Alfaro-Ponce et al., *Cogent Education* (2023), 10: 2191751
https://doi.org/10.1080/2331186X.2023.2191751

cogent education

Received: 01 February 2023
Accepted: 09 March 2023

*Corresponding author: Azeneth Patiño, Institute for the Future of Education, Tecnologico de Monterrey, Monterrey, Nuevo León 64700, Mexico
E-mail:azeneth.patino@tec.mx

Reviewing editor:
Marcin Gierczyk, University of Silesia: Uniwersytet Slaski w Katowicach, Poland

Additional information is available at the end of the article

INFORMATION & COMMUNICATIONS TECHNOLOGY IN EDUCATION | RESEARCH ARTICLE

Components of computational thinking in citizen science games and its contribution to reasoning for complexity through digital game-based learning: A framework proposal

Berenice Alfaro-Ponce[1], Azeneth Patiño[1]* and Jorge Sanabria-Z[1]

Abstract: Education has undergone many changes in teaching and learning, intensified by the significant technological developments that have responded to the fourth industrial revolution and other emergent situations. In this context, developing information and communication technologies has become vital in supporting new ways and learning models in the various educational levels to address a complicated environment where individuals must have complex and computational

Berenice Alfaro-Ponce

ABOUT THE AUTHORS

Berenice Alfaro-Ponce holds a Ph.D. in Social Sciences from the Autonomous University of the State of Hidalgo (UAEH). During her doctoral studies, she completed a research stay as an ERASMUS scholar at the University of Łódź. Moreover, she received a master's degree in Human Rights and Democracy from FLACSO, and a Bachelor's in International Relations from the Autonomous University of Guadalajara (UAG). Currently, she is a member of the National System of Researchers, level 1.
Azeneth Patiño, Ph.D in Educational Technology from the Faculty of Education at Laval University. Postdoctoral Researcher of the R4C-IRG research group at the Institute for the Future of Education (IFE) at Tecnológico de Monterrey. Her lines of research focus on Digital Game-based Learning, ICT integration in Formal Education for the development of 21st-century skills, Teaching, and Learning Second languages, and the use of emerging technologies in Continuing Education and Lifelong Learning.
Jorge Sanabria-Z, Received his PhD in Kansei Science (Affective Engineering) from the Center for Advanced Research in Neuroscience, Behavior and Kansei at the University of Tsukuba, Japan. He did a postdoctorate at the University of Guadalajara where he developed the Gradual Immersion Method, aimed at enhancing creative cognition. He is a member of the National System of Researchers (SNI) level 1, whose interest focuses on issues of creative cognition and development of 21st century competencies.

PUBLIC INTEREST STATEMENT

Nowadays, the fourth industrial revolution brought with it an evolution of emerging teaching-learning methods, which leads us to bet on these changes in our educational systems and where the incorporation of new technologies is crucial for new global configurations and challenges. Therefore, by adopting new teaching methods and strategies, such as the digital game-based learning approach, individuals can acquire the 21st-century computational and complex thinking skills and competencies needed for problem-solving. Considering this strategy and the urgency of addressing the major problems generated by the Anthropocene era, the citizen science perspective is an interesting emerging component that contributes to research projects while developing scientific vocations among citizens and by contributing to the development of these competencies. It is thereby important to discuss the generation of a framework aimed at developing problem-solving competencies, founded on digital game-based learning and citizen science

skills to respond to challenges. This study proposes a complex thinking framework that links citizen science and digital game-based learning to develop university students' computational thinking skills. The results indicate that (a) it is possible to consider the sub-competencies of complex thinking in the design of a digital citizen-science game to develop computational thinking, and (b) the digital game-based learning framework for citizen science topics can potentially increase students' engagement and teamwork in data collection and analysis while building their knowledge and computational thinking skills, and their complex thinking competency and sub-competencies.

Subjects: Educational Research; Higher Education; Education - Social Sciences

Keywords: Educational innovation; higher education; computational thinking; reasoning for complexity; citizen science

1. Introduction

The 21st century has been characterized by significant technological changes and their positive impact on society; however, demanding societal and environmental challenges have also arisen. In this context, we can observe that many scientific advances in different disciplines are based on technology, including medicine (Amisha et al., 2019; Shelton et al., 2017), biology (Fatimah et al., 2020; Johnson et al., 2020) and chemistry (Gomollón-Bel, 2019; Quinlivan et al., 2020), among others. These innovations contribute, for example, to improving life expectancy and quality of life thanks to new drugs and economic growth, among others (He & Li, 2020). Despite these positive developments, another scenario as these technologies evolve presents problems, those associated with the Anthropocene era, where human activity has an environmental impact with social and economic effects, among others (UNDP, 2020). An example is the migration or displacement of people due to the scarcity of natural resources or the violence associated with their exploitation (Baldwin et al., 2019; Bettini, 2019). In this sense, the 21st century is a highly tumultuous period that requires attention, through formal and nonformal education, using a complex approach to assimilate the technological evolution for problem-solving to benefit societies.

Currently, in higher education, the discussion on developing ways of thinking has been approached as an alternative to train critical citizens to resolve surrounding problems. Several are the skills and competencies that have been addressed and the importance they have in the formative processes and their impact on the development of people; for example, in the workplace, the discussions are about improving the performance and activity of workers, both within their workspaces and external interactions (Baird & Parayitam, 2019; Moore & Rudd, 2004; Rios et al., 2020). Another example is all levels in education, where these skills and competencies allow students to acquire knowledge more critically and articulately regarding what surrounds them (Rebele & St. Pierre, 2019). Also, there is the example of ordinary people who possibly have not passed through all educational levels, but life-long learning is fundamental for their daily lives (Burns, 2020; J. Kim & Park, 2020; Nygren et al., 2019); it allows them to experience activities that let them coexist with the environment. Thus, educational institutions are committed to including these skills and competencies in their educational models. Developing competencies and skills have become essential to respond to the disruption in various fields in today's world.

Globalization and Industry 4.0 have brought significant technological development worldwide that has altered some everyday activities and the interaction of actors and social dynamics, requiring new approaches and methods to address them. In this sense, education has benefited from the introduction of new technologies since the teaching and learning environment has moved from a traditional methodology to novel ones, where the use of technologies and methodologies has a fundamental impact on learning (Y.-C. Chen et al., 2021; French et al., 2020; Halasa et al., 2020). Education 4.0 is where the development, use, and application of new information and communication technologies have become critical to face the vertiginous changes taking place in the world (Keser & Semerci, 2019). Other phenomena of these trends have become significant, such as open science and its proposal for another way to conduct and share science (UNESCO, 2021). It presents novel spaces for knowledge development with different forms of interaction and communication among multi-disciplinary actors.

1.1. The relevance of pedagogical approaches: using digital game-based learning in citizen science

The teaching-learning process is crucial to education, which has been modified with relevance thanks to introducing new technologies. Like other social phenomena, education has developed per the various vertiginous international and local changes. In this sense, teaching methods have had to evolve to respond to the different demands (Hägg & Gabrielsson, 2020; Krishnakumaryamma & Venkatasubramanian, 2018; Valverde Berrocoso et al., 2020). Traditional teaching methods are no longer sufficient for the contemporary educational process, where advances in technology and communication are paramount for a thriving educational environment. Therefore, it is pertinent to integrate the technologies and transit to Education 4.0 to enhance results (Aziz Hussin, 2018; Bonfield et al., 2020; Cordeiro De Oliveira et al., 2022). Some new strategies are associated with teaching methods based on games, which have gained tremendous popularity due to greater access to information and communication technologies.

Pedagogical approaches, teaching-learning methods, and strategies undergo significant changes as technological development progresses. Pedagogical approaches emphasize diverse teaching and learning strategies, such as game-based learning with challenges (Gallagher & Savage, 2020) and problem-based learning (Guo et al., 2020; Tan, 2003; Troussas et al., 2020), among others. Pedagogical approaches are characterized by developing their methodologies and specific objectives to strengthen learning (Mavlonov, 2022). Different studies indicate that the choice of an appropriate pedagogical approach for students and their environment significantly impacts the success of students' learning. Thus, the importance of pedagogical approaches in education lies in enabling teachers to adapt their teaching methodologies to the needs and characteristics of their groups of students, leading to their better understanding and retention of knowledge (Bascopé et al., 2019; Lozano et al., 2019). The pedagogical approach is crucial in higher education as it enables university students to acquire the competencies and skills required by the labor market. So, professors must adapt their teaching methodology to meet these students' emerging needs.

Citizen science is a movement considered a key strategy of open science. While there are several similar concepts about citizen science (Haklay, 2018; Kullenberg & Kasperowski, 2016), noticeably, it can be described as a way of involving and sometimes engaging people in the process of scientific research. It is an initiative in which any interested person can actively participate in different research stages, such as data collection, observation of natural phenomena, and information analysis, to advance scientific knowledge (ECSA, 2015). Mainly, citizen science is based on collaboration among professional researchers or research centers and non-specialists (citizens of all ages), who collect data and analyze information. In this sense, some studies question how citizen science contributes bidirectionally to learning processes for the citizen when these are not necessarily of educational approach, as well as the impact on public policy issues or industry (Alfaro-Ponce, Sanabria-Z, et al., in press). Therefore, citizen science, having as its main characteristic the massive participation in data generation, has been placed as an effective basis for open science; it is a transformation agent of traditional science.

Citizen science can be accessible to all citizens, regardless of age, and depending on the type of project, citizen involvement can be a means of knowledge transfer. Historically, citizen science has had a more significant development in natural and basic science topics (Frigerio et al., 2021), bringing citizens closer to the problems of their environment and fostering a culture of environmental care that may have a positive impact on decision-making and public policy planning. It provides researchers and authorities with accurate and updated information on the community's environmental and social problems. In recent years, this approach has been used to address social problems (Alexandra et al., 2021; Heiss & Matthes, 2017), where the results have been positive and noteworthy such as in the case of topics regarding gender-based challenges (Iyawa et al., 2021). Some research, like Alfaro-Ponce, Ibañez-Muñoz, et al. (in press), emphasizes the interesting contributions from learning aspects and knowledge transfer of citizen science projects to citizens. Therefore, it is considered an appropriate approach for pedagogical purposes in formal and nonformal education.

According to the above, citizen science's potential as an educational approach becomes evident. On the one hand, it encourages the active participation of citizens in scientific research and, on the other hand, it favors science-related decision-making, thus opening science to the general public and defining it as part of human activity in which people are capable of participating (Bonney et al., 2009; Einsiedel, 2021). Current scientific, social, and technological problems are complex and often have significant societal implications (Bonney et al., 2014). This is the case of the Anthropocene era, where human activity's causes and effects profoundly impact environmental issues and climate change (UNDP, 2020). In this respect, through citizen science, people are prepared to assume an active role in scientific research and a leading function in decision-making related to science and the understanding of current scientific and technological problems where, in addition, they can acquire new knowledge.

In recent years, the use of citizen science for educational purposes has increased. Several studies indicate that students from different educational levels can actively participate in scientific research through a citizen science approach (Alfaro-Ponce, Sanabria-Z, et al., in press). In this context, the citizen science perspective can support experiential learning in higher education and develop competencies and skills expected at this educational stage. At the same time, it also contributes to citizenship development by engaging them in the different stages of the projects (Sanabria-Z et al., 2022). In addition, through citizen science, higher education students can experience real contexts where they can put into practice different knowledge acquired in their professional training and thus address problems in their immediate surroundings.

Nowadays, several citizen science projects involve many people, so introducing new strategies to improve citizens' participation in these projects is becoming increasingly relevant. In this context, different valuable tools for citizen science have been noted, such as platforms where citizens register different activities (Liu et al., 2021) or mobile phones that have helped to massify the participants' activity even more (Graham et al., 2011). Game-based pedagogies are characterized by using games for learning reinforcement (Shohel et al., 2022) and may or may not use digital media. Research such as Tobias et al. (2014) and Y. J. Kim and Ifenthaler (2019) has demonstrated student games' effectiveness in engagement, motivation, and learning progress. However, some studies emphasize that external motivational elements influence the success of these games (Erhel & Jamet, 2013). These strategies and tools can be used as educational resources that support, in a particular manner, the generation of new knowledge for the participants and the enhancement of their technological skills (Squire & Jenkins, 2011). Therefore, using novel resources derived from technological advances can profoundly contribute to pedagogical approaches for citizens.

Game-based learning is a pedagogical approach that uses games and ludic activities to teach skills and knowledge. Authors such as C. C. Chen and Tu (2021), Prensky (2006), Serrano (2019), and Tokac et al. (2019) mention that game-based learning promotes enhanced knowledge acquisition in the individuals engaged since the activities and tasks performed are usually entertaining. Gamification and game-based learning are two different but related concepts in the field of education. Gamification involves applying game elements, such as points, badges, and leaderboards, to non-game contexts to increase motivation and engagement (Deterding et al., 2011). On the other hand, game-based learning involves the use of games as the primary instructional tool, with the aim of facilitating learning outcomes (Connolly et al., 2012). While both approaches leverage the motivational power of games, game-based learning typically involves more immersive and interactive experiences, with a greater emphasis on learning outcomes. Gamification, on the other hand, can be applied to a wider range of contexts and often focuses more on extrinsic rewards to motivate learners. Understanding the differences between these two approaches is important for educators and designers to select the appropriate approach for their specific learning objectives. Games provide a motivating space where participants can be introduced to new knowledge while simultaneously developing new skills, contributing to a better understanding and retention of knowledge (Clark & Mayer, 2016; Hamari et al., 2014). Several studies suggest that game-based learning can improve conceptual understanding and critical thinking skills (Gee, 2003; Qian & Clark, 2016; Sousa & Rocha, 2019). Therefore, it is necessary to know the implications and possible contributions of this type of approach. From this perspective, game-based learning is a viable methodological strategy for the school population and those not necessarily attending school.

Within the game-based learning approach, we find the spectrum of digital elements that support teaching-learning dynamics with information and communication technologies. Digital game-based learning is a pedagogical approach where digital or video games are the primary tools to strengthen learning. This approach promotes the effectiveness of digital games as a teaching-learning method, where users are benefited and motivated through their interaction and participation on these platforms (Sailer et al., 2017; Song et al., 2013). Various authors suggest that using digital games in education can improve problem-solving and information retention, besides developing skills and abilities (Lamb et al., 2018; Tokac et al., 2019). Another quality of digital games is that developers provide a controlled learning environment tailored to the specific purposes of the game and the characteristics of the user, allowing users to experiment and explore new avenues, developing knowledge in complex scenarios that are exemplified in an entertaining manner (An & Bonk, 2009; Aziz Hussin, 2018). Therefore, digital game-based learning, on the one hand, allows users to get involved in entertaining activities while they learn and develop skills and abilities; on the other, the digital environments facilitate more accessibility of these media.

Digital game-based learning can be especially beneficial when used in citizen science projects. Studies such as Theses and Jagad (2011) and Magno de Jesus and Silveira (2021) highlight that playing digital games can strengthen collaboration and teamwork while users develop various competencies and skills. The above are fundamental elements sought in citizen science, a collaboration between citizens to address projects that generally impact their environment. In this context, the potential of digital games as a learning strategy to strengthen citizen engagement in scientific research projects and data-driven decision-making is evident (Egersdorfer, 2016; Miller et al., 2019; Schrier, 2018). Similarly, digital games can enhance scientific literacy and stimulate participation in citizen science projects. Studies such as those of Iacovides et al. (2013) indicate the use of digital games in citizen science. Although it has not been proven that they attract participants, it has been determined that the games contribute to the permanence and engagement of participants. Hence, incorporating digital game-based learning is a viable approach to enhance citizen science projects through the participation of citizens involved through games.

1.2. Computational thinking to enhance reasoning for complexity: a theoretical framework

The interconnectivity of interactions and interrelationships of problems make the environment an intricate space, which has become characteristic of the 21st century. Patiño et al. (2023) emphasize understanding these different scenarios, systems, and interconnected phenomena as complex. Complexity is challenging as it becomes fundamental to address various contexts with a multi-referential perspective (Ardoino, 1991, 2005). In this sense, reasoning-for-complexity is introduced as a valuable meta-competency for individuals to face complex processes. In this respect, the importance of complexity is highlighted by various organizations and authors since, through this, we can think of a sustainable future that depends to a great extent on education

(UNESCO, 2001). This complex thinking meta-competency consists of four sub-competencies (see Figure 1): critical, scientific, systemic, and innovative thinking (Ramírez-Montoya et al., 2022). Reasoning for complexity is essential for the challenges of the 21st century as it provides an opportunity to develop an awareness of the complex interactions and interdependencies of the phenomena surrounding us.

The fourth industrial revolution has brought significant changes in many areas that have distinguished it from previous revolutions. According to (Schwab, 2016), this fourth industrial revolution represents a transcendental mutation in how people currently coexist and thus affects how people relate to each other, their jobs, and their forms of organization, among others. Certainly, work environments are deeply affected by these changes, and with it, the educational environment, where the approaches that scale the development of competencies and skills to cope with the current industrial revolution becomes more necessary nowadays (Butler-Adam, 2018; Kayembe & Nel, 2019). The preceding leads us to further reflect on the development of advanced technologies in the field of artificial intelligence, such as automation and robotics, and their impact on the work environment (Carbonero et al., 2020; Humlum, 2019), which means that the traditional way we work will disappear to give way to other models where continuous training and re-skilling will be crucial for individuals.

Computational thinking is an alternative approach to abstract problem-solving by developing skills established in its framework; using computational technologies, individuals grasp an essential way of thinking in the digital era. Wing (2006) introduced this thinking and highlighted its five components: problem reformulation, recursion, problem decomposition, abstraction, and systematic testing to achieve problem-solving. In this context, computational thinking allows individuals to develop sub-competencies of reasoning for complexity by placing themselves partly in the development of creative, critical, and systemic thinking (Doleck et al., 2017; Kules, 2016) along with scientific thinking (Wing, 2008) (see Figure 2). This approach allows students to strengthen their systemic thinking for solving complex problems by developing solutions. Complex and computational thinking aim to develop specific skills and sub-competencies in individuals that enable them to thrive in challenging environments.

Figure 1. Complex thinking sub-competencies.

Note: Figure prepared by the authors based on Ramirez-Montoya et al. (2022).

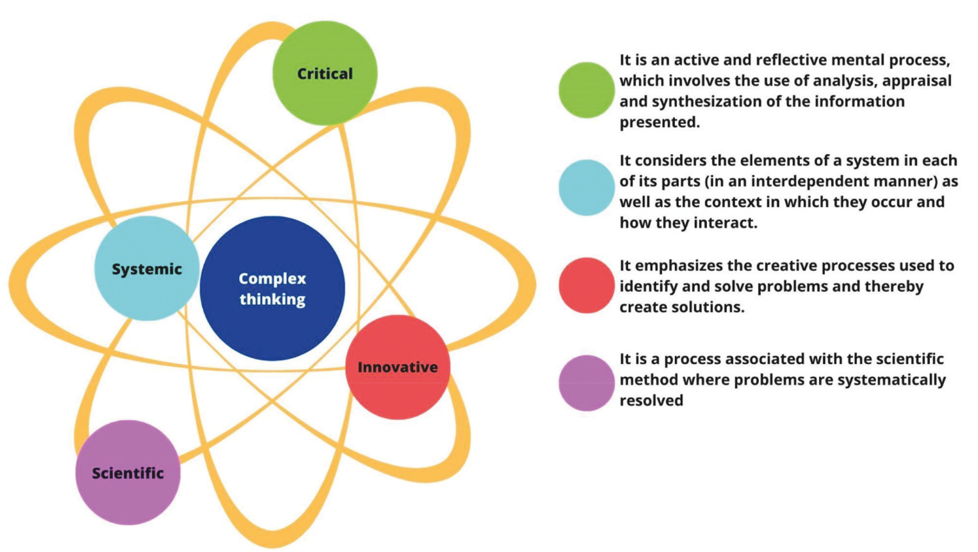


Table 1. Computational thinking components and relation with complex thinking

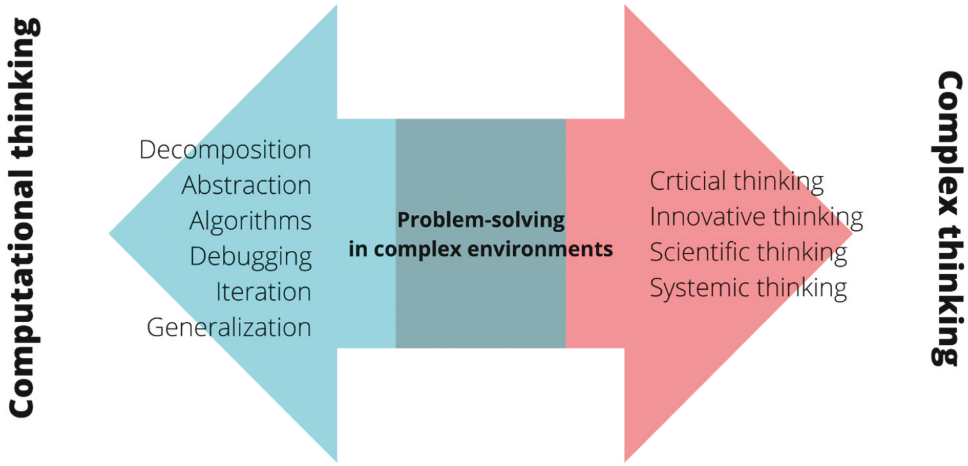
Component	Definition	Complex thinking approach
Decomposition	This component ensures that complex problems can be fragmented into smaller parts that can be identified in detail so that the core parts can be treated in a particular way.	Systemic and critical thinking
Abstraction	This component facilitates the identification of the essential elements of the complex problem, and according to Shute et al. (2017), it is composed of three subcategories: data collection and analysis, pattern recognition, and modeling	Innovative thinking, systemic thinking
Algorithms	This component is responsible for defining the set of logical and sequential processes to be performed to resolve specific problems or activities. It has four subcategories: algorithm design, parallelism, efficiency, automation	Scientific thinking, critical thinking
Debugging	The primary purpose of this component is to identify problems or errors in the process and correct them.	Critical thinking and innovative thinking
Iteration	The purpose of this component is to repeat the different tasks of the process as many times as necessary to improve them.	Scientific thinking
Generalization	This component aims to identify the problem's trends and patterns, relationships, forms of interaction, and solutions for replication to new situations.	Scientific thinking, systemic thinking

Since 2006, when the concept of computational thinking was first introduced, many authors and studies have investigated this topic. Considering this, we adopted the framework proposal of Shute et al. (2017). Based on a thorough analysis of the various concepts and a thematic proposal for complex problem solving, they finally defined six core components of computational thinking (see Table 1), which, like the sub-competencies of complex thinking, aim to help individuals develop the necessary skills for problem-solving in complex environments (see Figure 2). The potential of complex and computational thinking to help individuals to a broader, more effective, and assertive understanding of their environment is relevant as it establishes such exercise in a critical, creative, and systemic way (Shute et al., 2017).

As a result, the interest has arisen to delve deeper into the design and contents of citizen science games to develop computational thinking. On the one hand, digital games have been presented as technological solutions with the potential to engage students in computer programming for developing computational thinking (Akkaya & Akpinar, 2022; Fernandes et al., 2020; Sun et al., 2021; Troiano et al., 2020). On the other hand, citizen science projects have relied on digital game-based learning approaches to promote a more participatory and democratized approach to scientific research, giving people of all ages and backgrounds the opportunity to contribute to scientific discovery and advance their learning and skill development (Miller et al., 2019; Strobl et

Figure 2. Computational thinking and complex thinking imbrication.

Note: Figure prepared by the authors based on Shute et al. (2017)



al., 2019, 2020). This study proposes a framework that links citizen science and digital game-based learning approaches to develop computational thinking skills in university students. The following sections present the principles underpinning the proposed framework to gamify and democratize access to computational thinking development solutions.

2. Material and methods

We employed a qualitative exploratory approach to develop our method, which involved drawing from established game design frameworks and adapting game mechanics to suit the needs of citizen science projects and promote computational thinking. Our proposed framework incorporates citizen science as a means of fostering inclusivity and increasing participation. To guide game design and research, we have put forth a set of guidelines that encourage the use of complex problem-solving skills and computational thinking within game-based contexts.

Our conceptual paper can be classified as a "theory synthesis paper" as defined by Jaakkola (2020). This kind of paper involves integrating and linking multiple theories or literature streams to offer a new or enhanced view of a concept or phenomenon. The goal of the synthesis process is to enhance existing theoretical understanding by summarizing and integrating existing knowledge to identify commonalities and build coherence (Jaakkola, 2020). Our paper aims to integrate an extensive set of theories and phenomena under a novel theoretical umbrella to frame interventions to promote computational thinking development. The conceptual framework presented in this study has been developed following a series of phases. Firstly, the key concepts related to the topic under study, namely complex thinking, digital game-based learning, citizen science, and computational thinking, were identified and defined. Secondly, the relationships between these concepts were identified and established, with a focus on how they could be integrated to develop university students' computational thinking skills. The third phase involved the identification and selection of relevant literature that supported the conceptual framework, which was used to refine the definitions of the concepts and relationships between them, as well as to identify any gaps or inconsistencies in existing research. Finally, the conceptual framework was iteratively refined by the authors. Future studies and empirical data is to be collected to improve the framework.

2.1. Educational game design models

Educational game design models provide a structured and systematic framework for developing games that combine recreation and training. These models empower designers to identify educational objectives, select them, choose the appropriate content, set the game mechanics, define the evaluation strategy, and consider the user experience (Tokarieva et al., 2019). A 10-step framework for digital game design is proposed by Romero et al. (2020). The Asterale framework also emphasizes the importance of designing educational and entertaining games to ensure that players remain motivated and engaged throughout their learning experience. The overall goal of the framework is to provide game designers with a comprehensive set of guidelines and principles for designing games that effectively promote the development of skills in players.

The LM-GM model is a framework for designing serious games with a structured approach (Arnab et al., 2015). The model stands for "Learning Model-Game Mechanic" and consists of a learning model and a game mechanic. The learning model outlines the educational objectives and the learning goals of the game, while the game mechanic is the actual game design that supports the learning process. The model suggests that the game mechanic should be designed to align with the learning model, so players can engage in meaningful learning while playing. The LM-GM model emphasizes the importance of creating a balance between the educational goals and the entertaining aspect of the game so that players are motivated to continue playing and learning. This model is a valuable tool for creating games that are entertaining but also educational and effective in achieving their learning goals.

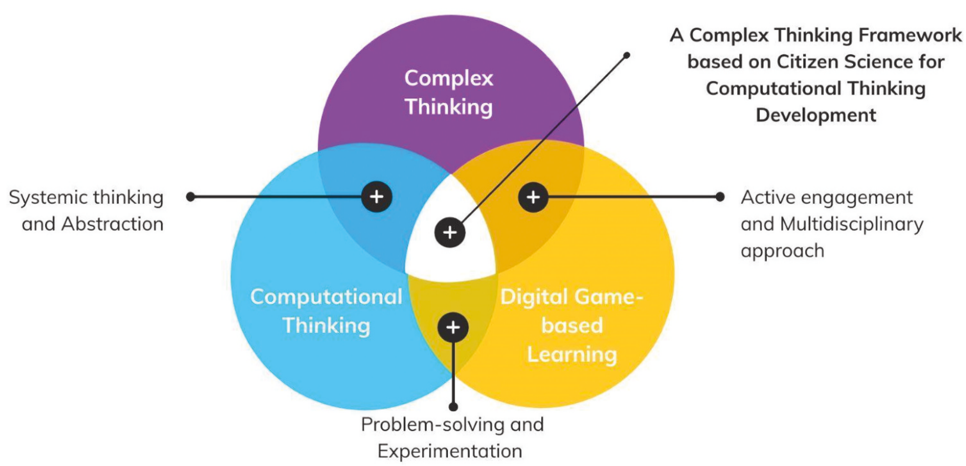
The TPACK framework for game design stands for Technological Pedagogical Content Knowledge and is a theoretical model for understanding the knowledge and skills required for successful technology-enhanced learning and teaching (Koehler et al., 2014). TPACK recognizes that effective technology integration in education requires a unique blend of three types of knowledge: Technological knowledge, Pedagogical knowledge, and Content knowledge. The TPACK framework asserts that the intersection of these three types of knowledge is necessary to design and implement technology-enhanced learning experiences that are effective and engaging. When applied to game design, the TPACK framework provides a roadmap for creating educational games that effectively balance technology, pedagogy, and content to achieve learning outcomes.

2.2. Game mechanics

Game mechanics in citizen science games are design strategies used to engage the public in scientific research through games. These mechanics gamify the scientific process, allowing players to collect, analyze, or interpret data and contribute to real-world scientific projects (Strobl et al., 2019). For instance, citizen science games often utilize an incentivized, reward-based system to keep players engaged and provide feedback on their contributions to the research process, like in the CrowdWater Game (Strobl et al., 2020). Citizen science mechanics aims to make science more accessible and interactive, fostering a sense of ownership and investment in the scientific process

Figure 3. Key constructs on the proposed Framework.

Note: Figure prepared by the authors.



among players. Citizen science game mechanics have proven effective in increasing public participation in science and increasing scientific literacy and have become an increasingly popular tool for engaging the public in scientific research (Baaden et al., 2018). For citizen science games to positively impact scientific research, they need to train players properly, which can be achieved by creating a tutorial that lays out a sequence of necessary skills and the interdependence of these skills (Miller et al., 2021).

Game mechanics in computational thinking games focus on specific cognitive skills related to computational thinking. For example, some game mechanics that specifically target these cognitive skills are puzzles, which require students to decompose a problem into smaller subproblems (Rowe et al., 2021). Another game mechanic with potential that has been studied concerning computational thinking development is collaboration (Turchi et al., 2019). Additionally, in scientific literature, game design as a mechanic is one of the most popular tasks to develop computational thinking skills (Wang et al., 2022). Escape games have also trained students in computational thinking tasks such as problem identification, sequencing, understanding algorithms, code optimization, completing programming tasks, solution evaluation, and conducting iterations. Menon et al. (2019) analyzed games based on adventure or fantasy, where players solve challenges or puzzles using resources within the game, within specific time limits, strategizing moves that impact game outcomes, and cooperating with peers to progress in the game.

2.3. Computational thinking learning objectives

A game design framework should aim to develop critical computational thinking skills such as decomposition, abstraction, algorithm design, debugging, iteration, and generalization, as proposed by Shute et al. (2017) This framework aims to guide game designers in creating games that challenge players to break down complex problems into smaller, manageable parts, extract the essence of a system, design logical and ordered instructions for solving problems, detect and fix errors, repeat the design process to refine solutions, and apply their skills in a variety of situations (da Silva et al., 2020; Wu & Richards, 2011). The game mechanics should be designed to reinforce the learning goals, for example, by presenting problems that require players to apply the skills outlined in the framework. The game should also be engaging and entertaining to encourage players to continue playing and practicing their skills. The overall goal of the proposed game design framework is to facilitate the creation of an enjoyable and practical learning experience that helps players develop their computational thinking skills and become confident, effective problem solvers (see Figure 3).

3. A complex thinking framework based on citizen science for computational thinking development

The Complex Thinking Framework for Computational Thinking Development through Citizen Science is a unique approach that leverages game mechanics to create educational games. The framework emphasizes using games as a fun and engaging tool to develop computational thinking skills and encourage active participation in citizen science initiatives. Games provide a dynamic and stimulating learning environment that fosters problem-solving and critical thinking skills by incorporating elements of competition, challenge, and reward. The framework aims to make learning about complex systems and processes accessible and enjoyable for all ages and backgrounds, ultimately enabling individuals to participate in scientific discovery and contribute to real-world problem-solving. To illustrate the practical application of our proposed framework, we have compiled a list of game mechanics in Table 2.

4. Discussion

This work presents a holistic, complex thinking framework proposal based on citizen science perspective for computational thinking development. Digital games that teach computational thinking should focus on specific cognitive processes such as decomposition, abstraction, pattern recognition, and algorithmic thinking (da Silva et al., 2020; Wu & Richards, 2011). This is relevant when we discuss citizen science projects, where the objective is to maintain citizen engagement on

Table 2. Linking Game Mechanics to Computational Thinking skills and tasks

Computational Thinking Tasks	Game Mechanics	Learning Components and Approaches
Decomposition	Puzzle	Break down a complicated problem/ system into smaller manageable pieces. The separate parts are not arbitrary segments but functional components that comprise the entire system/problem.
Abstraction	Puzzle, Analysis	Uncover the core of a complex system by gathering and examining data, identifying patterns, and modeling.
Algorithms	Demonstrations, Tutorials	Create a step-by-step and organized plan for finding a solution to a problem (algorithms).
Debugging	Cooperation, Collaboration	Locate and recognize errors to fix them.
Iteration	Action-Task, Feedback, Repetition	Keep refining the design process until the desired outcome is achieved.
Generalization	Game design, Action-Tasks, Challenges	Apply computational thinking to diverse scenarios to resolve problems efficiently.

the one hand and active participation in data and information collection on the other. In particular, the framework stresses the necessity of developing specific skills and competencies that allow citizens to acquire new knowledge for formal and nonformal education (Figure 3).

During the development of the framework, we discovered two key findings: (a) It is possible to consider the sub-competencies of complex thinking to design a digital citizen-science game that fosters computational thinking; thereby, both forms of thinking share problem-solving as a central goal (Fernandes et al., 2020; Patiño et al., 2023; Shute et al., 2017; Sun et al., 2021; Troiano et al., 2020) (Figure 2). (b) The digital game-based learning framework in citizen science topics is expected to increase engagement and teamwork in data collection and analysis while contributing to building users' knowledge and complex and computational thinking competencies (Martin et al., 2020; Schrier, 2018) (Figure 3).

Upon reviewing the proposed complex thinking framework that integrates citizen science and digital game-based learning to develop computational thinking skills, we have identified several limitations that must be addressed. Firstly, it may not be possible for all players to participate in citizen science projects, either due to lack of interest or limited access to technology. Additionally, aligning game design with the goals of citizen science initiatives and promoting the development of computational thinking skills can pose challenges. Balancing both aspects can be difficult and may result in a trade-off between the two. Furthermore, there are potential data privacy and security issues when collecting and utilizing player data in citizen science projects. These concerns are not addressed in the current version of the framework and should be addressed in future iterations. Finally, measuring the impact of the games on players' computational thinking development may be challenging and require a long-term evaluation of changes in behavior and thinking patterns. These limitations highlight the need for continued refinement and testing of the proposed framework to maximize its effectiveness and address potential challenges.

5. Conclusion

The work presented in this paper aimed to incorporate the construct of complex thinking and citizen science into the design of digital game-based learning solutions for computational thinking development through citizen science projects. The framework is built on information from scientific literature, including previous research studies and game design models. Nonetheless, the usefulness of this framework for analyzing, comparing, and designing game-based learning environments is yet to be validated. The next stage in its development is to bring in experts from various fields to examine the framework and its use in design and research. This framework might benefit game designers, practitioners, and researchers in developing serious games for computational thinking with an integrative approach based on complex thinking to support citizen science projects. Furthermore, using this framework to design digital game-based learning in citizen science can positively impact users, so it is of particular value to explore it in upcoming research.

Acknowledgments
The authors would like to thank the financial support from Tecnologico de Monterrey through the "Challenge-Based Research Funding Program 2022". Project ID # I003 - IFE001 - C2-T3 – T. Also, for the academic support of the Writing Lab, Institute for the Future of Education, Tecnologico de Monterrey, México.

Funding
The work was supported by the Institute for the Future of Education [Project ID # I003 - IFE001 - C2-T3 – T].

Author details
Berenice Alfaro-Ponce[1]
ORCID ID: http://orcid.org/0000-0002-7046-1019
Azeneth Patiño[1]
E-mail: azeneth.patino@tec.mx
ORCID ID: http://orcid.org/0000-0003-0919-8108
Jorge Sanabria-Z[1]
ORCID ID: http://orcid.org/0000-0001-8488-5499
[1] Institute for the Future of Education, Tecnologico de Monterrey, Monterrey, Mexico.

Authors' contributions
BA-P contributed to the study conception, design, and coordination. A-P contributed to the development of the methodological framework. BA-P, A-P, and J-SZ contributed to the writing of the manuscript. All authors read and approved the final manuscript.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Citation information
Cite this article as: Components of computational thinking in citizen science games and its contribution to reasoning for complexity through digital game-based learning: A framework proposal, Berenice Alfaro-Ponce, Azeneth Patiño & Jorge Sanabria-Z, *Cogent Education* (2023), 10: 2191751.

References

Akkaya, A., & Akpinar, Y. (2022). Experiential serious-game design for development of knowledge of object-oriented programming and computational thinking skills. *Computer Science Education*, *32*(4), 476–501. https://doi.org/10.1080/08993408.2022.2044673

Alexandra, A., Balázs, B., Butkevičienė, E., Mayer, K., & Perelló, J. (2021). Citizen social science: New and established approaches to participation in social research. In A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, R. Samson, K. Wagenknecht, & V. Katrin (Eds.), *The science of citizen science* (pp. 119–138). Springer International Publishing. https://doi.org/10.1007/978-3-030-58278-4_7

Alfaro-Ponce, B., Ibañez-Muñoz, C., & Sanabria-Z, J. (in press). Citizen science as a relevant approach to the challenges of complex thinking development in higher education: Mapping and bibliometric analysis. *Journal of University Teaching & Learning Practice*.

Alfaro-Ponce, B., Sanabria-Z, J., Rivero-Zambrano, F., & Ibañez-Muñoz, C. (in press). Citizen science's influence on public policy for addressing complexity: A systematic review of tech-based projects in higher education. *Journal of Social Studies Education Research*.

Amisha, G., Malik, P., Pathania, M., & Rathaur, V. (2019). Overview of artificial intelligence in medicine. *Journal of Family Medicine and Primary Care*, *8*(7), 2328. https://doi.org/10.4103/JFMPC.JFMPC_440_19

An, Y.-J., & Bonk, C. J. (2009). Designing digital game-based learning environments. *TechTrends: Linking Research and Practice to Improve Learning*, *53*(3), 43–48.

Ardoino, J. (1991). El análisis multirreferencial. In *Sciences de l'education, sciences majeures. Actes de Journees d'etude tenues a l'occasion des 21 ans des sciences de l'education* (pp. 173–181). Colección Recherches et Sciences de l'Education. http://publicaciones.anuies.mx/pdfs/revista/Revista87_S1A1ES.pdf

Ardoino, J. (2005). *Complejidad y formación : pensar la educación desde una mirada epistemológica*. Novedades Educativas.

Arnab, S., Lim, T., Carvalho, M. B., Bellotti, F., de Freitas, S., Louchart, S., Suttie, N., Berta, R., & de Gloria, A. (2015). Mapping learning and game mechanics for serious games analysis. *British Journal of Educational Technology*, *46*(2), 391–411. https://doi.org/10.1111/bjet.12113

Aziz Hussin, A. (2018). Education 4.0 made simple: Ideas for teaching. *International Journal of Education and Literacy Studies*, *6*(3), 92. https://doi.org/10.7575/aiac.ijels.v.6n.3p.92

Baaden, M., Delalande, O., Ferey, N., Pasquali, S., Waldispühl, J., & Taly, A. (2018). Ten simple rules to create a serious game, illustrated with examples from structural biology. *PLoS Computational Biology*, *14*(3), e1005955. https://doi.org/10.1371/journal.pcbi.1005955

Baird, A. M., & Parayitam, S. (2019). Employers' ratings of importance of skills and competencies college graduates need to get hired: Evidence from the New England region of USA. *Education + Training*, *61*(5), 622–634. https://doi.org/10.1108/ET-12-2018-0250

Baldwin, A., Fröhlich, C., & Rothe, D. (2019). From climate migration to Anthropocene mobilities: Shifting the debate. *Mobilities*, *14*(3), 289–297. https://doi.org/10.1080/17450101.2019.1620510

Bascopé, M., Perasso, P., & Reiss, K. (2019). Systematic review of education for sustainable development at an early stage: Cornerstones and pedagogical approaches for teacher professional development. *Sustainability*, *11*(3), 719. https://doi.org/10.3390/SU11030719

Bettini, G. (2019). And yet it moves! (Climate) migration as a symptom in the Anthropocene. *Mobilities*, *14*(3), 336–350. https://doi.org/10.1080/17450101.2019.1612613

Bonfield, C. A., Salter, M., Longmuir, A., Benson, M., & Adachi, C. (2020). Transformation or evolution?: Education 4.0, teaching and learning in the digital age. *Higher Education Pedagogies*, *5*(1), 223–246. https://doi.org/10.1080/23752696.2020.1816847

Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., & Shirk, J. (2009). Citizen science: A developing tool for expanding science knowledge and scientific literacy. *BioScience*, *59*(11), 977–984. https://doi.org/10.1525/bio.2009.59.11.9

Bonney, R., Shirk, J. L., Phillips, T. B., Wiggins, A., Ballard, H. L., Miller-Rushing, A. J., & Parrish, J. K. (2014). Next steps for citizen science. *Science*, *343*(6178), 1436–1437. https://doi.org/10.1126/SCIENCE.1251554

Burns, R. (2020). *The adult learner at work*. Routledge. https://doi.org/10.4324/9781003134213

Butler-Adam, J. (2018). The fourth industrial revolution and education. *South African Journal of Science*, *114* (5/6). https://doi.org/10.17159/sajs.2018/a0271

Carbonero, F., Ernst, E., & Weber, E. (2020). *Robots worldwide: The impact of automation on employment and trade*. https://www.econstor.eu/handle/10419/224602

Chen, Y.-C., Lu, Y.-L., & Lien, C.-J. (2021). Learning environments with different levels of technological engagement: A comparison of game-based, video-based, and traditional instruction on students' learning. *Interactive Learning Environments*, *29*(8), 1363–1379. https://doi.org/10.1080/10494820.2019.1628781

Chen, C. C., & Tu, H. Y. (2021). The effect of digital game-based learning on learning motivation and performance under social cognitive theory and entrepreneurial thinking. *Frontiers in Psychology*, *12*, 5477. https://doi.org/10.3389/fpsyg.2021.750711

Clark, R. C., & Mayer, R. E. (2016). *E-learning and the science of instruction: Proven guidelines for consumers and designers of multimedia learning* (4th ed.). Wiley. https://www.wiley.com/en-us/e+Learning+and+the+Science+of+Instruction%3A+Proven+Guidelines+for+Consumers+and+Designers+of+Multimedia+Learning%2C+4th+Edition-p-9781119158660

Connolly, T. M., Boyle, E. A., MacArthur, E., Hainey, T., & Boyle, J. M. (2012). A systematic literature review of empirical evidence on computer games and serious games. *Computers & Education*, *59*(2), 661–686. https://doi.org/10.1016/j.compedu.2012.03.004

Cordeiro De Oliveira, L., Guerino, G. C., Cordeiro De Oliveira, L., & Pimentel, A. R. (2022). Information and communication technologies in Education 4.0 paradigm: A systematic mapping study. *Informatics in Education*. https://doi.org/10.15388/INFEDU.2023.03

da Silva, T. C., de Melo, J. B., & Tedesco, P. (2020). The creative process in the development of computational thinking in higher education. *Proceedings of the 12th International Conference on Computer Supported Education* (pp. 215–226). https://doi.org/10.5220/0009346502150226

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: Defining gamification. *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments* (pp. 9–15). Tampere, Finland.

Doleck, T., Bazelais, P., Lemay, D. J., Saxena, A., & Basnet, R. B. (2017). Algorithmic thinking, cooperativity, creativity, critical thinking, and problem-solving: Exploring the relationship between computational thinking skills and academic performance. *Journal of Computers in Education*, 4(4), 355–369. https://doi.org/10.1007/S40692-017-0090-9

ECSA. (2015). *Ten principles of citizen science*. European Citizen Science Association. https://doi.org/10.17605/OSF.IO/XPR2N

Egersdorfer, D. (2016). Using digital game-based learning to engage science students: The case of minecraft. https://doi.org/10.14288/1.0305061

Einsiedel, E. F. (2021). Public participation in science and technology: Dialogue, disputations, and collaborations. *Routledge Handbook of Public Communication of Science and Technology*, 267–290. https://doi.org/10.4324/9781003039242-15/PUBLIC-PARTICIPATION-SCIENCE-TECHNOLOGY-EDNA-EINSIEDEL

Erhel, S., & Jamet, E. (2013). Digital game-based learning: Impact of instructions and feedback on motivation and learning effectiveness. *Computers & Education*, *67*, 156–167. https://doi.org/10.1016/j.compedu.2013.02.019

Fatimah, Y. A., Govindan, K., Murniningsih, R., & Setiawan, A. (2020). Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *Journal of Cleaner Production*, *269*, 122263. https://doi.org/10.1016/J.JCLEPRO.2020.122263

Fernandes, K. T., da Silva Aranha, E. H., Lucena, M. J. N. R., & de Souza Fernandes, G. L. (2020). Developing computational thinking and reading and writing skills through an approach for creating games. *2020 IEEE Frontiers in Education Conference (FIE)*, 1–8. https://doi.org/10.1109/FIE44824.2020.9274065

French, R., Imms, W., & Mahat, M. (2020). Case studies on the transition from traditional classrooms to innovative learning environments: Emerging strategies for success. *Improving Schools*, *23*(2), 175–189. https://doi.org/10.1177/1365480219894408

Frigerio, D., Richter, A., Per, E., Pruse, B., & Vohland, K. (2021). Citizen science in the natural sciences. *The Science of Citizen Science*, 79–96. https://doi.org/10.1007/978-3-030-58278-4_5

Gallagher, S. E., & Savage, T. (2020). Challenge-based learning in higher education: An exploratory literature review. *Teaching in Higher Education*, 1–23. https://doi.org/10.1080/13562517.2020.1863354

Gee, J. P. (2003). What video games have to teach us about learning and literacy. *Computers in Entertainment (CIE)*, *1*(1), 20. https://doi.org/10.1145/950566.950595

Gomollón-Bel, F. (2019). Ten chemical innovations that will change our world: IUPAC identifies emerging technologies in Chemistry with potential to make our planet more sustainable. *Chemistry International*, *41* (2), 12–17. https://doi.org/10.1515/ci-2019-0203

Graham, E. A., Henderson, S., & Schloss, A. (2011). Using mobile phones to engage citizen scientists in research. *Eos*, *92*(38), 313–315. https://doi.org/10.1029/2011EO380002

Guo, P., Saab, N., Post, L. S., & Admiraal, W. (2020). A review of project-based learning in higher education: Student outcomes and measures. *International Journal of Educational Research*, *102*, 101586. https://doi.org/10.1016/J.IJER.2020.101586

Hägg, G., & Gabrielsson, J. (2020). A systematic literature review of the evolution of pedagogy in entrepreneurial education research. *International Journal of Entrepreneurial Behaviour and Research*, *26*(5), 829–861. https://doi.org/10.1108/IJEBR-04-2018-0272

Haklay, M. (2018). Participatory citizen science. In M. Haklay, S. Hecker, A. Bowser, Z. Makuch, J. Vogel, & A. Bonn (Eds.), *Citizen science: Innovation in open science, society, and policy* (pp. 52–62). UCL Press. https://doi.org/10.14324/111.9781787352339

Halasa, S., Abusalim, N., Rayyan, M., Constantino, R. E., Nassar, O., Amre, H., Sharab, M., & Qadri, I. (2020). Comparing student achievement in traditional learning with a combination of blended and flipped learning. *Nursing Open*, *7*(4), 1129–1138. https://doi.org/10.1002/nop2.492

Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? - A literature review of empirical studies on gamification. *Proceedings of the Annual Hawaii International Conference on System Sciences* (pp. 3025–3034). https://doi.org/10.1109/HICSS.2014.377

Heiss, R., & Matthes, J. (2017). Citizen science in the social sciences: A call for more evidence. *GAIA - Ecological Perspectives for Science and Society*, *26*(1), 22–26. https://doi.org/10.14512/GAIA.26.1.7

He, L., & Li, N. (2020). The linkages between life expectancy and economic growth: Some new evidence. *Empirical Economics*, *58*(5), 2381–2402. https://doi.org/10.1007/s00181-018-1612-7

Humlum, A. (2019). *Robot adoption and labor market dynamics*. https://www.semanticscholar.org/paper/Robot-Adoption-and-Labor-Market-Dynamics-Humlum/9c546d533fcb3f0df9974dc78332b94a53a629cf

Iacovides, I., Jennett, C., Cornish-Trestrail, C., & Cox, A. L. (2013, April). Do games attract or sustain engagement in citizen science? A study of volunteer motivations. *Conference on Human Factors in Computing Systems - Proceedings* (pp. 1101–1106). https://doi.org/10.1145/2468356.2468553

Iyawa, G. E., Akinmoyeje, B. A., Kays, R., Mutelo, S., & Ipinge, R. (2021). Women as citizen scientists: Identifying potential digital solutions for addressing gender-based challenges. *2021 IST-Africa Conference (IST-Africa)* (pp. 1–8).

Jaakkola, E. (2020). Designing conceptual articles: Four approaches. *AMS Review*, *10*(1–2), 18–26. https://doi.org/10.1007/s13162-020-00161-0

Johnson, B. A., Mader, A. D., Dasgupta, R., & Kumar, P. (2020). Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations. *Global Ecology and Conservation*, *21*, e00812. https://doi.org/10.1016/J.GECCO.2019.E00812

Kayembe, C., & Nel, D. (2019). Challenges and opportunities for education in the fourth industrial revolution. *Science Translational Medicine*, *11*(3). https://doi.org/10.1126/scitranslmed.aaw9414

Keser, H., & Semerci, A. (2019). Technology trends, Education 4.0 and beyond. *Contemporary Educational Researches Journal*, *9*(3), 39–49. https://doi.org/10.18844/cerj.v9i3.4269

Kim, Y. J., & Ifenthaler, D. (2019). *Game-based assessment: The past ten years and moving forward*. https://doi.org/10.1007/978-3-030-15569-8_1

Kim, J., & Park, C.-Y. (2020). Education, skill training, and lifelong learning in the era of technological revolution. https://doi.org/10.22617/WPS200008-2

Koehler, M. J., Mishra, P., Kereluik, K., Shin, T. S., & Graham, C. R. (2014). The technological pedagogical content knowledge framework. *Handbook of Research on Educational Communications and Technology: Fourth Edition*, 101–111. https://doi.org/10.1007/978-1-4614-3185-5_9/COVER

Krishnakumaryamma, A. N., & Venkatasubramanian, S. (2018). Technology-mediated pedagogies for skill acquisition toward sustainability education. In O. Bernad Cavero & L.-C. Núria (Eds.), *New pedagogical challenges in the 21st century - Contributions of research in education* (pp. 21–32). InTechOpen. https://doi.org/10.5772/intechopen.74336

Kules, B. (2016). Computational thinking is critical thinking: Connecting to university discourse, goals, and learning outcomes. *Proceedings of the Association for Information Science and Technology*, *53*(1), 1–6. https://doi.org/10.1002/PRA2.2016.14505301092

Kullenberg, C., & Kasperowski, D. (2016). What is citizen science?-A scientometric meta-analysis. *PLoS One*, *11*(1), 147152. https://doi.org/10.1371/journal.pone.0147152

Lamb, R. L., Annetta, L., Firestone, J., & Etopio, E. (2018). A meta-analysis with examination of moderators of student cognition, affect, and learning outcomes while using serious educational games, serious games, and simulations. *Computers in Human Behavior*, *80*, 158–167. https://doi.org/10.1016/J.CHB.2017.10.040

Liu, H.-Y., Dörler, D., Heigl, F., & Grossberndt, S. (2021). Citizen science platforms. *The Science of Citizen Science*, 439–459. https://doi.org/10.1007/978-3-030-58278-4_22

Lozano, R., Barreiro-Gen, M., Lozano, F. J., & Sammalisto, K. (2019). Teaching sustainability in European higher education institutions: Assessing the connections between competences and pedagogical approaches. *Sustainability*, *11*(6), 1602. https://doi.org/10.3390/su11061602

Magno de Jesus, Â., & Silveira, I. F. (2021). Game-based collaborative learning framework for computational thinking development. *Revista Facultad de Ingeniería Universidad de Antioquia*, *99*(99), 113–123. https://doi.org/10.17533/UDEA.REDIN.20200690

Martin, F., Dennen, V. P., & Bonk, C. J. (2020). A synthesis of systematic review research on emerging learning environments and technologies. *Education Tech Research Dev*, *68*, 1613–1633. https://doi.org/10.1007/s11423-020-09812-2

Mavlonov, R. (2022). Integration of pedagogical approaches and their application in the educational process. *Central Asian Journal of Social Sciences and History*, *3*(6), 25–27. https://www.cajssh.centralasianstudies.org/index.php/CAJSSH/article/view/322

Menon, D., Romero, M., & Viéville, T. (2019). Computational thinking development and assessment through tabletop escape games. *International Journal of Serious Games*, *6*(4), 3–18. https://doi.org/10.17083/ijsg.v6i4.319

Miller, J. A., Horn, B., Guthrie, M., Romano, J., Geva, G., David, C., Sterling, A. R., & Cooper, S. (2021). How do players and developers of citizen science games conceptualize skill chains? *Proceedings of the ACM on Human-Computer Interaction*, *5*(CHI PLAY) (pp. 1–29). https://doi.org/10.1145/3474671

Miller, J. A., Narayan, U., Hantsbarger, M., Cooper, S., & El-Nasr, M. S. (2019). Expertise and engagement. *Proceedings of the 14th International Conference on the Foundations of Digital Games* (pp. 1–11). https://doi.org/10.1145/3337722.3337735

Moore, L. L., & Rudd, R. D. (2004). LEADERSHIP SKILLS and COMPETENCIES for EXTENSION DIRECTORS and ADMINISTRATORS introduction and theoretical framework. *Journal of Agricultural Education*, *22*(3), 22–33. https://doi.org/10.5032/jae.2004.03022

Nygren, H., Nissinen, K., Hämäläinen, R., & de Wever, B. (2019). Lifelong learning: Formal, nonformal, and informal learning in the context of the use of problem-solving skills in technology-rich environments. *British Journal of Educational Technology*, *50*(4), 1759–1770. https://doi.org/10.1111/BJET.12807

Patiño, A., Ramírez-Montoya, S., & Buenestado-Fernández, M. (2023). Open Access Smart Learning Environments Active learning and Education 4.0 for complex thinking training: Analysis of two case studies in open education. *Smart Learning Environments*, *10*(8). https://doi.org/10.1186/s40561-023-00229-x

Prensky, M. (2006). "Don't bother me, Mom, I'm learning!": How computer and video games are preparing your kids for twenty-first-century success and how you can help. In *2006* (1st ed.) (pp. 254). Paragon House.

Qian, M., & Clark, K. R. (2016). Game-based learning and 21st-century skills: A review of recent research. *Computers in Human Behavior*, *63*, 50–58. https://doi.org/10.1016/J.CHB.2016.05.023

Quinlivan, L., Chapman, D. V., & Sullivan, T. (2020). Validating citizen science monitoring of ambient water quality for the United Nations' sustainable development goals. *The Science of the Total Environment*, *699*, 134255. https://doi.org/10.1016/J.SCITOTENV.2019.134255

Ramírez-Montoya, M. S., Castillo-Martínez, I. M., Sanabria-Z, J., & Miranda, J. (2022). Complex thinking in the framework of Education 4.0 and open innovation—A systematic literature review. *Journal of Open Innovation, Technology, Market, and Complexity*, *8*(1), 4. https://doi.org/10.3390/JOITMC8010004

Rebele, J. E., & St. Pierre, E. K. (2019). A commentary on learning objectives for accounting education programs: The importance of soft skills and technical knowledge. *Journal of Accounting Education*, *48*, 71–79. https://doi.org/10.1016/J.JACCEDU.2019.07.002

Rios, J. A., Ling, G., Pugh, R., Becker, D., & Bacall, A. (2020). Identifying critical 21st-century skills for workplace success: A content analysis of job advertisements. *Educational Researcher*, *49*(2), 80–89. https://doi.org/10.3102/0013189X19890600

Romero, M., Dumont, L., Barma, S., Daniel, S., Ferrer, M., Hénaire, V., Răileanu, M.-B., Lepage, A., Lille, B., & Patino, A. (2020). *Digital games and learning*. JFD Éditions.

Rowe, E., Almeda, M. V., Asbell-Clarke, J., Scruggs, R., Baker, R., Bardar, E., & Gasca, S. (2021). Assessing implicit computational thinking in Zoombinis puzzle gameplay. *Computers in Human Behavior*, *120*, 106707. https://doi.org/10.1016/j.chb.2021.106707

Sailer, M., Hense, J. U., Mayr, S. K., & Mandl, H. (2017). How gamification motivates: An experimental study of the effects of specific game design elements on psychological need satisfaction. *Computers in Human Behavior*, *69*, 371–380. https://doi.org/10.1016/J.CHB.2016.12.033

Sanabria-Z, J. C., Molina Espinosa, J. M., Alfaro Ponce, B., & Vycudilíková Outlá, M. (2022). A threshold for citizen science projects: Complex thinking as a driver of holistic development. *RIED-Revista Iberoamericana de Educación a Distancia*, *25*(2). https://doi.org/10.5944/ried.25.2.33052

Schrier, K. (2018). Designing learning with citizen science and games. *The Emerging Learning Design Journal*, *4*(1). https://digitalcommons.montclair.edu/eldj/vol4/iss1/3

Schwab, K. (2016, January 14). *The fourth industrial revolution: What it means and how to respond*. World Economic Forum.

Serrano, K. (2019). The effect of digital game-based learning on student learning: A literature review. *Graduate Research Papers*. https://scholarworks.uni.edu/grp/943

Shelton, P. G., Corral, I., & Kyle, B. (2017). Advancements in undergraduate medical education: Meeting the challenges of an evolving world of education, healthcare, and technology. *The Psychiatric Quarterly*, *88*(2), 225–234. https://doi.org/10.1007/s11126-016-9471-x

Shohel, M. M. C., Ashrafuzzaman, M., Naomee, I., Tanni, S. A., & Azim, F. (2022). Game-based teaching and learning in higher education. In *Handbook of Research on Acquiring 21st Century Literacy Skills Through Game-Based Learning* (pp. 78–106). https://doi.org/10.4018/978-1-7998-7271-9.ch005

Shute, V. J., Sun, C., & Asbell-Clarke, J. (2017). Demystifying computational thinking. *Educational Research Review*, *22*, 142–158. https://doi.org/10.1016/j.edurev.2017.09.003

Song, H., Kim, J., Tenzek, K. E., & Lee, K. M. (2013). The effects of competition and competitiveness upon intrinsic motivation in exergames. *Computers in Human Behavior*, *29*(4), 1702–1708. https://doi.org/10.1016/J.CHB.2013.01.042

Sousa, M. J., & Rocha, Á. (2019). Leadership styles and skills developed through game-based learning. *Journal of Business Research*, *94*, 360–366. https://doi.org/10.1016/j.jbusres.2018.01.057

Squire, K., & Jenkins, H. (2011). *Video games and learning: Teaching and participatory culture in the digital age*. Teachers College Press.

Strobl, B., Etter, S., van Meerveld, I., & Seibert, J. (2019). The CrowdWater game: A playful way to improve the accuracy of crowdsourced water level class data. *PLoS One*, *14*(9), e0222579. https://doi.org/10.1371/journal.pone.0222579

Strobl, B., Etter, S., van Meerveld, H. J. I., & Seibert, J. (2020). Training citizen scientists through an online game developed for data quality control. *Geoscience Communication*, *3*(1), 109–126. https://doi.org/10.5194/gc-3-109-2020

Sun, L., Guo, Z., & Hu, L. (2021). Educational games promote the development of students' computational thinking: A meta-analytic review. *Interactive Learning Environments*, 1–15. https://doi.org/10.1080/10494820.2021.1931891

Tan, O.-S. (2003). *Problem-based learning innovation: Using problems to power learning in the 21st century* (O. S. Tan Ed., 1st ed.). Gale Cengage Learning.

Theses, C., & Jagad, L. (2011). Online gaming and teamwork [Communication Theses]. https://doi.org/10.57709/2351660

Tobias, S., Fletcher, J. D., & Wind, A. P. (2014). Game-Based Learning. In J. Spector, M. Merrill, J. Elen, & M. Bishop (Eds.) *Handbook of Research on Educational Communications and Technology*. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-3185-5_38

Tokac, U., Novak, E., & Thompson, C. G. (2019). Effects of game-based learning on students' mathematics achievement: A meta-analysis. *Journal of Computer Assisted Learning*, *35*(3), 407–420. https://doi.org/10.1111/jcal.12347

Tokarieva, A. V., Volkova, N. P., Harkusha, I. V., & Soloviev, V. N. (2019). Educational digital games: Models and implementation. *Educational Dimension*, *1*, 5–26. https://doi.org/10.31812/educdim.v53i1.3872

Troiano, G. M., Chen, Q., Alba, Á. V., Robles, G., Smith, G., Cassidy, M., Tucker-Raymond, E., Puttick, G., & Harteveld, C. (2020). Exploring how game genre in student-designed games influences computational thinking development. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–17). https://doi.org/10.1145/3313831.3376755

Troussas, C., Krouska, A., & Sgouropoulou, C. (2020). Collaboration and fuzzy-modeled personalization for mobile game-based learning in higher education. *Computers & Education*, *144*, 103698. https://doi.org/10.1016/J.COMPEDU.2019.103698

Turchi, T., Fogli, D., & Malizia, A. (2019). Fostering computational thinking through collaborative game-based learning. *Multimedia Tools and Applications*, *78*(10), 13649–13673. https://doi.org/10.1007/s11042-019-7229-9

UNDP. (2020). *Human development report 2020: The next frontier: Human development and the Anthropocene*. (United Nations Development Programme, Ed.). United Nations Development Programme.

UNESCO. (2001). Seven complex lessons in education for the future. *UNESCO*, *11*(10), 2528. https://unesdoc.unesco.org/ark:/48223/pf0000123074.locale=es

UNESCO. (2021). *UNESCO recommendation on open science*. https://unesdoc.unesco.org/ark:/48223/pf0000379949.locale=en

Valverde Berrocoso, J., Del Carmen Garrido-Arroyo, M., Burgos-Videla, C., & Morales-Cevallos, M. B. (2020). Trends in educational research about e-learning: A systematic literature review (2009–2018). *Sustainability*, *12*(12), 5153. https://doi.org/10.3390/SU12125153

Wang, C., Shen, J., & Chao, J. (2022). Integrating computational thinking in STEM education: A literature review. *International Journal of Science and Mathematics Education*, *20*(8), 1949–1972. https://doi.org/10.1007/s10763-021-10227-5

Wing, J. M. (2006). Computational Thinking. *Communications of the ACM*, *49*, 33–35. https://doi.org/10.1145/1118178.1118215

Wing, J. M. (2008). Computational thinking and thinking about computing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *366*(1881), 3717–3725. https://doi.org/10.1098/rsta.2008.0118

Wu, M. L., & Richards, K. (2011). Facilitating computational thinking through game design. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *6872 LNCS* (pp. 220–227). https://doi.org/10.1007/978-3-642-23456-9_39/COVER

Cogent Education

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/oaed20

Components of computational thinking in citizen science games and its contribution to reasoning for complexity through digital game-based learning: A framework proposal

Berenice Alfaro-Ponce, Azeneth Patiño & Jorge Sanabria-Z

To cite this article: Berenice Alfaro-Ponce, Azeneth Patiño & Jorge Sanabria-Z (2023) Components of computational thinking in citizen science games and its contribution to reasoning for complexity through digital game-based learning: A framework proposal, Cogent Education, 10:1, 2191751, DOI: 10.1080/2331186X.2023.2191751

To link to this article: https://doi.org/10.1080/2331186X.2023.2191751

Published online: 20 Mar 2023.