Research Framework for Serious Educational Games: Understanding Computational Thinking in Pasteur's Quadrant

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Abstract

There is an ongoing interest in education with using technology to support students learning through complex tasks. Reference [1] and [2] both emphasized that computational thinking (CT) is a fundamental skill for everyone in the 21st century. There is a need to understand how people interact with computation, and learn to think through the language of computation, in the field of education. We suggest that Serious Educational Games (SEGs) is one of the viable approaches in understanding the learning sciences on computational thinking by adopting the research strategy called Pasteur's quadrant. Employing SEGs has the potential for modeling both individual and distributed computational thinking, which may lead to advances in understanding of those processes in an ecologically valid setting.

Keywords

Computational Thinking; Serious Educational Games; Pasteur's Quadrant; Cognitive; Learning Sciences; Impulse Theory

Introduction

Serious Educational Games (SEGs) are becoming more pervasive, and as such there needs to be a research framework for the community to follow. According to [3], SEGs are electronic or computer-access games that are designed to target K-20 content knowledge. These games allow teachers and students to connect real-world scenarios with school curriculum and content. There are many benefits that are associated with video games, including the inherent motivational aspects of gameplay, complex logical reasoning, interactivity, and developing expertise, that may foster learning [4] [5] [6]. Thus, the strength of SEGs has distinguished them from many other traditional learning contexts.

The fundamental level of computer-based games can be described as the systems of rules in which players operate on representations; those rules are generally executed and enforced by the game itself [7]. Reference [8] listed three basic rules governing any game: (a) implicit rules (the unwritten rules of the game and concern proper game behavior and etiquette), (b) operational rules (the explicit instructions that guide the behavior of players) and (c) constitutive rules (the underlying mathematical structure or the game's own logic that exists independently from the player). It can be proposed that computational thinking is the required process used to identify rules and internal relationships of games, and SEGs in particular.

Computational Thinking (CT)

There is an increased research interest in understanding how people interact with computation, and learn to think through the language of computation, in the field of education [1]. In the report [1], computational thinking (CT) can be defined as using the methods, language, and systems of computer science to understand a wide variety of topics, ranging from designing the computational models of scientific phenomena to creating algorithms to solve hard problems efficiently. Seymour Papert in *Mindstorms* [9] coins this type of thinking as "procedural thinking" which learners use programmatic representations and symbol systems to solve problems. Reference [10] describes computational thinking as the "cognitive pillar" of computational literacy.

Reference [1] and [2] both emphasized that computational thinking is a fundamental skill for everyone. According to [1], it states that many directed CT at only scientists and engineers but by implication, CT is relevant to a broad range of individuals in various fields including linguistics, archeology and law. CT involves problem solving, analytical thinking, systems design, and understanding human behavior [1]. Reference [2] stated that CT is not equivalent to computer programming; instead, it requires thinking at multiple levels of abstraction as CT is using abstraction and decomposition to tackle a complex problem or design a large complex system.

Reference [1] uses the term *distributed computational thinking* in order to describe it as one social aspect that distinguishes computational thinking from computer science. By this definition, computational thinking as a process is not restricted to programmers and computer science students. Rather, CT is a systematic thinking habit which guides people to solve problems creatively and effectively. Thus, it is critical for researcher to look into ways of how to inspire the public's interest in CT.

Research Framework of CT and SEGs (Pasteur's Quadrant)

This paper argues that the research of SEGs have much to offer the learning sciences on computational thinking by adopting the research strategy that Donald Stokes called *Pasteur's quadrant* [11]. His quadrant model of scientific research has been transforming the standard one-dimensional view that science progresses from pure to applied research to engineering implementation to a two-dimensional dynamic way to link research in a dual dichotomy and a fourfold table or quadrants (see Fig. 1).

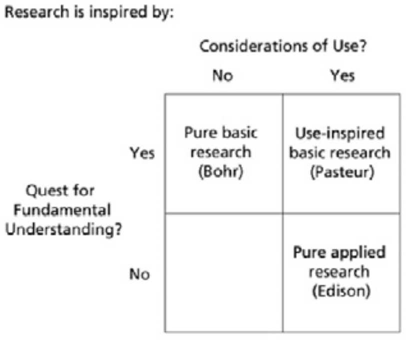


FIG. 1 QUADRANT MODEL OF SCIENTIFIC RESEARCH [11]

The upper left quadrant "includes basic research that is guided solely by the quest for understanding without thought of practical use" [11] (p.73) such as Niels Bohr's quest of a model atomic structure. The lower right quadrant "includes research that is guided solely by applied goals without seeking a more general understanding of the phenomena of a scientific field" [11] (p.74). The knowledge was usually contributed by inventor and industrial research laboratory, and therefore, is also known as "Edison's quadrant." The upper right quadrant "includes basic research that seeks to extend the frontiers of understanding but is also inspired by considerations of use" (p.74). Stokes calls it Pasteur's quadrant to illustrate how research is driven by the desire to solve practical problems. Such problems inspire and set concrete goals for research; using empirical data to understand the underlying sciences. Stokes does not name the lower left quadrant as there are too few examples to merit a name. This quadrant defines as "research that is inspired neither by the goal of understanding nor by the goal of use" (p.74). One might well question the purpose of research driven neither by a desire for basic understanding nor a defined use for the outcomes.

Stokes further emphasizes the dynamic importance of research in Pasteur's quadrant. Fig. 2 illustrates the interaction of science and technology, including the role of new research technologies in the creation of operational technologies, as well as the availability of commercialized measurement methods that may support new fundamental science. Reference [12] [13] and [14] have suggested that educational research and cognitive psychology should be working in Pasteur's quadrant in order to develop deeper scientific understanding in conjunction with practical and useful applications of that knowledge to improve learning. Reference [14] stated that human mind represents very complex mechanisms that are hidden deeply in the billions of interconnected neurons and neural circuits, in effect an emergent property of numerous, interconnected systems. It may be more useful for a researcher to study the problems at the level of normal, representative mental function under a particular context than to seek to explain global phenomena, in light of the need for applicability.

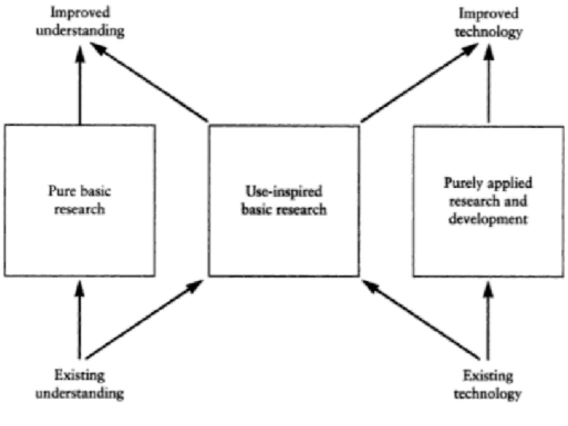
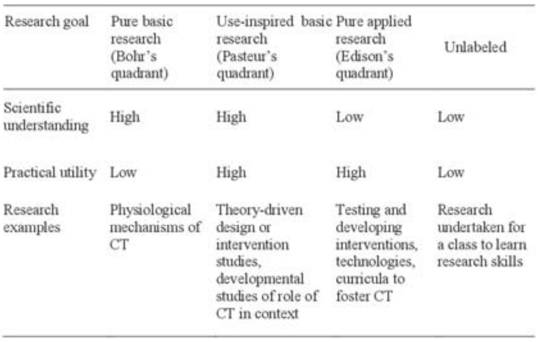


FIG. 2 A REVISED DYNAMIC MODEL [11]

There is a need to employ use-inspired basic research, or work in Pasteur's quadrant, to understand computational thinking in an educational context (see Table 1). Researchers should strive to contribute to basic scientific understanding of CT, as well as develop useful ideas to improve CT in educational settings. Work in Edison's quadrant, on the other hand, may also serve to provide insight on the practicality of interventions and technologies.

TABLE 1 DIFFERENT TYPES OF RESEARCH IN COMPUTATIONAL THINKING



Research goal	Pure basic research (Bohr's quadrant)	Use-inspired basic research (Pasteur's quadrant)	Pure applied research (Edison's quadrant)	Unlabeled
Scientific understanding	High	High	Low	Low
Practical utility	Low	High	High	Low
Research examples	Physiological mechanisms of CT	Theory-driven design or intervention studies, developmental studies of role of CT in context	Testing and developing interventions, technologies, curricula to foster CT	Research undertaken for a class to learn research skills

As in the field of learning sciences, it is important to apply Pasteur's quadrant strategy in understanding the theory-driven intervention on CT, as well as the developmental role of CT in the context of SEGs. Reference [15] explored how the theory-driven game design tools foster middle school students' computational thinking ability, yet were not able to establish a causal link between CT and games. The limited research in this area indicates a need for more dedicated, longer series of studies in order to fully understand the effects of SEGs on CT development. The purpose of the paper is to introduce several research approaches in the study of CT and SEGs as the work in Pasteur's quadrant.

Computational Thinking in SEGs: A Situative Approach

Human-computer interaction and computational thinking can be examined in two approaches: the *individual cognitive* and *interactional* approaches. According to [16], individual cognitive research focuses on individual cognition and learning, whereas interactional study focuses on the whole activity system and identifies patterns of interaction. Reference [16] also discusses a research discipline in the learning sciences known as "situative." He defines this situative approach as "instead of focusing on individual learners, the main focus of analysis is on activity systems: complex social organizations containing learners, teachers, curriculum materials, software tools, and the physical environment" (p.79). From the situative perspective, learning scientists aim to explain how and why activities in a particular context result in changes in individual achievement. The goal is also to identify patterns of interaction in which the several components (human and nonhuman) of systems coordinate their behaviors as they participate in their joint activity.

Individual Cognition Approach: Cognitive and Metacognitive Perspectives on CT

Cognitive science is the interdisciplinary study of mind and its processes [17]; it focuses on the activities of individual as they solve problems, respond to stimuli, or make decisions, as well as the processes individuals use to construct, store, retrieve, and modify patterns of information [16]. To understand CT and how an individual can develop CT in formal and informal contexts, an analysis of computational thinking has been conducted. It has been broken down into three levels (see Table 2): (a) the information-processing analysis of CT, (b) cognitive structures of CT, and (c) metacognitive structure of CT.

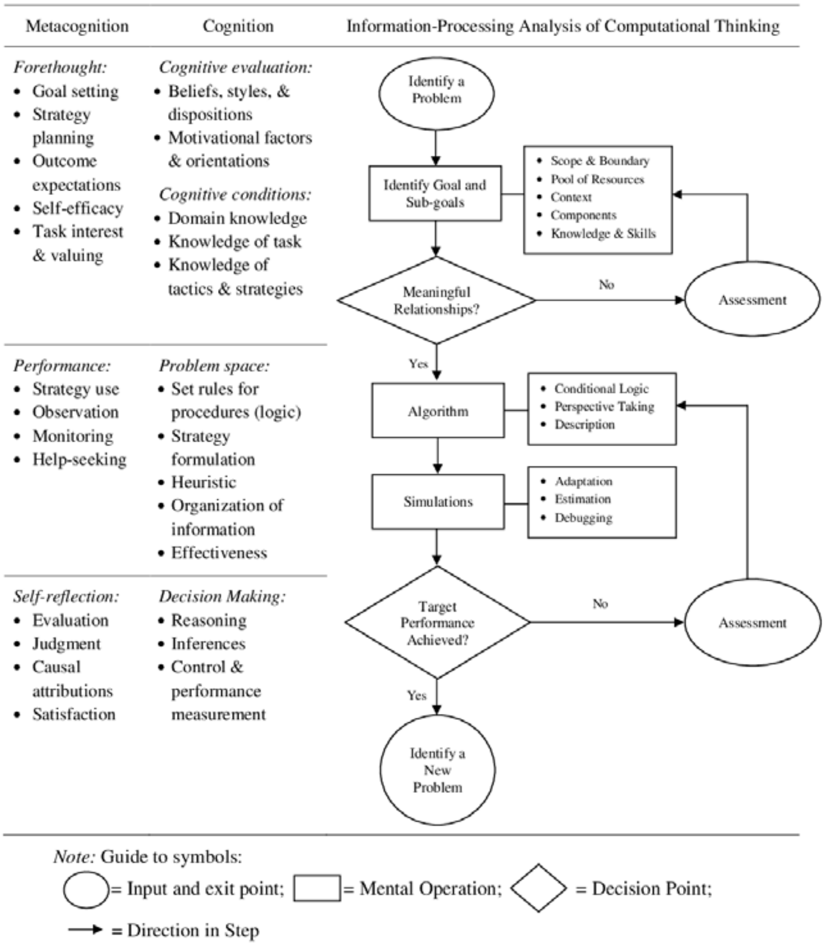
Information-Processing Analysis of CT

The information-processing theory evolved from Broadbent's famous filter theory, composed of a sequence of processing stages from input through encoding, memory storage and retrieval, to output [18] [19]. Hence, information-processing analysis traces the sequence of mental operations and their products in the performance of a particular cognitive task. By reference to [20], an information-processing analysis of CT involves the following mental processes: (a) identify a complex problem and collect as much information about the task and its content; (b) state the goal in the form of a representative test question; and (c) decompose the problem into its constituent components, each of which must be addressed (consciously or subconsciously) in order to attain the goal. The most well-matched subroutines are employed sequentially, with or without modification, to attempt to meet the goal; results are sometimes stored for later changes to the heuristics (subroutines) when facing a similar problem [21].

Cognitive Structure of CT

Research has shown that cognitive evaluation is necessary for the learner to determine how well a task meets one's needs and how competent and in control

TABLE 2 COGNITIVE AND METACOGNITIVE PERSPECTIVES ON THE PROCESS OF COMPUTATIONAL THINKING



Metacognition	Cognition	Information-Processing Analysis of Computational Thinking
Forethought: • Goal setting • Strategy planning • Outcome expectations • Self-efficacy • Task interest & valuing	*Cognitive evaluation:* • Beliefs, styles, & dispositions • Motivational factors & orientations *Cognitive conditions:* • Domain knowledge • Knowledge of task • Knowledge of tactics & strategies	
Performance: • Strategy use • Observation • Monitoring • Help-seeking	*Problem space:* • Set rules for procedures (logic) • Strategy formulation • Heuristic • Organization of information • Effectiveness	
Self-reflection: • Evaluation • Judgment • Causal attributions • Satisfaction	*Decision Making:* • Reasoning • Inferences • Control & performance measurement	

Note: Guide to symbols:
◯= Input and exit point; ▭= Mental Operation; ◇ = Decision Point;
→ = Direction in Step

one feels when completing a task, and specifies factors correlated to intrinsic motivation [22] [23] [24]. Prior to solving a problem, the individual then has to recognize the conditions of that problem, and apply, with or without adaptation, the best available sequence of steps [25].

Reference [26] proposed that task performance was affected by knowledge of content, discourse, and strategies. Her study showed that students' writing performance would be influenced by their language processes (decoding and comprehension), ability to monitor their performance (metacognition), as well as their knowledge of content (domain knowledge). Studies also showed that domain knowledge plays an important role in task performance and in the development of expertise [27] [28]. Domain-specific knowledge, as defined by [29], as "the declarative, procedural, or conditional knowledge one possesses relative to a particular field of study" (p.376). Declarative knowledge refers to factual information; procedural knowledge refers to knowledge about how to do things; whereas conditional knowledge refers to when and where to access particular facts and procedures [29] [30]. Therefore, the quality and quantity of domain-specific knowledge is essential to initiate the effective learning on CT which is indicated in Table 2 "cognitive conditions."

Since a significant portion of CT is problem solving, in developing the instructions a computer (or human) must execute to solve a problem, one must view the initial problem state and the goal state within a problem space. A problem space is "the universe of all possible actions that can be applied to solving a problem, given any constraints that apply to the solution of the problem" [31] (p.437). During the process, algorithms will be listed out, strategy will be formed, a set of rules is organized hierarchically, and heuristics maybe used as a mental short-cuts for solving problem. Finally, a conscious decision on whether or not the target performance has been achieved through reasoning and evaluation. Frequently, this decision to select a heuristic and evaluation of the outcome is rooted in what solution appears acceptable, rather than ideal [32].

Metacognitive Structure of CT

In order to activate and sustain a learner's behavioral conduct, cognitive and affective function, one must focus on the process of self-regulated learning. Reference [33] defined self-regulated learning as a process that learners are "metacognitively, motivationally, and behaviorally active participants in their own learning process" (p.4). A main aspect of self-regulation is metacognition, which includes planning, monitoring, and regulating activities. Metacognition is often referred to as thinking about thinking [34]. Therefore, in this analysis (Table 2), we consider metacognitive processes in CT as domain general and metacognitive skills to be transferable across contexts [35].

Reference [36] states that "solving a complex problem requires more than mere knowledge; it requires the motivation and personal resourcefulness to undertake the challenge and persist until a solution is reached" (p.233). They proposed a three-phase cyclical model in self-regulatory processes involving forethought, performance, and self-reflection (see Fig. 3). The cyclical nature stems from its reliance on feedback from prior performance efforts to make adjustments during current efforts. In brief, task analysis processes and self-motivation beliefs are the two major categories of the *forethought phase*; the *performance phase* focuses on implementing a particular method and their self-observation on particular outcomes; and the *self-reflection phase* involves self-judgments and self-reactions [37].

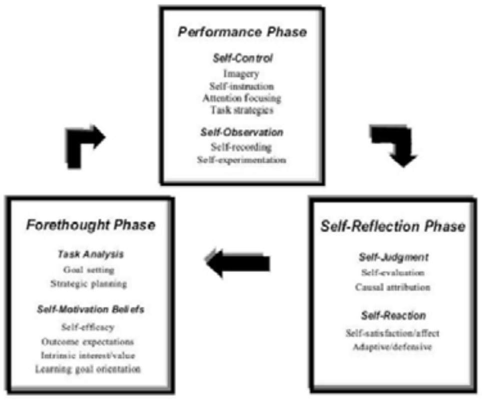


FIG. 3 SELF-REGULATORY PHASES AND PROCESSES [36]

Throughout the sequence of mental operations CT, learners have opportunities to use metacognition to monitor the properties of information, their declarative and procedure knowledge, and their cognitive experience in order to maintain one's motivation during problem-solving (and CT in this case) in a variety of contexts. Moreover, learners in the Zimmerman and Campillo's three-phase cyclical model will experience a sense of personal agency that can sustain long-term solution efforts.

Interactional Approach: Information-Processing Model of SEGs.

A working model of computational thinking must first take into account the various subtasks that are involved in the interaction of the mind with the computer interface (see Fig. 4). Regardless of the type of computer interface being used, information must first reach the brain through sensory perception, although which regions of the brain are activated is dependent upon the specific computer activity. For our purposes, a SEG that involves both text and graphics will be used as an example. In this case, information must be processed visually (disregarding auditory inputs for purposes of simplicity), but the sensory information is rapidly dispersed in accordance with the properties; tracking the motion of an object and recognizing what the object happens to be are handled with two discrete portions of the brain [38]. The textual portions of the screen must then be processed by the language centers in the left parietal lobe, while the relative positions and movements of on-screen objects are dealt with in spatial reasoning areas in the right parietal lobe. Language processing is then linked to the phonological loop (short-term memory dedicated solely to language, whether it is written or spoken). All three active areas (phonological loop, ventral visual stream, and spatial reasoning module) in turn activate the working memory, in which the conscious decisions regarding the onscreen activities, including anything that might foster learning, are made.

Unlike a personal computer, the human mind seems to be poorly adapted to running tasks in parallel, and is only capable of concentrating on one incoming stimuli at a time [39]. Rather, while the subconscious processes run simultaneously, all are necessary to complete a given cognitive task, and different tasks appear to be completed in unison through rapid attentional shifts; sharing attention between two or more tasks is shown to rapidly degrade performance in each task [40] [41]. Given this information, it is particularly important in designing and implementing computer-based activities, including SEGs, that the number of perceptual inputs is kept to a minimum and distracters (a student listening to music or verbal

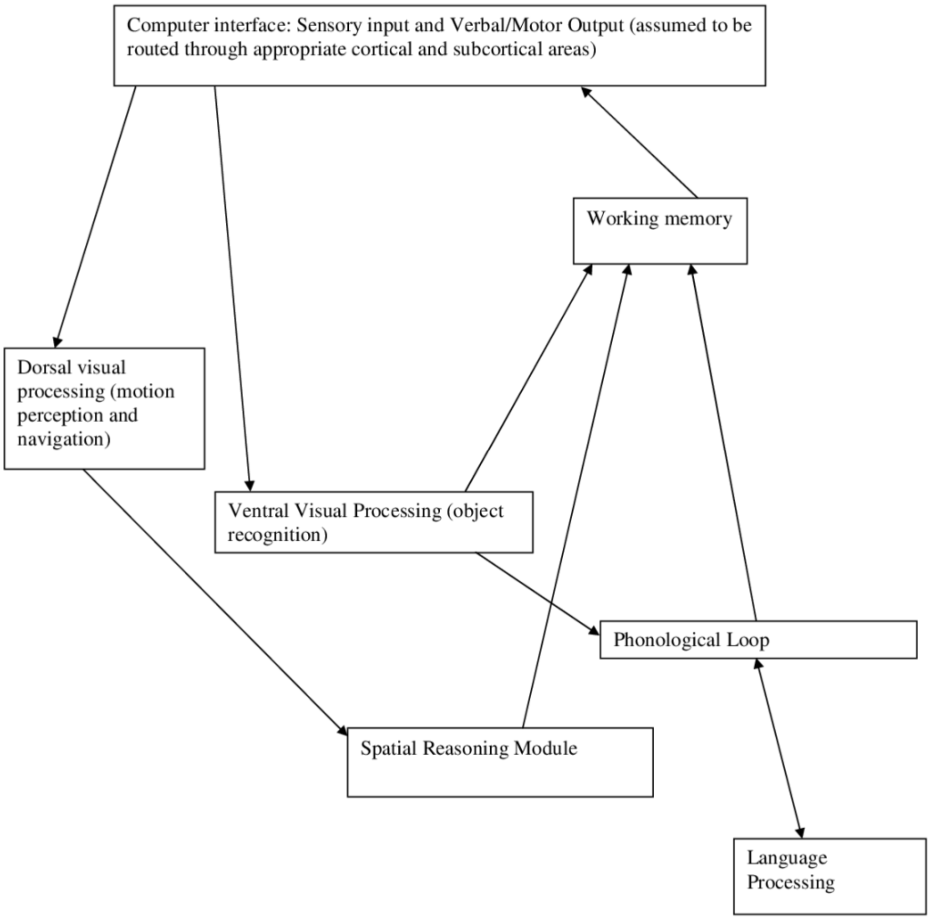


FIG. 4 AN INFORMATION-PROCESSING MODEL ON COMPUTATIONAL THINKING

instructions from the teacher whilst playing a SEG, for example) are eliminated.

Understanding how the information presented is processed, along with the nature of how that processing can be affected by other stimuli, is crucial to the development of computer activities that reduce cognitive load and the understanding of how individual differences and disabilities might create challenges in using such activities for educational purposes. However, the key to the development of quality SEGs and other computer-based educational activities is an understanding of the processes occurring in working memory, the cognitive load that those processes incur, and how those processes translate into learning.

The Uniqueness of SEGs in CT Development

Engagement is a crucial indicator of learning and the relationships that inform engagement are equally crucial. Learning and motivation are key components to the development of understanding student engagement. The *Len Diagram*, seen in Fig. 5 [42] revisits the relationship between competition, motivation and problem-based learning (PBL) with engagement. As it pertains to SEGs, engagement is key because it cognitively immerses the player, or in our work the game developer, on a level where they need to think computationally.

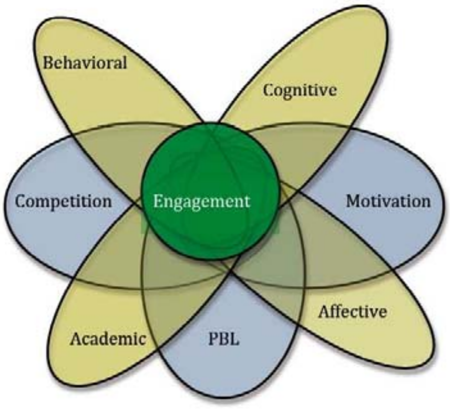


FIG. 5 LEN DIAGRAM

Double Helix of Thinking

If we can imagine the double helix of DNA as a visual representation of SEG research, we can then envision a framework of engagement in computational thinking. The double helix approach allows for a visual concept entailing threads or areas or research. Computational thinking needs to be transdisciplinary, as full engagement stems from activation of multiple information sources to garner attention [43].We often rely too heavily on isolated factoids, rather than interconnected concepts tied together through visualization, science process skills, socio-cultural situativity, and the ilk. Those intangibles that tie memory strands together are the protein connectors in the chromosome of computational thinking, linking related DNA strands Other protein bridges to be considered are 21st century assessments, ethics and entrepreneurship, backward design, predicting, testing, concluding, and perseverance.

Impulse Theory

Within narrative driven Serious Educational Games, there is a point where the game changes form and function not unlike a literary plot twist. Reference [44] called this change in game momentum *Impulse Theory*. This is where avatars and Non-Player Characters (NPCs) interact with each other and their reactions create a change in a games momentum. Impulse Theory can be viewed as a spin-off of Transactional Theory [45], which applies to literary criticism and the teaching of literature, suggesting a "reciprocal, mutually defining relationship" between the reader and the literary text. Narrative driven SEGs can be viewed as a more immersive form of literature where the player takes an epistemic perspective with a game character creating a similar relationship as that defined in Transactional Theory. So, in SEGs there is a transactional relationship but unlike static literary text SEGs are dynamic and the story changes based on player decisions. Impulse is defined in physics as the force that changes an object's momentum, which is an integral force with respect to time. Impulse Theory is impacted by the computational thinking ability of the player and, in essence, is the integral force that changes the Flow of game play. Designing SEGs require the developer to use basic computational models such as if/then/else, loops, cause-and-effect, input/output, etc.

The visual representation depicted by the *Len Diagram* (Fig. 5) can inform the theory by illustrating the connections and overlaps for the integration of the factors of engagement. With the informative nature of the *Len Diagram* it can be used to drive the development of the theory by showing areas and factors of interaction where research can take place.

The *Len Diagram* suggests that the development of a SEG can be accomplished through the proper blending and overlap of the characteristics shown to make up engagement. Through movement of the engagement circle, appropriate measure using the Student Engaged Learning in a Technology Rich Interactive Classroom (SELTIC; [42]) and use of the elements motivation, competition and PBL it is possible to create a proper "mix" resulting in the proper placement of the engagement circle.

Conclusion

The synthesis of various strands of cognitive and learning sciences research in this paper has resulted in both a working model of computational thinking, a specific example as related to SEGs, and a definition that unites the key themes in the current literature on CT. This final addition is essential to moving research in CT forward, and in creating the opportunity for CT research to be conducted in Pasteur's quadrant; in effect, the combined research on computational thinking and SEGs allows us an avenue to pursue knowledge that will both further the theoretical understanding of CT and translate directly to greater levels of engagement and learning in the classroom. We suggest that SEGs are the viable means of conducting this research and, more importantly, of marrying the diverse elements of engagement whilst providing learner the opportunity to improve their computational thinking and 21st century skills. Employing SEGs in this role also has the potential for modeling both individual and distributed CT, which may lead to advances in understanding of those processes in an ecologically valid setting. Given the applicability of CT to every day problem solving, and the greater incorporation of technology into society, the goal of explicitly improving computational thinking seems necessary to the advancement of the learners of this and future generations.

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