REFLECTIONS ON PRACTICE

Reimagining the Singapore Pre-university Biology Curriculum with Computational Thinking

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ABSTRACT

As the digital landscape expands and grows increasingly relevant, a worthwhile goal is to prepare and equip students with the necessary skills to thrive in such a society. Broadly known as computational thinking (CT), its wide reception is evident from educators' efforts to incorporate it into national curricula worldwide. While some treat it as an independent discipline, this reflection argues that CT skills ought to be treated as an interdisciplinary skill. Using biology curricula as an example, we highlight the current gaps of integrating CT into biology through our teaching experiences at university level, which we believe stems from the descriptive nature that biology education has adopted in Singapore. With pre-university students seldom engaging in algorithmic approaches to analyse and understand biological data, we find that many students struggle to construct and test models using computational approaches at the university level. As such, we leverage on our experiences and propose a curriculum design at the pre-university level that embeds authentic application of CT into biological practice by mapping conceptual parallels between biology, computer science and CT. In the process, we detail elements of the curricula that are designed to cultivate deeper interdisciplinarity alongside the challenges that may be experienced in its setup. Envisioned to work in tandem with university courses, this works towards a first-point insertion for enabling future learners to understand more advanced digital literacies such as data analytics and machine learning that will be critical, if not commonplace, in the future field of biology.

Keywords: Computational thinking; biology; education; data science (DS); digital literacy

INTRODUCTION

As biology undergoes a technological revolution to produce unimaginable quantities of data, the need to analyse the consequently complex output will require computational strategies and ideas, whereby the future pursuit of biology will either require an interdisciplinary (requiring more than one expertise in an individual) or multidisciplinary (requiring different experts to work together) approach (Bentley, 2002) (see Table 1 under Appendix). Hence, it makes sense to develop the capacity for interdisciplinary and multidisciplinary work early on, amidst the multifaceted challenges of the 21st century. Computational thinking (CT) is one suitable problem-solving approach where learners engage with "the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" (Wing 2006, 2008). The fundamental principles and concepts that underlie CT skills are also broad, allowing students to become divergent thinkers who can approach problems with different perspectives for the best solution (Wing, 2011). From the perspective of biology, CT provides a new way of interdisciplinary training to establish robust problem-solving and inquiry skills (Barr & Stephenson, 2011), allowing students to make meaningful connections across the various subfields and topics within biology (Pevzner & Shamir, 2009) and beyond.

The significance of CT is acknowledged by educators in this growing information age through its incorporation into national curricula worldwide (Table 2), with some keeping CT skills as an independent discipline with separate curriculum time (e.g. Sweden and Taiwan), and others integrating CT skills into school curricula (e.g. Australia and South Korea). However, these implementation differences can result in varying learning outcomes, for example the ability of learners in using new technological skills (Hsu et al., 2018). Infusing CT skills across subjects has shown more effective and deeper learning (Bocconi et al., 2016). Mr Lawrence Wong (former Education Minister of Singapore) also highlighted interdisciplinary learning as one of the four main strategies to prepare students for a dynamic and uncertain future. The explosion of knowledge makes it important to have the ability to see the broader connection of things and to be able to work seamlessly across different disciplines. Many problems in the real-world are complex and cross-cutting, and cannot be solved with skills from a single discipline (Wong, 2020).

In Singapore, the "Learn for Life" movement by the Ministry of Education (2020) has driven plans to instil CT into mathematics curricula. However, we argue that this needs to be extended into other disciplines, and in this reflection we use local biology curricula as an example. We find little reflection of CT within biology curricula in Singapore, and local pre-university biology remains traditionally taught as a didactic subject where students memorise large amounts of facts without really developing awareness of how bespoke facts were derived (Poon, 2014). With scientific terms presented as content knowledge to be memorised (Rosen & Julyan, 1989), we believe students miss out on the value and processes of scientific pursuit. Considering the prevalence of information technology contributing to the growing complexity of biological data, framing young minds with the thought processes to decode the data and troubleshooting skills is imperative in fostering better appreciation and understanding of biology (Mohaghegh & McCauley, 2016).

REFLECTIONS ON CURRENT COURSES IN A UNIVERSITY CONTEXT

At the School of Biological Sciences at Nanyang Technological University (NTU), our concrete effort to instil CT can be observed through our six integrative CT courses (Figure 1). Notably, they tap upon innovative pedagogies (Metz, 2008) such as flipped classroom models utilising NTU's e-learning management platform, team-based learning (TBL), problem-based learning (PBL) alongside case studies and freestyle projects, which have also been described as being part of the 16 strategies for learners to apply CT skills (Hsu et al., 2018) and to induce deeper learning (Qin, 2009).

Level	Category	Module			
University	Introductory Core Modules	Biostatistics (BS1008)	• Importance of biostatistics in conducting biological experiments • Types of data and graphs for visualization	• Basic statistics concept • Probability distribution and estimation • Binomial distribution • Poisson distribution	• Hypothesis testing • ANOVA • Correlation and regression • Non-parametric methods
University	Introductory Core Modules	Introduction to Computational Thinking (BS1009)	• Basic programming constructs • Different programming languages • Implementing algorithms to solve problems	• Problem solving with abstraction and decomposition • Problem solving with pattern recognition • Computer hardware and software	• Limits of computing and algorithmic complexity • Current computing trends • Issues and ramifications of computer's pervasiveness
University	Introductory Core Modules	Introduction to Data Science (BS0004)	• Data science in Singapore landscape • Socio-ethical implications of data science and artificial intelligence • Qualities and skillsets required of a data scientist	• Relevance of data science in Biology • Importance of graphs in communication • Research design considerations and confounding effect • Organization of data using databases	• Logical thinking process • Network theory and network biology • Machine learning evaluation metrics • Examples of machine learning algorithms
University	Advanced Digital Biology Modules (Optional)	Statistical Programming in R (BS3349)	• Fundamentals of programming • R syntax, data types and data structures	• Working with vectors, matrices, data frames and lists • Deploying statistical testing in R	• Story-telling with data and graphics
University	Advanced Digital Biology Modules (Optional)	Data Science for Biologists (BS3033)	• Data science in biology • Fundamentals of computer science • Programming languages and why R? • R for data science	• R and BioConductor • Refresher on statistics • The art of statistics: Anna Karenina and the careless null hypothesis • The art of statistics: The p-values lie	• Research design • Databases • Machine learning • Data visualization
University	Advanced Digital Biology Modules (Optional)	High-Throughput Bioinformatics (BS4017)	• How next-generation sequencing data is produced and pre-processed • How to use Linux operating system and command line interface	• General tools for processing different data types and file format standards for each data type • How to analyse transcriptomics and genomics sequencing data	• Common research questions that can be addressed with genomic sequencing and transcriptomics data

Figure 1. A curriculum map of current NTU modules that aims to instil CT skills from introductory to advanced levels.

Given our experiences running these courses, we find that students did not completely appreciate the connections between biology and computing. This could be seen through introductory courses such as BS1009 "Introduction to Computational Thinking", a compulsory course for freshmen, which have students locked in too early into the syntax of a single programming language instead of CT concepts such as iteration, nesting, loops and Boolean logic. We believe that the consequent struggle arises from a failure in applying concepts appropriately to problem sets, arising from a weak CT foundation. To circumvent fixation on mastery of the programming language, students are encouraged to learn and use whatever programming language they prefer in advanced data science courses such as BS3033 "Data Science for Biologists" to place more emphasis on problem solving. However, the drawback is that it becomes intensive to conduct, making such courses difficult to upscale and replicate. Furthermore, we realised the successes in the advanced course may stem from students who already have prior computing backgrounds and enrol based on their interest as compared to introductory courses which are compulsory for all first-year students. Overall, these experiences point to the need for stronger CT grounding amongst students, which we believe can be established earlier through strategic interventions in the pre-university arena.

INTEGRATING COMPUTATIONAL THINKING INTO PRE-UNIVERSITY BIOLOGY CURRICULUM

To address these concerns, this reflection presents a pre-university biology curricula design infused with CT, since an earlier introduction would prime students for solving problems at an earlier age (Qualls & Sherrell, 2010). While CT could be introduced as a standalone course, merely injecting CT into current biology curricula as yet another "add-on" or "extension topic" is inadequate, given the prevalence of bias and misconception regarding learning of biology by teachers and students at both pre-university and university levels (Qin, 2009). By decontextualising its practices, we run the risk of removing its authenticity when students attempt to apply it to real-world problems (Weintrop et al., 2015), inevitably leading to practice-theory gaps. It is hence worthwhile to leverage on the existing relationship between pre-university and university environments by developing a comprehensive CT programme in biology (Bio-CT for short). This could be done as an integrated two-tiered curriculum, with two strategic insertion points leading up to university (Figure 2).

	Pre-University (***Bio-CT***)		University
	Introductory (***iBio-CT***)	Advanced (***aBio-CT***)	Introductory & Advanced
Objective	To align the teaching of Biology with Computation Thinking Principles	To become familiar with Computational Principles while entrenched in the biological domain	To become adept at deploying Computational Thinking Principles and use these for creative-problem solving across a variety of problems
Outcomes	• To see the parallels between biological systems and computers • Gain a basic understanding of the 5 cornerstones of Computation Thinking • To use the 5 cornerstones of Computation thinking in solving low to moderate level problems	• To use the parallels between biological systems and computer systems strategically in analysing problems • To be comfortable in using the 5 cornerstones towards solving biological problems • To develop basic programming skills and use these to solve higher-level problems	• To see the high-level connection between Computational Thinking and Data Science • To be comfortable towards integrating the 5 cornerstones of Computation Thinking with key Data Science concepts • To develop modelling and statistical analysis skills in addition to Computational Thinking skills and use these for solving bio-data science problems.

Figure 2. Desired learning objectives and outcomes from the Bio-CT programme.

The first insertion point would be an introductory Bio-CT programme (iBio-CT) as a "plug-in" to pre-university biology curriculum (suitable for the last two years of high school before university), and the second, an optional advanced Bio-CT (aBio-CT) module for final-year high school students who show aptitude in the introductory programme. Together, Bio-CT seeks to embed CT principles within current biology concepts. This will not just draw interdisciplinary parallels between biological and computational fields, but also provide students with a foundation for future application of CT skills at higher levels. The teaching philosophy of embracing CT concepts as an integral component of biology will also update and sharpen existing biology educators' interdisciplinary understanding (Wing, 2011).

In envisioning instructional material as a scaffold for both students and teachers, we used a five-cornerstone model to articulate the encompassing skills of CT (Figure 3). The model serves as a theoretical framework where acquired CT knowledge can be translated as biological inquiries embedded within real-world contexts. This is crucial, as relevant connections and applications are reportedly effective for demonstrating conceptual parallels between CT and biology (Kong & Abelson, 2019).

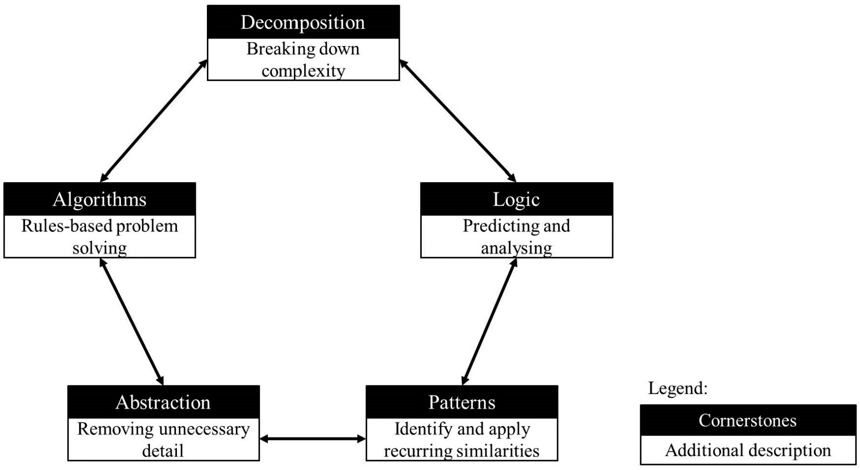

Figure 3. The five cornerstones of CT (Selby & Woollard, 2013).

Considering the parallels and connections between biology and CT may not be as clear-cut as the intuitive manifestations of CT within computer science (CS), we developed a relationship map within the three by drawing interdisciplinary parallels to CS manifestations (Figure 4).

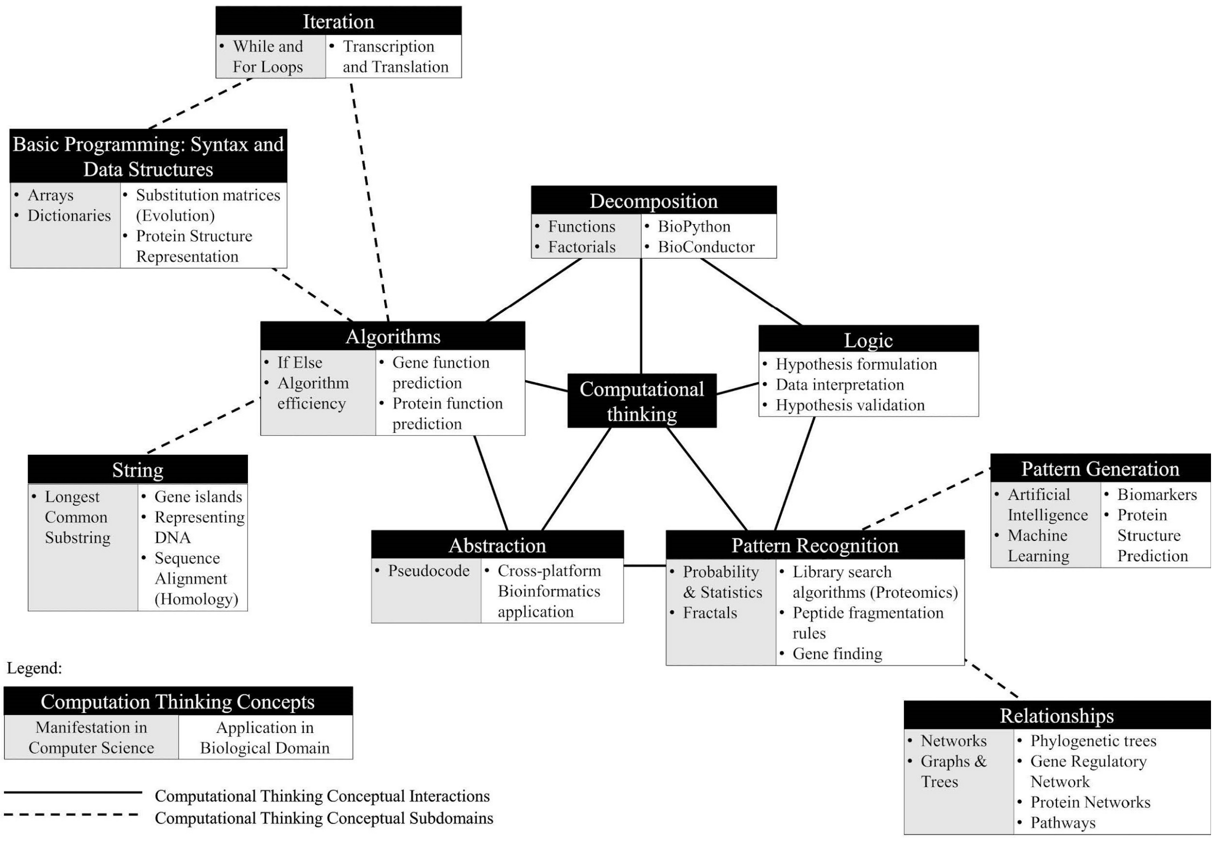

Figure 4. Relationship map between biological domains and CT concepts through computer science (CS) manifestations.

Each biology topic can then be bridged to relevant CT cornerstones as illustrated in Table 3 (under Appendix), forming the basis of our proposed Bio-CT pre-university curriculum in Figure 1 (under Appendix). To further elaborate on what can happen during a lesson, we demonstrate an example of how HIV biology can be taught through posing a problem for students to discuss in groups, where they will apply CT skills to solve it collaboratively (Figure 5).

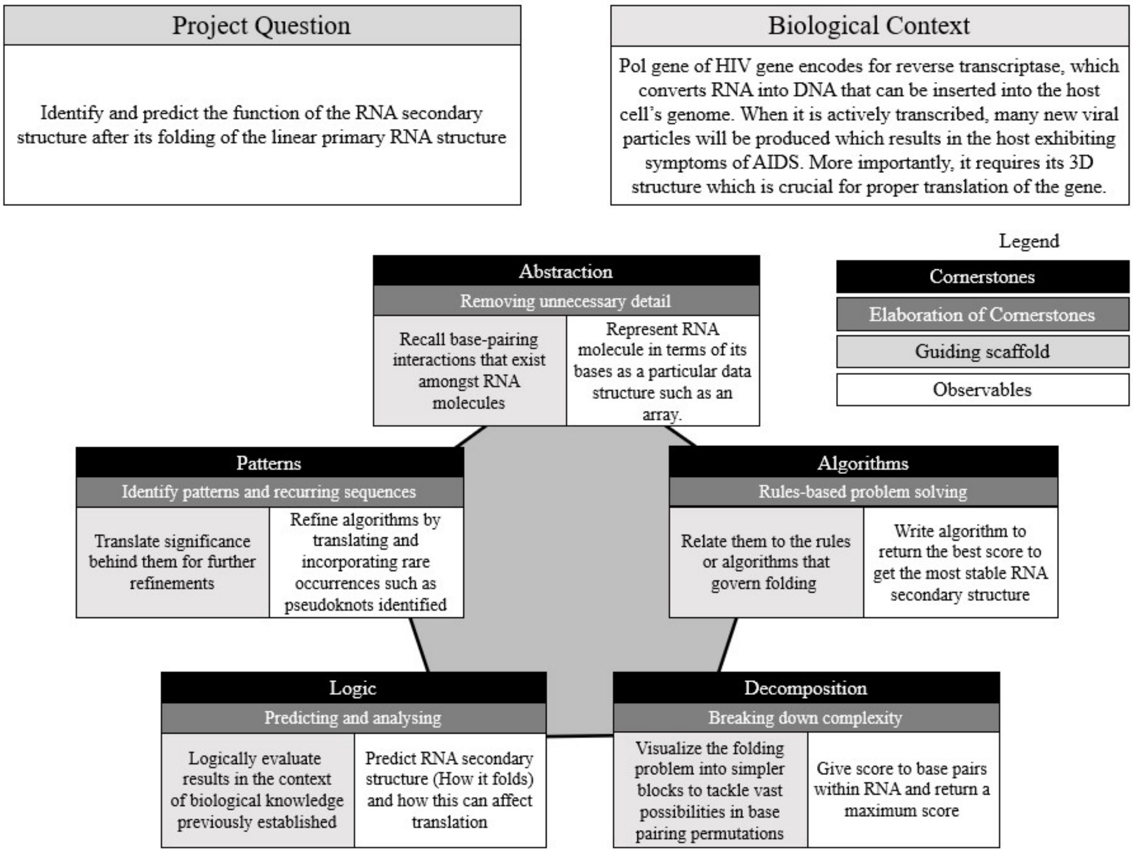

Figure 5. An example of how students can apply CT skills in approaching the problem within the biology of HIV through the CT cornerstones (Figure 2).

Overall, we envision instructional material in this Bio-CT course to be designed for self-paced learning, preferably online, with real-world problem-solving components and self-contained computational tools for hands-on practice. This approach encourages creativity and risk-taking in students, and also reduces teachers' workload. Each lesson package will come with clear learning outcome assessments, structured easy-to-higher-level tutorial questions (all to be answered online with immediate feedback), freeing up the teachers' time in looking for additional resources and grading assignments. Through their performances in mini-assessments and group problem-solving tasks set within iBio-CT, students can then gauge their aptitude and interest and opt for the aBio-CT module in their final year of the pre-university programme.

In line with advancing the 21st-century competencies in Singapore (Tan et al, 2017), we intend to generate student interest and curiosity in such courses and hope that they have the commitment to successfully complete them. As current Education Minister Mr Chan Chun Sing said, curiosity will propel student learning, and discipline enables the students to pursue, master, and perfect whatever they desire to learn (Ministry of Education, 2021).

CHALLENGES AND OPPORTUNITIES

We imagine incorporating CT into biology will present growing pains. Due to differences in computer science and biological science learning traditions, important learning outcomes to a competent computer science student may not be applicable in the biology context (Wooley & Lin, 2005; Goth, 2010), the converse is also true. The challenge hence unfolds in adeptly navigating the tensions between the two traditions (Denning, 2017). Taking reported examples of Bio-CT curricula and approaches (Wilensky & Reisman, 2006; Libeskind-Hadas & Bush, 2013; Libeskind-Hadas & Bush, 2014; Rubinstein & Chor, 2014; Arraki et al., 2015; Burgett et al., 2015; Helikar et al., 2015; Orton et al., 2016; Mulder et al., 2018; Goh & Sze, 2019), alongside our experiences in designing and conducting Bio-CT and Physics-CT courses at NTU, we view the nature of implementing this curriculum as a translational one—distilling what has shown to work in one context (our university curricula) and implementing it within the pre-university context as a self-contained curricula package.

Beyond implementation difficulties, it is important to recognise that its feasibility hinges on how palatable the courses are to students. For many, biology may be the field of choice for those wishing to pursue a science discipline which involves little mathematics (Wachsmuth et al., 2017), and such a fixed mindset along with a strong disinterest in math is challenging for our proposed Bio-CT curriculum (Grover et al., 2016). To circumvent these issues, participating students need to receive the appropriate messaging to manage their expectations and predispositions. Additionally, the development of CT elements should engage student interest, of which the Bebras site provides suitable examples (Bebras International Challenge of Informatics and Computational Thinking, 2021).

Lastly, a paradigm shift in thinking is also necessary for teachers as they are key stakeholders in fostering educational change (Villoutreix, 2021). To them, these ideologies may not translate into instructional practices due to many factors, be it internally through their own personal beliefs and commitment to the innovation (Tan & Nashon, 2017; Coenders et al., 2008), or externally through the lack of support and constraints to develop and integrate the new learning practices into the classroom (Lam et al., 2013). For example, school teachers in South Korea face great challenges when tasked to teach “software education”, due to their minimal training in computer science (Park, 2016). To overcome such attitudes and challenges, concerted effort expended in ensuring teachers have sufficient time and opportunity to experience and reflect upon CT problem-solving skills will increase their confidence (Leong et al., 2011). Leaving the practical details of implementation to the teachers’ own discretion to carry out the teachings have also shown success in Scandinavia (Kristensen, 2020), increasing their sense of ownership and autonomy in ensuring the programme’s success and sustainability.

Implementing curriculum changes is no easy feat, and constant discussions amongst all stakeholders will be necessary to ensure adequate support is provided on the ground in terms of resource allocation and training. Whether this change has a definite positive impact, it also needs timely monitoring and continued systematic analysis (So et al., 2020). Future work in developing appropriate assessment measures (didactic, portfolio, interview etc.) that can bolster personal engagement will also be vital for ensuring the curriculum’s success (Grover & Pea, 2013; Klement, 2020).

CONCLUSION

As we seek to prepare future students for the rich opportunities of the information age, we understand that developing computational thinking early on is difficult but an imperative. We propose the insertion of CT concepts into biology curriculum for both pre-university and university levels. In doing so, we wish to break down the structural barriers that inhibit interdisciplinary discussion while challenging current perceptions to education. Moving towards learning for life, this reflection hopes to reframe education as a space for skills development and not merely an information delivery system.

AUTHORS' CONTRIBUTIONS

ACYC and LYX wrote the manuscript with input from all authors. KTS, CCS and WWBG conceptualised the biology and computational thinking curriculum. WWBG supervised the writing of the manuscript. All the authors have read and approved the manuscript.

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APPENDIX

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