Development and Implementation of an Online Adaptive Gamification Platform for Learning Computational Thinking

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***Abstract*—This Innovative Practice Full Paper presents the development and implementation of an innovative online adaptive gamification platform for learning Computational Thinking (CT). CT is an essential problem-solving skill set in this modern era of digitization and technological advancements. To build students' knowledge and skills in CT while maximizing students' motivation and engagement in learning, a novel online adaptive gamified course called Computational Thinking Quest (CTQ) was introduced. The CTQ was designed and developed by a multidisciplinary team of students and faculty members. The key features of CTQ are (1) an interactive storyline with animated avatars, mini-games, and questions created using Unity three-dimensional cross-platform game engine and Blockly block-based visual programming language; (2) questions at three different levels of difficulty for effective adaptive and self-learning approach; (3) an answer and feedback to each question for increased students' confidence and enthusiasm towards learning; (4) hyperlinks to online learning resources for further reading; (5) a badge and a leaderboard to motivate active participation and encourage success; and (6) a course management system with automatic data saving capability to enable learning at own pace, anytime, anywhere. The CTQ was rolled out to some newly matriculated first-year undergraduate Engineering (ENG) and InfoComm Technology (ICT) students. A total of 54 ENG and 53 ICT students' learning performance and feedback were collated and analyzed. Statistical results from the paired Student's t-test and the Wilcoxon signed rank test consistently reveal that (1) the median of post-test marks is significantly higher than that of pre-test marks ($p < 0.001$); (2) the median of CT knowledge scores after taking CTQ is significantly higher than that of before CTQ ($p < 0.001$); and (3) the median time taken to complete the post-test is significantly lower than the pre-test ($p < 0.001$). Furthermore, more than 75% of ENG and ICT students, separately, stated that CTQ is an engaging or very engaging learning platform; 81% of them indicated that the educational content of CTQ is enriching or very enriching; and 83% of them commented that CTQ has motivated independent learning. The CTQ can also serve as a bridging course to narrow the heterogeneity gap among students with heterogeneous prior knowledge on computer programming languages and ease students into programming-related modules, thereby enhancing teaching and learning effectiveness.**

Keywords—computational thinking, gamification, adaptive learning, independent learning, online education platform

I. Introduction

Computational Thinking (CT) is an indispensable problem-solving skill set for every individual in this modern digital world of increasing technological advancements [1-3]. The skill set is not only relevant to computer science students, but to every student, regardless of their discipline [4, 5]. CT fosters students to be more creative and effective problem-solvers and motivates them to generate techniques to solve problems rather than use existing techniques. CT consists of four cornerstones: decomposition, abstraction, pattern recognition, and algorithm design [5-8]. Decomposition refers to breaking down a complex problem into smaller parts that are more manageable and easier to comprehend; it is usually the first step to solve a complex problem. Abstraction involves identifying and extracting essential information while neglecting irrelevant details; it helps individuals develop a general framework for solving problems in the same categories. Pattern recognition refers to observing similar trends and regularities within and among problems; it guides individuals to establish connections between identical problems. Lastly, algorithm design involves developing a sequence of instructions to solve a problem or perform a task.

Engineering (ENG) is a profession that applies science and mathematics to research and develops economical solutions to technical problems [9, 10]. There are a number of specializations in engineering including chemical engineering, civil engineering, electrical engineering, and mechanical engineering. CT is essential for engineers to tackle complex engineering problems and systems within real-world constraints [11]. Employers highly value engineers who can comprehend and apply engineering and computational principles to solve engineering problems in the workplace [12]. In contrast, InfoComm Technology (ICT) is a technical discipline that looks at solving problems using computing resources. It encompasses computing-related fields such as computer science, software engineering, information systems, computer engineering, and cybersecurity. While CT is recognized as a fundamental skill set that is essential for problem-solving across numerous disciplines, including science, business, finance, and even humanities, it is especially more relevant to ICT students as it lays the foundation for ICT students to handle complicated computational problems [13].

With the increasing demand on individuals with CT competencies, educational institutions are set to equip and empower their students with CT knowledge and skills through various teaching and learning strategies [7, 14], aiming to instill and enhance students' CT competence desired in today's technology-driven world. Traditional teaching is the oldest instructional method [15], where teacher is the sender, educational materials are message, and student is the receiver of the message. While it enables interaction between the teacher and peers face-to-face, it can inhibit the student's ability to learn CT. Being the sole source of information, the teacher decides everything in the classroom and may not pay attention to individual differences. Some students, who find the teaching pace is too fast, may struggle, whereas other students, who find it too slow, may be bored and disengaged with the learning. On top of that, traditional teaching deters students from thinking independently; hence, defeating teaching CT, which is to inject thinking abilities to the students to help them solve problems systematically.

To address the limitations of traditional teaching, He et al. [16] designed activities using the principles and strategies of CT for high vocational colleges. These activities involved constructing a computing environment, constructing a problem-solving process based on computing environment, and constructing a verification method of the problem-solving process. They provided a teaching case about "Domain" in the course on "Network Architecture with Active Directory" and evaluated the validity of the proposed teaching method. The students' scores in the final exam and the teaching feedback for teaching method with CT were found to be greater than traditional teaching. On the contrary, Gao et al. [17] introduced a pedagogical method PBL-VP to facilitate novice programming students to solve practical problems with CT. The PBL-VP incorporated problem-based learning with visual programming Blocky. The teaching process of PBL-VP involved problem selection and lead-in; problem abstraction and modeling; algorithm design; programming implementation; and code generation. The mean final grades of students in PBL-VP class were shown to be better than those in traditional class.

Liao et al. [18], on the other hand, adopted blended learning, a combination of traditional teaching and online learning, to develop CT ability among college students. Learning activities in experimental group were lectures amounting to 40% of the total teaching hours; collaborative project of group learning to 30%; asynchronous online communication to 15%; and academic dialogue and show to 15%. The average post-test score for experimental group was higher than control group. To improve student motivation and engagement in learning [19-21], Vasconcelos et al. [22] incorporated gamification into blended learning in a CT course. Hyperlinks to YouTube videos covering topics seen in class and links to files containing class notes were provided to students. Quizzes were generated using Kahoot, a game-based learning platform, and students accumulated points through the ranking at the end of each quiz. Pre-test and post-test were implemented to investigate the development of CT skills in students; the average post-test score was higher than the average pre-test scores, especially for questions on pattern recognition and algorithms.

In many pedagogical strategies, as exemplified above, learners are assumed to be of homogenous characteristics. Thus, a one-size-fits-all teaching approach is taken, where each learner is required to follow the same learning path, regardless of their prior knowledge and learning abilities. However, studies have consistently revealed that learners are unique in their learning habits and pace. Hence, an adaptation of personalized learning is of immense advantage to learners as the learning environment changes to suit individual's learning characteristics [23-25]. Furthermore, online learning is indispensable because it enables learning to occur anytime and anywhere via electronic media, for instance, internet and intranets; this adds flexibility and enables self-paced learning to help learners succeed [26, 27].

Combining the benefits of online learning, adaptation, and gamification in education, this paper aims to develop and implement an innovative online adaptive gamification platform for learning CT in Singapore Institute of Technology (SIT), an autonomous university in Singapore that offers applied learning with extensive work-study degrees [28]. To build students' knowledge and skills in CT while maximizing students' motivation and engagement in learning, we introduced a novel online adaptive gamified course called Computational Thinking Quest (CTQ). Section II describes the design and development of CTQ. Section III illustrate the implementation and evaluation of CTQ. Quantitative and qualitative results are presented and discussed in Section IV, completed with concluding remarks in Section V.

II. Design and Development of CTQ

The CTQ was innovatively designed and developed on an adaptive gamified e-learning platform by a multidisciplinary team of students and faculty members in SIT. The disciplines are ENG; ICT; Chemical Engineering and Food Technology; Health and Social Sciences; and Design and Specialized Businesses. Six key features, coupled with effective and interesting game elements and mechanics [19-21], of CTQ were created using Unity three-dimensional cross-platform game engine and Blockly block-based visual programming language, as exhibited in Figure 1.

1) *An interactive storyline with animated avatars, mini-games, and questions.* Avatars were modelled to represent the virtual versions of the learners and help boost their esteem [29]. The learners could also personalize the look of avatars. In addition, narratives were composed to convey information and intrigue the learners. Mini-games and questions pertaining to seven CT topics were created and seamlessly blended into the storyline, integrating educational elements into the game flow. The topics are (i) decomposition, (ii) abstraction, (iii) pattern recognition, (iv) algorithm design with operators and variables, (v) algorithm design with control structures, (vi) algorithm design with iterations, and (vii) algorithm design with functions.
2) *Questions at three different levels of difficulty for effective adaptive and self-learning approach.* Three difficulty levels (i.e., easy, moderate, and hard) corresponding to the complexity of questions were implemented. The learner will be first prompted with a moderate question. If the learner answers the question correctly, the next question will be of hard difficulty. However, if the learner answers incorrectly, the next question will be of easy difficulty. To ensure question relevance and correctness, all questions were verified and validated by faculty members with computing background and years of teaching experience.
3) *An answer and feedback to each question for increased students' confidence and enthusiasm towards learning.* An answer and feedback were incorporated into each question. Upon answering a question correctly or incorrectly, a detailed explanation of the correct response will be displayed to reinforce the learners' understanding. Points, as a numerical representation of learner success, will be given when the learner

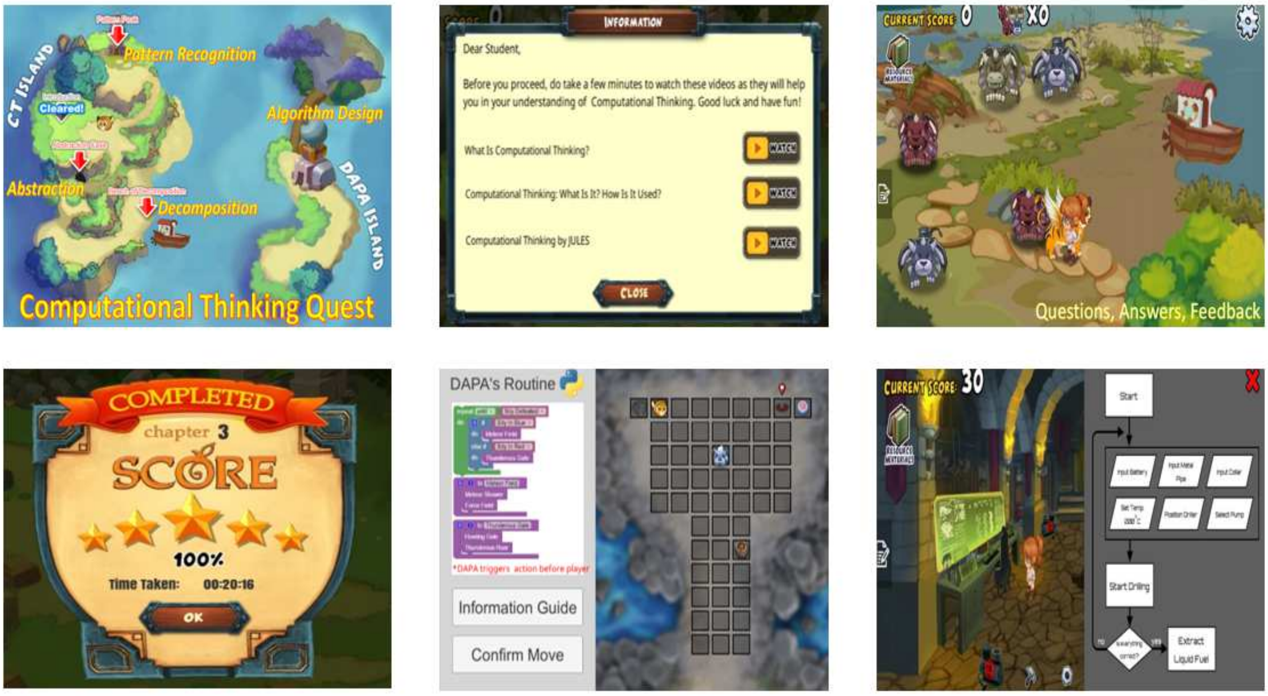

Fig. 1. Computational Thinking Quest key features with game elements and mechanics.

correctly answers a question or successfully completes a mini-game. The learners can also visualize and track their progression through a progress bar.

4) *Hyperlinks to online learning resources for further reading.* Relevant hyperlinks were integrated to guide the learners to external resources for more information. The hyperlinks are links to online articles and videos illustrating CT concepts with examples and applications. Basic programming topics for algorithm design, such as operators and variables, control structures, iterations, and functions, are also provided via the hyperlinks. When a hyperlink is clicked, a new screen will be displayed.

5) *A badge and a leaderboard to motivate active participation and encourage success.* A badge and a leaderboard were constructed to improve the learners' intrinsic motivation and performance [30]. The badge provides easy visualization representing learner progression, whereas the leaderboard elicits social comparison by allowing the learners to know their respective rankings and compare their performance with others.

6) *A course management system with automatic data saving capability to enable learning at own pace, anytime, anywhere.* Data are automatically saved in a reliable and secure server so that the learners can complete the CT learning journey at their own pace, anytime, anywhere that is comfortable for them. Through such a learning process, the learners can also cultivate new skills leading to life-long learning [31].

III. Implementation and Evaluation of CTQ

The CTQ was rolled out to some newly matriculated first-year undergraduate ENG and ICT students in August 2020, one month before the academic year began, which allowed the students to independently learn CT before the school started in September. The students were invited to complete CTQ via email invitations. Upon consent, the students were directed to the link for CTQ via SIT's Learning Management System, where a single sign-on is needed to access CTQ hosted on SIT's server. Before embarking on their personalized CT learning journey, the students' current level of CT knowledge was assessed through an online pre-test containing 14 multiple choice questions – two from each of the seven CT topics. At the end of their learning journey, they were re-assessed through an online post-test containing the same 14 multiple choice questions for a fair comparison [32]. No answers and feedback were given to the students for both the pre-test and post-test questions.

Information, such as test marks and time spent to complete each test, was recorded through the course management system with automatic data saving capability. Subsequently, the test marks and time spent on the pre-tests and post-tests were analyzed and compared using the paired Student's t-test [33] and the Wilcoxon signed rank test [33]. The former is a statistical parametric test on the means of quantitative data (i.e., test marks and time spent) with normality assumption, whereas the latter is a statistical non-parametric test on the median difference of quantitative data without normality assumption.

In addition to quantitative analysis, qualitative analysis was performed using qualitative data gathered from student feedback surveys conducted online after the post-test. The students' interest in CT was examined using a bipolar 5-point Likert scale [34]. The scale has two bipolar adjectives at either end of the scale and a neutral option connected with intermediate answer options. For example, 1 = very unengaging and 5 = very engaging, and 1 = very unenriching and 5 = very enriching. Students were also asked to self-assess their CT knowledge before and after the CT learning journey using an 11-point rating scale ranging from 0 to 10 [34], where 0 being the lowest and 10 being the highest.

TABLE I. RESULTS OF STATISTICAL ANALYSIS OF PRE-TEST AND POST-TEST SCORES

		Pre-Test Score (%)	Post-Test Score (%)		Paired Student's T-Test			Wilcoxon Signed Rank Test	
Discipline	**N**	***Mean (SD)***	***Mean (SD)***	***Mean difference***	***t***	***df***	***p***	***z***	***p***
ENG	54	51.98 (16.67)	61.11 (17.26)	9.13	4.64	53	< 0.001	4.16	< 0.001
ICT	53	60.51 (19.13)	69.00 (16.63)	8.49	4.11	52	< 0.001	3.52	< 0.001
All (ENG+ICT)	107	56.21 (18.36)	65.02 (17.33)	8.81	6.21	106	< 0.001	5.44	< 0.001

TABLE II. RESULTS OF STATISTICAL ANALYSIS OF SELF-ASSESS KNOWLEDGE SCORES

		Self-Assess Knowledge Score			Paired Student's T-Test			Wilcoxon Signed Rank Test	
Discipline	**N**	***Mean (SD) before CTQ***	***Mean (SD) after CTQ***	***Mean difference***	***t***	***df***	***p***	***z***	***p***
ENG	54	4.59 (1.83)	7.17 (1.28)	2.58	10.06	53	< 0.001	6.04	< 0.001
ICT	53	5.30 (2.17)	7.42 (1.42)	2.12	9.27	52	< 0.001	5.74	< 0.001
All (ENG+ICT)	107	4.94 (2.03)	7.29 (1.35)	2.35	13.62	106	< 0.001	8.32	< 0.001

TABLE III. RESULTS OF STATISTICAL ANALYSIS OF PRE-TEST AND POST-TEST DURATIONS

		Pre-Test Duration (minute)	Post-Test Duration (minute)		Paired Student's T-Test			Wilcoxon Signed Rank Test	
Discipline	**N**	***Mean (SD)***	***Mean (SD)***	***Mean difference***	***t***	***df***	***p***	***z***	***p***
ENG	54	22.07 (11.41)	13.24 (9.27)	-8.83	-5.41	53	< 0.001	-4.71	< 0.001
ICT	53	25.41 (12.38)	12.01 (5.65)	-13.40	-8.48	52	< 0.001	-5.78	< 0.001
All (ENG+ICT)	107	23.72 (11.96)	12.63 (7.69)	-11.09	-9.63	106	< 0.001	-7.48	< 0.001

IV. RESULTS AND DISCUSSION

A total of 54 ENG and 53 ICT students' learning performance and feedback were collated and analyzed. The study aims to ascertain the usefulness of CTQ for students to acquire CT knowledge and skills, as well as compare the performance across the two different disciplines.

A. Quantitative Data Analysis and Findings

Table I shows the results of statistical analysis of pre-test and post-test marks from ENG and ICT students, separately, as well as from all the students (ENG and ICT) combined. Based on the paired Student's t-test [33] and the Wilcoxon signed rank test, there are significant differences between the pre-test and post-test marks (all $p < 0.001$) for ENG (51.98% versus 61.11%), ICT (60.51% versus 69.00%), and all students combined (56.21% versus 65.02%). The median of post-test marks is significantly higher than that of pre-test marks ($p < 0.001$). The mean pre-test marks for ICT students are higher than the mean pre-test marks for ENG students; however, ENG students have a higher improvement in marks (+9.13%) than ICT students (+8.49%).

These results are in line with the self-assess knowledge scores of CT, which were gathered from the student online feedback surveys. As demonstrated in Table II, the median of CT knowledge scores after taking CTQ is significantly higher than before CTQ ($p < 0.001$). The mean differences between the CT knowledge scores before and after CTQ for ENG students, ICT students, and both ENG and ICT students combined are 2.58, 2.12, and 2.35, respectively.

Besides that, there are significant differences in the pre-test duration and post-test duration (all $p < 0.001$) for ENG (22.07 minutes versus 13.24 minutes), ICT (25.41 minutes versus 12.01 minutes), and all students combined (23.72 minutes versus 12.63 minutes). The median time taken to complete the post-test is significantly lower than the pre-test ($p < 0.001$), as evidenced in Table III. While the mean pre-test duration for ICT students is greater than ENG students, there is a larger decrease in the post-test duration for ICT students (-13.40 minutes) than ENG students (-8.83 minutes).

These findings suggest that CTQ can help students acquire CT knowledge and skills regardless of disciplines. Specifically, our results suggest that, by completing CTQ, students improve their CT competencies, resulting in an increase in their CT assessment scores and allowing students to finish their CT assessments in a shorter duration as students become more familiar with the CT topics.

B. Qualitative Data Analysis and Findings

To provide a more comprehensive appraisal of CTQ's effectiveness at fostering CT, students were also asked to complete an online feedback survey after the post-test. Some survey questions are highlighted below.

- "How would you rate CTQ as a learning platform?" (Likert scale: 1 = very unengaging and 5 = very engaging)
- "How would you rate CTQ in terms of its educational content?" (Likert scale: 1 = very unenriching and 5 = very enriching)
- "Has CTQ motivated independent learning?" (Two choice answers: Yes/No)

As illustrated in Figure 2, 75.93% of ENG students and 77.36% of ICT students stated that CTQ is an engaging or very engaging learning platform, being slightly higher for ICT than for ENG. Moreover, 81.48% of ENG students and 81.13% of ICT students indicated that the educational content of CTQ is

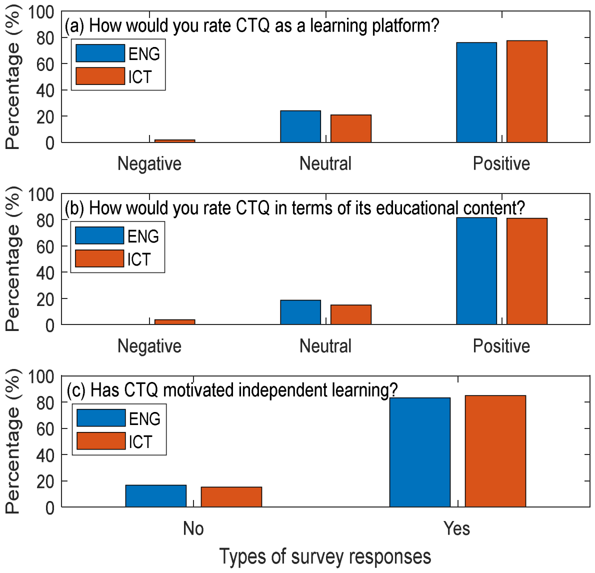

Fig. 2. Survey responses to (a) CTQ's level of engagement, where negative represents unengaging or very unenaging, and positive represents engaging or very enaging; (b) CTQ's level of enrichment, where negative represents unriching or very unriching, and positive represents enriching or very enriching; and (c) CTQ's motivation in independent learning.

enriching or very enriching. In terms of independent learning, 83.33% of ENG students and 84.91% of ICT students commented that CTQ has motivated independent learning. These high positive responses across all questions are likely attributed to the online adaptive gamification platform of CTQ.

Some quotes for CTQ from the students are as follows.

- "It is interactive and contains relevant information that is easy to understand about CT, which arouses my interests in CT."
- "I managed to learn new skills through interactive games."
- "It is enriching, entertaining, and encourages the user to learn more CT topics."
- "It captivates the user's attention and pushes the user to progress."
- "It reminds me how important learning things by myself is, by taking the initiative to find out how to get it right, and by making mistakes and learning from them."
- "It is fun and engaging. I hope there is more of such type of learning."
- "I would like to have more elaboration and resources for answering questions."
- "I think there should be more mini-games because they are more enjoyable than the standard text questions."

V. Conclusions

In this modern world of digitization and technological advancements, CT is a vital set of problem-solving skills for every individual. To develop students' knowledge and skills in CT while augmenting students' motivation and engagement in learning, an innovative CTQ was innovatively designed and developed on an adaptive gamified e-learning platform with fun and effective game elements and mechanics. Quantitative and qualitative data on students' learning performance and feedback were collected and analyzed from 54 ENG and 53 ICT newly matriculated first-year undergraduate students. Statistical results using the paired Student's t-test and the Wilcoxon signed rank test demonstrate significant difference before and after CTQ for ENG students, ICT students, and both ENG and ICT students combined (all $p < 0.001$). Feedback survey results are also positive, confirming the usefulness and merits of CTQ.

Apart from building students' knowledge and skills in CT, CTQ can also address the concern of teaching students with heterogeneous prior knowledge on computer programming languages. Computer programming language modules are commonly offered to undergraduate students in local and overseas universities. These students may come from diverse academic backgrounds and hence are heterogeneous in their prior computer programming knowledge. The CTQ can serve as a bridge to narrow the heterogeneity gap within the cohort and ease students into programming-related modules by equipping them with CT knowledge and skills, thereby enabling effective teaching and learning.

Acknowledgment

This study was approved by the local Institutional Review Board, and written informed consent was obtained from all subjects.

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