplines for pedagogical applications and their production needs the cooperation between artists and STEM educators.

The NSF supported also projects related to arts and Robotics. For example, the projects “Artbotics project” is a project combining Computing with art and robotics (Martin et al., 2009). In school settings also, we can implement STEAM. For example, use of Scratch and Pencil Code can help students to develop applications combining computing and music.

There are also theoretical considerations for the integration of STEM with Arts, similar to our discussions before. For example, Land (2013) states that “Supporters of the STEAM initiative may theorize how STEAM looks in the classroom, but it is the

educators job to develop and/or implement the curriculum. When it boils down to it, STEAM is cross-curricular collaboration.”

## 5. THE COMPUTATIONAL SCIENCE EDUCATION

### 5.1 *The Computational Science in general*

Computational Science (C.S.), in general, has its origins in Monte Carlo modeling and algorithms like Lanczos algorithm, for applications of stochastic statistical sampling for solving complex problems in Physics (Landau et al., 2008; Psycharis, 2015).

Computational Science (C.S.) is the integration of Mathematics, Computer Science and any other discipline to explore authentic-complex problems. It brings together concepts from a variety of cognitive subjects (Landau et al., 2008) and is considered to be part of the Computational Science-Engineering community.

In recent surveys by Dongarra & Sullivan (2000), they list the ten top algorithms of the 20th century, which include (Hjorh, 2007):

1. The Monte Carlo method or Metropolis algorithm, devised by John von Neumann, Stanislaw Ulam, and Nicholas Metropolis.
2. The simplex method of linear programming, developed by George Dantzig.
3. Krylov Subspace Iteration method for large eigenvalue problems in particular, developed by Magnus Hestenes, Eduard Stiefel, and Cornelius Lanczos.

According to (Yasar, 2004; Yasar & Landau, 2003) Computational Science( C.S.) overlaps with many other knowledge areas, so an educational program in Computational Science, naturally draws strength from all of them. Nevertheless, in addition to overlapping with computer science, math, and science and engineering application areas, Computational Science has its own core knowledge area.

Although some computer science and mathematics programs have championed this new field, Computational Science, also finds strong allies in other disciplines, particularly physics and biology. Computational Science and computer science have common concerns when it comes to computer performance and application optimization; computational science and mathematics have common concerns when it comes to applied math technique".

Juszczak (2015) states that Computational Science, in both natural and social sciences, "is different than the usage of computers to analyze complex systems and data sets. Computational Science is a non-empirical science. Data that is gathered in computational science is the result of simulations and virtual experiments".

The key distinction between a true "computational science" and a science that uses computation is in the nature of evidence: traditional science and science experimentation that use computation to assist

in the analytic and experimental process have, as their threshold of truth, empirical evidence. Computational Science, on the other hand, conducts experiments that are only virtually true and attempts to use data about the real world in order to conduct real experiments in a virtual universe".

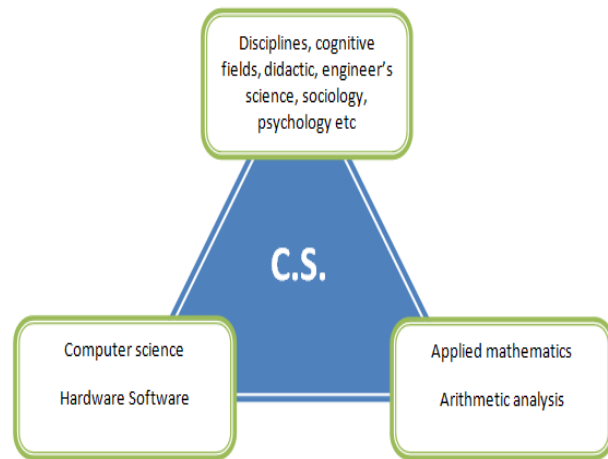


Figure 1. The C.S. cognitive area

Using Computational Science, we accept that we can conduct experiments and iterations that could never be conducted in the real world with results equivalent to the classical experiments. For this reason, cognitive areas like computational psychology, computational biology, computational astrophysics, computational chemistry, and computational sociology have developed over the past several decades.

### 5.2 *The Computational Science in Education (CSE)*

Initially Computational Science was considered as a bridge between different disciplines but after the first phase (recognition phase) this area developed its own methods that can be a useful and effective tool for implementing STEM education in class.

CSE can be an effective methodology to support learners to solve a STEM problem using computer simulations and this includes diverse tasks, such as: formulating the problem in a way suitable for simulations using models (connection with CT); choosing an efficient computational algorithm (connection with CT); running the simulations and collecting numerical data) (connection with CT); analyzing the data obtained connection with CT); finding patterns in order to generalize the method to other problems (connection with CT), extracting the solution of the problem in a form that can lead to the creation of artifacts. According to the scientific community, there is a clear need for CSE courses that: focus on the science aspects of CSE/ Mathematics/ Engineering etc; provide students hands-on experience in de-

signing, implementing, running and debugging algorithms; play a role similar to that of a physical laboratory (hands on) courses for experiment. CSE focuses on the form of an authentic problem to solve and follows a scientific problem-solving paradigm (Computational experiment - CSE-approach), with a sequence of steps: a. Problem (from science/real world); b. Modelling (Mathematical relations between selected variables-decomposition of the problem); c. Simulation Method (time dependence of the state variables, discrete, continuous or stochastic processes, selection of proper interfaces ); d. Development of the algorithm based on numerical analysis methods; e. Implementation of the algorithm (using Java, Scratch, Python, Arduino, raspberry pi etc); and f. Assessment and Visualization through explo-

ration of the results and comparison with real data received from authentic phenomena. CSE shares many commonalities with CT and may serve as the background platform to implement applications that include the dimensions of CT. In Figure 2, we present the problem-solving paradigm of computational experiment (CE).

One of the crucial components of CSE is also the abstraction of a physical phenomenon to a conceptual model and its translation into a computational model that can be validated. This leads us to the notion of a computational experiment (CE), where the model and the computer take the place of the 'classical' experimental set-up and where simulation replaces the experiment (Psycharis & Kotzampasaki, 2017; Psycharis et al. 2017a, Psycharis et al., 2018).

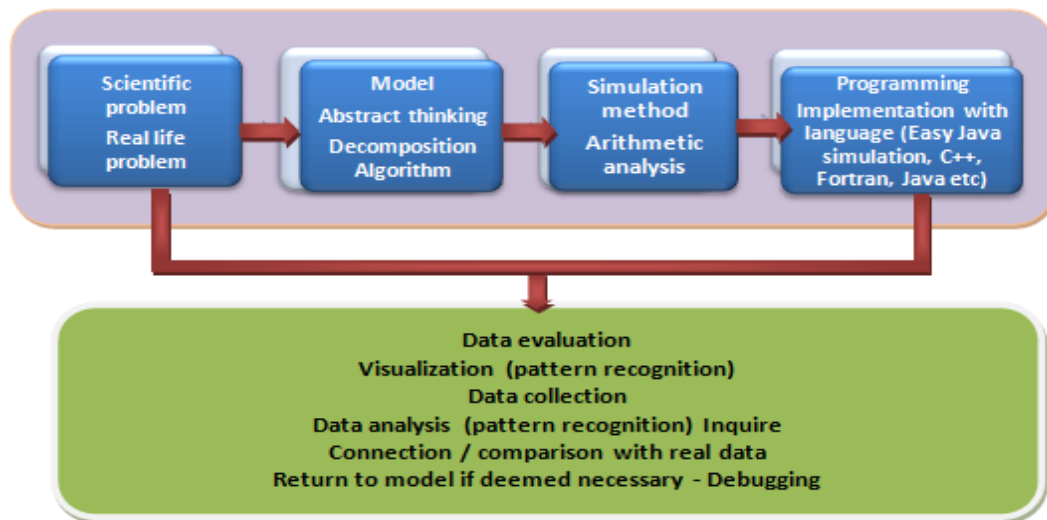


Figure 2. The Computational Science Experiment (CE experiment)

We consider modelling as a central issue in the CSE methodology while the CE experiment implements CT in practice in accordance to research (see for example Isbell et al. 2010) and (Bienkowski et al., 2015), where it is clearly stated computational science tend to emphasize data, modeling, and systems thinking (see also section 1.2 of this article).

### 5.3 The Computational Pedagogy

The term Computational Pedagogy was introduced by Yasar et al (2016) as an extension of TPACK and was called Computational Pedagogical Content Knowledge. Yasar (2003) states that "Computational modeling and simulations provide us with a deductive pedagogical approach by enabling us to introduce a topic from a simplistic framework and then move deeper into details after learners gain a level of interest to help them endure the hardships and frustration of deeper learning. Once the learner

grasps important facts surrounding the topic, a reverse (inductive) process can be facilitated through hypothetical and investigative simulations that enable discovery of relevant principles and skills. Such a stepwise progression is in alignment with the basic pedagogical principles and scaffolding strategy to balance skills with challenges. Computational pedagogy carries both strategies as part of its nature. It puts the learner at the center of a constructivist experience that utilizes both bottom-up (abstraction) and top-down approaches to teaching".

The process of abstraction is an inductive process by which we sort out/organize details and connect the dots to arrive at more general patterns and conclusions. Abstraction is also connected to pattern recognition and is included in the CE experiment methodology.

Yasar et al (2016) propose a model (CMST) in which "computational modeling and simulation

technology (CMST) is used to improve technological pedagogical content knowledge (TPACK) of teachers.

CMST has shown to be effective on both teaching and learning. Results show that it helps teachers to integrate technology into their teaching in a more permanent, constructive, and tool-independent way. It has also shown to improve student learning in a constructive fashion by first enabling deductive introduction of a topic from a general simplistic framework and then guiding the learner to inductively discover underlying STEM principles through experimentation”.

Yasar et al. (2015) use the cognitive psychology to make an argument that (CPACK) is an interdisciplinary process. They state that “exposure to new concepts through links to multiple views from different fields of study is an effective retrieval strategy recommended by cognitive psychologists and this interleaved retrieval practice forms a cognitive foundation for the interdisciplinary computational pedagogical content knowledge (CPACK)”.

According to authors, when mathematics, computing, and sciences are integrated, “their integration gives birth not only to a new content domain of computational science, as witnessed by degree programs in the past two decades but also a particular computational pedagogy. This multi-faceted interdisciplinary knowledge domain has been called Computational Pedagogical Content Knowledge (CPACK) domain framework” (see Figure 3).

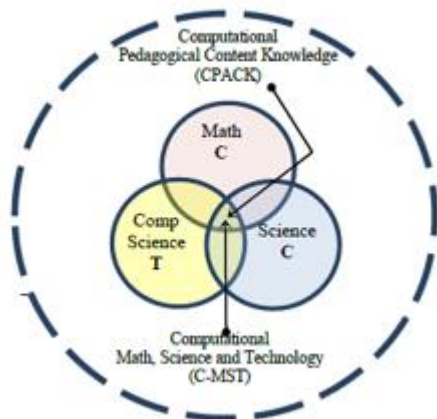


Figure 3. The CPACK Computational Pedagogy (Yasar et al., 2015, 2016)

In this article we adopt the model of Yasar et al. (2016) with some slight modifications and we add to engineering design practices to the so called computational experiment spaces. This will lead to modifications of Figure 1 and Figure 2 and their replacement by Figure 4 and Figure 5.

## 6. OUR PROPOSAL FOR THE COMPUTATIONAL STEM IN EDUCATION

NSF and NSTA (2008) suggest that -at early stages-computational thinking education should “involve easy experimentation (learners must be able to quickly set up and run a model using an intuitive user interface and high interactivity (models need to evolve quickly and include smooth visualizations for providing interactions and feedback to users)”.

Psycharis (2015, 2016), (Psycharis & Kotzampasaki, 2017; Psycharis et al., 2017) discussed the spaces of the computational experiment and proposed inquiry based activities at each space. To use the model and simulation in the inductive process of teaching, we need proper environments that favor the use of mathematics and algorithms, so the computational experiment will be “equivalent” to the physical experiment.

In our model we integrate the inquiry based teaching and learning approach, the CE spaces (CE experiment), CSE and EEE and, integrating Arts, we call our model of teaching “Computational STEAM Pedagogy”.

Inquiry-based Learning is considered a pedagogy for improving STEM disciplines learning in many countries (Bell et al., 2010; Asay & Orgill, 2010) and can be defined as the “deliberate process of diagnosing problems, critiquing experiments, distinguishing alternatives, planning investigations, researching conjectures, searching for information, developing models, debating with peers, and forming consistent arguments”.

Bell et al. (2010) identified nine main science inquiry processes, supported by different computational environments that could be used in inquiry-based content STEAM, namely: orienting and asking questions; generating hypotheses; planning; investigating; analyzing and interpreting; exploring and creating models; evaluating and concluding; communicating; predicting. In the table I below, we extend previous model suggested by (Psycharis, 2015, 2016, 2018) and we include the engineering design and CT as well as EEE and Arts. Engineering design and CT was added in previous suggestions by (Psycharis, 2015, 2016; Psycharis & Kotzampasaki, 2017; Psycharis et al., 2017; Psycharis et al., 2018) leading to the so called “Computational STEAM Pedagogy-CSP”.

*Table I. Connection of the spaces of CSE with essential features of Inquiry, Dimensions of CT, CSE, and EEE*

| Spaces of the Computational Experiment | Essential Features of Inquiry<br>STEM content -Transdisciplinary epistemology -EEE                                                                                                                                                                                                                                                                                                                                                                                                                                     | Inquiry tools                                                                            |
|----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Hypotheses space                       | <p><u>Essential Features of Inquiry</u></p> <p>Question, Provision of Art schemata and creations</p> <p><u>Dimensions of CT</u></p> <p>Abstraction, decomposition</p> <p><u>STEM Epistemology</u></p> <p><u>Use of a product from real life - Unplugged activities</u></p> <p><u>EEE</u></p> <p>Provision of Engineering products in a form of a video, picture, artifact</p>                                                                                                                                          | <p>Orienting and asking questions;</p> <p>generating hypotheses</p>                      |
| Experimental space                     | <p><u>Essential Features of Inquiry</u></p> <p>Evidence, Analyze, Explain</p> <p><u>Dimensions of CT</u></p> <p>Abstraction, algorithmic thinking</p> <p><u>STEM Epistemology</u></p> <p>Intertwine science and mathematics to model the phenomenon</p> <p>Creation of Code to control artefacts -maybe use of physical computing</p> <p><u>EEE</u></p> <p>Design of artefact based on the simulation-revision -if necessary- of the prototype</p> <p>Cooperation of the STEM disciplines to produce Art creations</p> | <p>Planning</p> <p>Investigating</p> <p>Analysis and interpretation</p> <p>Modelling</p> |
| Prediction Space                       | <p><u>Essential Features of Inquiry</u></p> <p>Connect, Communicate</p> <p><u>Dimensions of CT</u></p> <p>Debugging and generalization</p> <p><u>STEM Epistemology</u></p> <p>Generalize the methodology to other similar cases, maybe use of remixing</p> <p><u>EEE</u></p> <p>Provide design patterns for future use-metacognitive experiences</p> <p>Thinking for “similar” Art creations</p>                                                                                                                       | <p>Conclusion-</p> <p>Evaluation-</p> <p>Prediction</p>                                  |

After the discussion presented we propose the following pictures to better visualize our model.

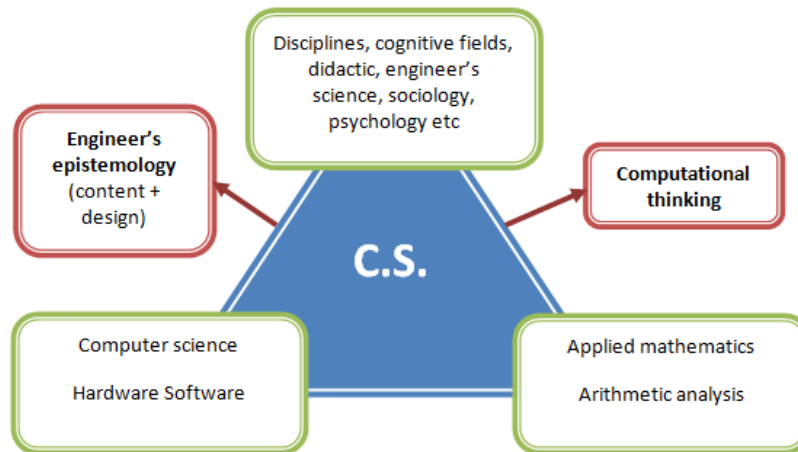


Figure 4. The C.S. cognitive area embedded with engineering design and CT

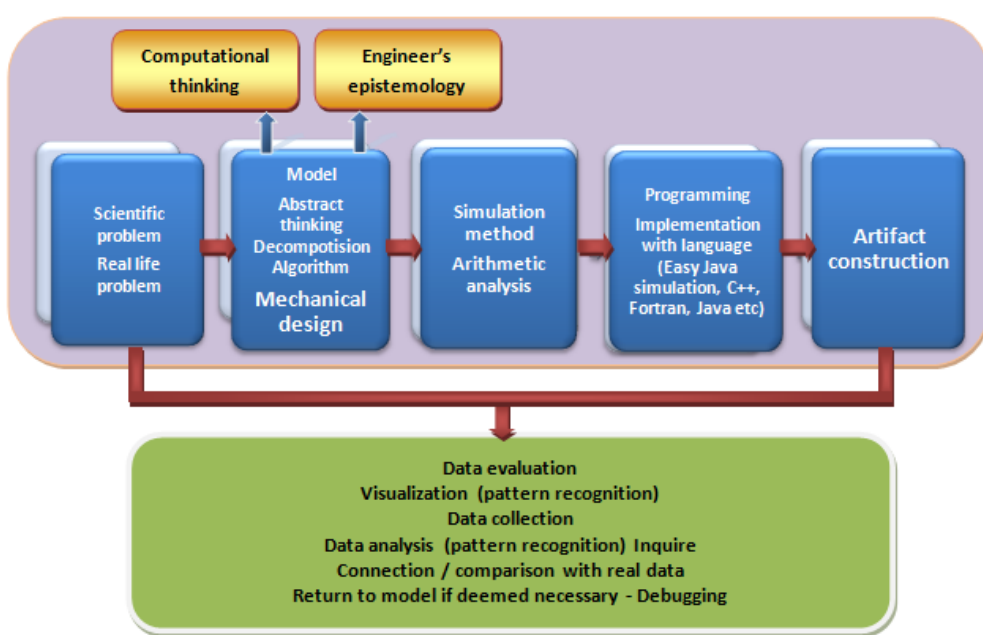


Figure 5. The Computational Science Experiment (CE experiment) with engineering design and CT

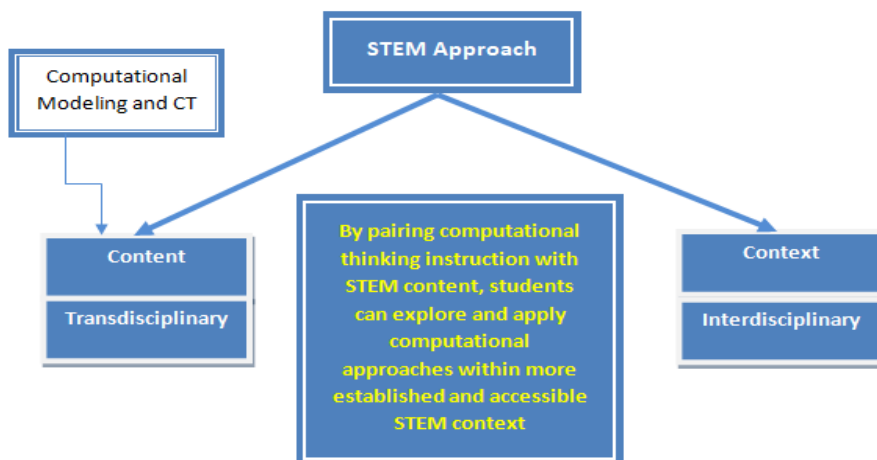


Figure 6. STEM integration as content and in transdisciplinary epistemology



## 7. CONCLUSIONS-RECOMMENDATIONS

In this commentary, I have argued for a focus on STEAM integration based on Transdisciplinary Mode-2 approach, with a more balanced focus on each of the disciplines as a whole with a “panoramic” view in disciplines and in the space between the disciplines.

I have also argued for the inclusion of the Computational Experiment Methodology as a proper methodology for the inclusion of models and simulations considering the computational experiment as a “real” experiment with data from the physical world but, of course, implemented virtually.

Preliminary results show that the “Computational Content STEAM Pedagogy”, seems to be effective in teaching and learning as well as on students’ capacity to implement this in a form of didactic scenario. Students can use this methodology-epistemic approach to develop inquiry based scenario, to collect and analyze data and to decompose a real-life problem. They can also be engaged in the abstraction process and in developing code using optical and text-based programming as well as physical computing. In addition, they can design and make artifacts

based on engineering, engage in the creation of prototype and understand that prototype should be tested according to the outcomes of the data they collected from their model.

The present article adds to the literature as an introduction of a pedagogical approach, the “Computational STEAM Pedagogy-CSP”, when the engineering education is added in the computational experiment approach in the framework of the transdisciplinary epistemology which also integrates Arts in STEM. Research is in progress for investigation of the impact of this approach to large scale to schools and Universities. Findings will be of special interest to individuals, teachers, Vocational School and tertiary Education educators and stakeholders who concern about the STEAM integration in the curriculum, the quality of STEAM education and it will also trigger discussions of what STEAM education should be.

In a repository operated under the Hellenic Education Society of STEM.E3STEM ([www.e3stem.edu.gr](http://www.e3stem.edu.gr)), many of these activities will be included and will be implemented in non-formal settings.

## ACKNOWLEDGEMENTS

I will like to thank my master students Evangelia Kotzampasaki, Paraskevi Iatrou, Polydoros Stavropoulos, Stylianos Moschonissiotis, Panayiotis Mourkakos, Aris Paliouras and Konstantinos Kalovrektis for their inspiring discussions suggestions through writing this article

## REFERENCES

- Aho, A. V. (2012). Computation and computational thinking. *Computer Journal*, 55(7):832 – 835.
- Antola Crowe, H., Brandes, K., Davison Avilés, B., Erickson, D. & Hall, D. (2013). Transdisciplinary teaching: Professionalism across cultures. *International Journal of Humanities and Social Science* 3(13).
- Asay, L. D., & Orgill, M.K. (2010). Analysis of essential features of inquiry found in articles published in *The Science Teacher*, 1998-2007. *Journal of Science Teacher Education*, 21(1), 57-79.
- Balsiger, P.W. (2004). Supradisciplinary research practices: history, objectives and rationale. in *Futures* 36:4, 407-421.
- Barr, V. & Stephenson, C. (2011). Bringing Computational Thinking to K-12: What Is Involved and What Is the Role of the Computer Science Education Community? *ACM Inroads*, 2(1), 48-54. doi:10.1145/1929887.1929905
- Bell, T., Urhahne, D., Schanze, S., & Ploetzner, R. (2010). Collaborative inquiry learning: models, tools and challenges. *International Journal of Science Education*, 32(3), 349-377.
- Berland, L. K., Martin, T. H., Ko, P., Peacock, S. B., Rudolph, J. J. & Golubski, C. (2013). Student learning in challenge-based engineering curricula. *Journal of Pre-College Engineering Education Research (J-PEER)*, 3(1), 5.
- Bienkowski, M., Snow, E., Rutstein, D. W., & Grover, S. (2015). Assessment design patterns for computational thinking practices in secondary computer science: A first look (SRI technical report). Menlo Park, CA: SRI International.
- Bootstrap. (2015). Bootstrap materials: curriculum and software. Retrieved December 5, 2015 from <http://www.bootstrapworld.org/materials/fall2015/index.shtml>
- Borrego, M., & Newswander, L. K. (2008). Characteristics of Successful Crossdisciplinary Engineering Education Collaborations. *Journal of Engineering Education*, 97(2), 123-134.
- Borrego, M., & Newswander, L. K. (2010). Definitions of Interdisciplinary Research: Toward Graduate-level Interdisciplinary Learning Outcomes. *Review of Higher Education*, 34(1), 61-84.

- Bundy, A. (2007). Computational Thinking is Pervasive. *Journal of Scientific and Practical Computing*, 1(2), 67-69.
- California Department of Education. (2014). Science, technology, engineering, & mathematics (STEM) information. <http://www.cde.ca.gov/PD/ca/sc/stemintrod.asp>. accessed December, 2014.
- Chande, S. (2015). A Conceptual Framework for Computational Thinking as a Pedagogical Device. *International Journal of Innovative Research in Computer and Communication Engineering*, vol. 3, Issue 11, November 2015
- Chandler, J., Fontenot, A. D. & Tate, D. (2011) Problems associated with a lack of cohesive policy in K-12 precollege engineering. *Journal of Pre-College Engineering Education Research (J-PEER)* 1, 5 (2011).
- Cooper, S., Prez, L. C., & Rainey, D. (2010). Education k-12 computational learning. *Communications of the ACM*, 53(11):27.
- Czerniak, C.M., Weber, W.B., Sandmann, Jr., A., & Ahern, J. (1999). Literature review of science and mathematics integration. *School Science and Mathematics*, 99(8), 421-430.
- Daugherty, M. K. (2013). The Prospect of an 'A' in STEM Education, *The Journal of STEM Education*, April-June 2013, 14(2), pp. 10.
- Dede, C., Mishra, P., & Voogt, J. (2013). Working group 6: Advancing computational thinking in 21st century learning. [http://www.curtin.edu.au/edusummit/local/docs/Advancing\\_computational\\_thinking\\_in\\_21st\\_century\\_learning.pdf](http://www.curtin.edu.au/edusummit/local/docs/Advancing_computational_thinking_in_21st_century_learning.pdf). Accessed 28 January 2017
- Denning, P. (2003). Great Principles of Computing. *Communications of the ACM*, 46(11). 15-20.
- Després, C., Brais, N. & Avellan, S. (2004). Collaborative Planning for Retrofitting Suburbs: Transdisciplinarity and intersubjectivity in action. *Futures*. 36:4, 471-486
- Dongarra, J. & Sullivan, F. (2000). *Computing in Science and Engineering*, 2:22, 2000. Morten Hjorth-Jensen Computational Physics, Oslo 2007
- Dym C.L., Agogino, A., Eris, O., Frey, D.D. & Leifer L.J. (2005). Engineering design thinking, teaching, and learning. *J Eng Educ*. doi:10.1109/EMR.2006.1679078
- English, L. (2016). STEM education K-12: perspectives on integration. *International Journal of STEM Education*, 3(3), 1-8.
- Frykholm, J. & Glasson G. (2005). Connecting science and mathematics instruction: pedagogical context knowledge for teachers. *School Science and Mathematics* 105(3), 127-141.
- Ghanbari, S. (2015). Learning across disciplines: A collective case study of two university programs that integrate the arts with STEM. *International Journal of Education & the Arts*, 16(7). Retrieved from <http://www.ijea.org/v16n7/>.
- Glass, R. L. (2006). Call it problem solving, not computational thinking. *Communications of the ACM*, 49(9):13.
- Glyn, E. (2009). *Annotated Bibliography: Interdisciplinarity*. Project Report. National Centre for Research Methods.
- Guzey, S.S., Moore, T.J., Harwell, M. & Moreno, M. (2016). STEM Integration in Middle School Life Science: Student Learning and Attitudes. *J SciEducTechnol*. 25: 550. <https://doi.org/10.1007/s10956-016-9612-x>
- Habermas, J. (2001). *On the pragmatics of social interaction: Preliminary studies in the theory of communicative action*. Cambridge, MA: MIT Press.
- Hetland, L. (2013). *Studio Thinking 2: The Real Benefits of Visual Arts Education*. Teachers College Press.
- Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research*, 67(1), 88-140.
- Honderich, T. (1995). *The Oxford companion to philosophy*. NY: Oxford University Press.
- Horowitz, C.R., Robinson, M. & Seifer, S. (2009). Community-based participatory research from the margin to the mainstream: Are researchers prepared? *Circulation* 2009, 119 (19), 2633-2642.
- Hoyles, C., & Noss, R. (2015). Revisiting programming to enhance mathematics learning. Paper presented at the *Math + Coding Symposium*. Western University.
- Hughes, T. (1998). *Rescuing Prometheus*, Rescuing Pantheon Books. 1998
- Isbell, C. L., Stein, L. A., Cutler, R., Forbes, J., Fraser, L., Impagliazzo, J., Proulx, V., Russ, S., Thomas, R., & Xu, Y., (2010) "(Re) defining computing curricula by (re) defining computing". *ACM SIGCSE Bulletin*, Vol. 41, No. 4, 2010, pp. 195-207
- Jona, K., Wilensky, U., Trouille, L., Horn, M. S., Orton, K., Weintrop, D., & Beheshti, E. (2014). Embedding computational thinking in science, technology, engineering, and math (CT-STEM). In *future directions in computer science education summit meeting, Orlando, FL*.

- Juszczak, M. D. (2015). From Towards a Computational Pedagogy – Analysis of ABM Deployment in Pedagogical Instances. *International Journal of Pedagogy Innovation and New Technologies*. DOI: 10.5604/23920092.1159113 Vol. 2, No. 1, 2015, pp. 2-13
- Kallia, M. (2017). Assessment in Computer Science courses: A Literature Review. Royal Society.
- Katehi, L., Pearson G., & Feder M. (2009). Engineering in K-12 education: Understanding the status and improving the prospects. Washington, DC: National Academy of Engineering and National Research Council.
- King, B. A., & Magun-Jackson, S. (2009). Epistemological beliefs of engineering students. *The Journal of Technology Studies*, 35 (2), 56-64.
- Kolodner, J.L., Camp, P.J., Crismond, D., Fasse. B., Gray, J., Holbrook, J. & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle schools science classroom: putting learning by design TM into practice. *J Learn Sci* 12(4):495-547
- Kotsopoulos, D., Floyd, L., Khan, S., Namukasa, I. K., Somanath, S., Weber, J., & Yiu, C. (2017). A pedagogical framework for computational thinking. *Digital Experiences in Mathematics Education*, 3(2), 154-171.
- Land, M. H. (2013). Full STEAM ahead: The Benefits of Integrating the Arts Into STEM. *Procedia Computer Science*, 20, 547-552.
- Landau, R. (2006). Computational physics: A better model for physics education? *Computing in science & engineering*, 8(5), 22-30.
- Landau, R.H., Páez, J. & Bordeianu, C. (2008). *A Survey of Computational Physics: Introductory Computational Science*. Princeton and Oxford: Princeton University Press.
- Lawrence, R. J., & Despres, C. (2004). Futures of Transdisciplinarity. *Futures*, 36(4), 397-405.
- Lu, J. & Fletcher, H. (2009). Thinking about computational thinking, Proceedings of the 40th ACM technical symposium on Computer science education, March 04-07, 2009, Chattanooga, TN, USA. doi:10.1145/1508865.1508959
- Maeda, J. (2013). STEM + Art = STEAM. *STEAM Journal*, 1(1)
- Martin, F., Greher, G., Heines, J., Jeffers, J., Kim, H. J., Kuhn, S., Roehr, K., Selleck, N., Silka, L. & Yanco, H. (2009). Joining computing and the arts at a mid-size university. *Journal of Computing Sciences in Colleges*, 24(6), 87-94.
- Max-Neef, M. A. (2005). Foundations of transdisciplinarity. *Ecological Economics*, 53: 5-16.
- McGregor, S. (2006). *Transformative practice: New pathways to leadership*. Lansing, MI: Kappa Omicron NuHonor Society.
- McGregor, S. (2015). Transdisciplinary knowledge creation. In P. T. Gibbs (Ed.), *Transdisciplinary professional learning and practice* (pp. 9-24). New York, NY: Springer.
- Mittelstrass, J. (2011). On Transdisciplinarity TRAMES (2011), 10.3176/tr.2011.4.01
- Moore, T.J., Stohlmann, M.S., Wang, H-H, Tank, K.M., Glancy, A.W. & Roehrig, G.H. (2014). Implementation and integration of engineering in K-12 STEM education. In: Strobel J., Purzer S., Cardella M. (eds) *Engineering in precollege settings: synthesizing research, policy, and practices*. Purdue University Press, Lafayette, IN
- Moore, T. J. (2008). STEM integration: Crossing disciplinary borders to promote learning and engagement. Invited presentation to the faculty and graduate students of the UTeachEngineering, UTeachNatural Sciences, and STEM Education program area at University of Texas at Austin, December 15, 2008.
- Morin, E., (1992). From the concept of system to the paradigm of complexity. *Journal of Social and Evolutionary Systems* 15 (4), 371- 385. JAI Press
- National Academy of Engineering (NAE) & National Research Council (NRC). (2014). *STEM integration in K-12 education: status, prospects, and an agenda for research*. The National Academies Press, Washington
- National Academy of Engineering and National Research Council [NAE & NRC]. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington: National Academies Press.
- National Research Council (2011a) *Learning science through computer games and simulations*. The National Academies Press, Washington, DC
- National Research Council. (2011b) *Report of a workshop of pedagogical aspects of computational thinking*. The National Academies Press, Washington, DC

- National Research Council. (2012a) A framework for K-12 science education: practices, crosscutting concepts, and core ideas. National Academies Press, Washington, DC
- National Research Council. (2012b) Discipline-based education research: understanding and improving learning in undergraduate science and engineering. National Academies Press, Washington, DC
- National Research Council. (2010). Report of a workshop on the scope and nature of computational thinking. The National Academies Press, Washington, DC
- Nègre, A. (1999). *A transdisciplinary approach to science and astrology*. Retrieved at 1 April 2018 from <http://cura.free.fr/quinq/02negre2.html>
- NGSS Lead States (2013) Next generation science standards: for states, by states. The National Academies Press, Washington, DC
- Nicolescu, B. (1985). *Nous, la particule et le monde* [We, the particle and the world]. Paris, France: Le Mail.
- Nicolescu, B. (2000). Transdisciplinarity and Complexity. Bulletin Interactif du CIRET, Paris.
- Nicolescu, B. (2002). Manifesto of transdisciplinarity [Trans. K-C. Voss]. New York, NY: SUNY.
- Nicolescu, B. (2004). Gurdjieff's philosophy of nature. In J. Needleman & G. Baker (Eds.), Gurdjieff (pp. 37-69). New York, NY: The Continuum International Publishing Group.
- Nowotny, H. (2003). Democratizing expertise and socially robust knowledge. *Science and public policy*, 30(3), 151-156.
- NSF Report. (2008). Fostering Learning in the Networked World. National Science Foundation. Retrieved at March 2018 from <http://www.nsf.gov/pubs/2008/nsf08204/nsf08204.pdf>.
- NSTA Report. (2008). Technology in the Secondary Science Classroom. National Science Teachers Association. (Eds) Bell, L. R., Gess-Newsome, J., and Luft, J.
- Pedaste, M., & Palts, T. (2017). Tasks for Assessing Skills of Computational Thinking. The 2017 ACM Conference
- Psycharis, S., & Kotzampasaki, E. (2017). A Didactic Scenario for Implementation of Computational Thinking using Inquiry Game Learning. In *Proceedings of the 2017 International Conference on Education and E-Learning* (pp. 26-29). Published by ACM.
- Psycharis, S. (2015). The Impact of Computational Experiment and Formative Assessment in Inquiry Based Teaching and Learning Approach in STEM Education. *Journal of Science Education, and Technology* .25(2),316-326 (JOST) DOI 10.1007/s10956-015-9595-z
- Psycharis, S. (2016). Inquiry-based computational experiment, acquisition of threshold concepts and argumentation in science and mathematics education. *Journal of Educational Technology & Society*, 19(3), 282.
- Psycharis, S., Kalovrektis, K., Sakellaridii, E., Chatzarakis, G. & Oikonomopoulou, M. (2018). Physical Computing, Computational Thinking, and Computational Experiment in Engineering Pedagogy. An implication for the Engineering Education Epistemology. EDUCON 2018-IEEE Global Engineering Education Conference. Submission Type / Conference Track: Special Session: IT and Engineering Pedagogy" - ITEP'18.
- Psycharis, S., Kalovrektis, K., Sakelalridi, E., Korres, K., & Mastorodimos, D. (2017). Unfolding the Curriculum: Physical Computing, Computational Thinking and Computational Experiment in STEM's Transdisciplinary Approach. *European Journal of Engineering Research and Science (EJERS)*, I.F. 0.65. DOI 10.24018/ejers.2018.0., <http://www.ejers.org/index.php/ejers/article/view/639/0>
- Ramadier, T., (2004). Transdisciplinarity and its challenges: the case of urban studies. *Futures* 36, 423-439.
- Roehrig, G. H., Moore, T. J., Wang, H. H., & Park, M. S. (2012). Is adding the E enough?: Investigating the impact of K-12 engineering standards on the implementation of STEM integration. *School Science and Mathematics*, 112(1), 31-44.
- Rorty, R. (1991). Objectivity, relativism, and truth. *Philosophical papers (Vol I)*. Cambridge, England, UK: Cambridge University Press.
- Rugarcia, A., Felder, R. M., Woods, D. R. & Stice, J. E. (2000). The future of engineering education: I. A vision for a new century. *Chemical Engineering Education*. 34, 16-25
- Sanders, M. (2009). STEM, STEM education, STEMmania. *The Technology Teacher, December/January*, 20-26.
- Satchwell, R. E., & Loepf, F. (2002). Designing and implementing an integrated mathematics, science, and technology curriculum for the middle school. *Journal of Industrial Teacher Education*, 39 (3), 41-66.
- Schnittka, C. G., Bell, R. L., & Richards, L. G. (2010). Save the penguins: Teaching the science of heat transfer through engineering design. *Science Scope*, 34(3), 82-91.

- Shahali, E. H. M., Halim, L., Rasul, M. S., Osman, K., & Zulkifeli, M. A. (2017). STEM Learning through Engineering Design: Impact on Middle Secondary Students' Interest towards STEM. *EURASIA Journal of Mathematics, Science and Technology Education*, 13(5), 1189-1211.
- Shirey, K. (2017). Teacher Productive Resources for Engineering Design Integration in High School Physics Instruction (Fundamental). In Proceedings of the 2017 ASEE Annual Conference, Columbus, OH, June 2017.
- Spiro, R. J., W. L. Vispoel, J., Schmitz, A., Samarapungavan, and Boerger, A. (1987). Knowledge acquisition for application: Cognitive flexibility and transfer in complex content domains. In Executive Control Processes, eds. B. C. Britton and S. Glynn. Hillsdale, NJ: Erlbaum.
- Stohlmann, M. S., Moore, T. J., & Roehrig, G. H. (2012). Considerations for teaching integrated STEM education. *Journal of Pre-College Engineering Education Research*, 2(1), Article 4.
- Stokols, D. (2011). Transdisciplinary action research in landscape architecture and planning: Prospects and challenges. *Landsc. J.* 2011, 30, 1-5.
- Toomey, A.H., Markusson, N., Adams, E. & Brockett, B. (2015). 'Inter- and trans-disciplinary research: a critical perspective'. GSDR 2015 Brief. New York, NY: United Nations (<https://sustainabledevelopment.un.org/content/documents/612558-Inter-%20and%20Trans-disciplinary%20Research%20-%20A%20Critical%20Perspective.pdf>).
- Tsupros, N., Kohler, R. & Hallinen J., (2009). *STEM education: A project to identify the missing components*, Intermediate Unit 1 and Carnegie Mellon, Pennsylvania.
- Tucker, A., McCowan D., Deek F., Stephenson C., Jones J. & Verno, A. (2003). A model curriculum for K-12 computer science: Report of the ACM K-12 Task Force Computer Science Curriculum Committee. *Association for Computing Machinery ACM*, New York, NY, 2003.
- Vasquez, J., Sneider, C., & Comer, M. (2013). STEM lesson essentials, grades 3-8: integrating science, technology, engineering, and mathematics. Portsmouth, NH: Heinemann.
- Voogt, L., Fisser, P., Good, J., PunyaMishra, P., Yadav, A. (2015). Computational thinking in compulsory education: Towards an agenda for research and practice. *Education and Information Technologies*, 2015, Volume 20, Number 4, Page 715.
- Wang, H., Moore, T., Roehrig, G., & Park, M.S. (2011). STEM Integration: Teacher perceptions and practice. *Journal of Pre-College Engineering Education Research*, 1(2), 1-13.
- Watson, A.D., Watson, G. H. (2013). Transitioning STEM to STEAM: Reformation of Engineering Education. *Journal for Quality and Participation*, Vol 36, No.3, pp. 1-5.
- Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining Computational Thinking for Mathematics and Science Classrooms. *Journal of Science Education and Technology*, 25(1), 127-147. DOI: 10.1007/s10956-015-9581-5
- Wickman, P. (2004). The practical epistemologies of the classroom: A study of laboratory work. *Science Education*, 88(3), 325-344.
- Wilber, K. (2001). *The theory of everything*. Boston, MA: Shambhala.
- Wilber, K. (2003). Foreword. In F. Visser, Ken Wilber: Thought as passion (pp. xi-xv). New York, NY: SUNY Press.
- Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, 49(3), 33-35.
- Wing, J. M. (2008). Computational thinking and thinking about computing. *Philosophical transactions of the royal society of London A: mathematical, physical and engineering sciences*, 366(1881), 3717-3725.
- Yadav A, Zhou N, Mayfield C, Hambruch S & Korb JT (2011). Introducing computational thinking in education courses. In: Proceedings of the 42nd ACM technical symposium on Computer science education, ACM, pp 465-470
- Yaşar, O. (2003). Teaching Science through Computation. *International Journal of Science, Technology and Society*. Vol. 1, No. 1, 2013, pp. 9-18. doi: 10.11648/j.ijsts.20130101.12
- Yaşar, O. (2004). Computational math, science and technology: A new pedagogical approach to math and science education. In: Lagana, A., Gavrilova, M.L., Kumar, V., Mun, Y., Tan, C.J.K., Gervasi, O. (eds) ICCSA 2004. LNCS, vol.3045, pp.807-816. Springer, Heidelberg (2004)
- Yaşar, O. (2013). Teaching Science through Computation. *International Journal of Science, Technology and Society*. Vol. 1, No. 1, 2013, pp. 9-18. doi: 10.11648/j.ijsts.20130101.12
- Yaşar, O., Landau, R (2003): Elements of CSE Education. *SIAM Review*. 45(4), 787-805.

- Yaşar, O., Veronesi, P., Maliekal, J. & Little, L. (2015) "Computational Pedagogical Content Knowledge (CPACK)," in D. Slykhuis & G. Marks (Eds.), *Proceedings of Society for Information Technology & Teacher Education Conference 2015* (pp. 3514-3521).
- Yasar O., Veronesi P., Maliekal J., Little L. J., Vattana S. E. & Yeter I. H. (2016). Presented at: ASEE Annual Conference and Exposition. Presented: June 2016. Project: SCOLLARCIT
- Yu, J., Luo, Y., Sun, Y., & Strobel, J. (2012). A conceptual K-6 teacher competency model for teaching engineering. *Procedia-Social and Behavioral Sciences*, 56(8), 243-252.
- Yu, J.H., & Strobel, J. (2011). Instrument Development: Engineering-specific Epistemological Epistemic and Ontological Beliefs, *Proceedings of the Research in Engineering Education Symposium*, pp. 1-8, 2011.
- Zendler, A. & Spannagel, C. (2008). Empirical Foundation of Central Concepts for Computer Science Education. *ACM Journal on Educational Resources in Computing*, 8(2), 6.
- Zscheischler, J., Rogga, S., & Busse, M. (2017). The Adoption and Implementation of Transdisciplinary Research in the Field of Land-Use Science – A Comparative Case Study. *Sustainability*, 9(11), 1926.