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Contact Author: Yuanlin Zhang (y.zhang@ttu.edu)

Department of Computer Science, Texas Tech University, Lubbock Texas 79424, USA

INTRODUCTION

There is an urgent need for a well-prepared workforce in STEM and Computing in this century (President's Council, 2010; Smith, 2016). There is consensus that computing should be an important part of the K-12 curriculum (White House 2017). Computing is not only a STEM discipline in its own right but also a discipline integral to the practice of all other STEM disciplines (STEM education act, 2015). It is a very challenging problem on how best we can teach Computational Thinking (CT) and how to integrate it with STEM disciplines to improve STEM learning (National Research Council, 2011).

One interesting line of research is on finding a systematic approach to integrate the teaching and learning of STEM subjects. One representative is the work by Sengupta and colleagues (2013) that employs agent-based computation to integrate STEM subjects. Motivated by this line of work, we studied the STEM subject integration problem. Our rationale can be best summarized below:

- Thousands of years of effort to understand how thinking works leads to the birth of *mathematical logic*, a formal form of logic. The greats contributed to this work include Aristotle, Boole, Frege, Cantor and Russel among others. Einstein has a good summary of the role of logic in Science: *"Development of Western science is based on two great achievements: the invention of the formal logical system (in Euclidean geometry) by the Greek philosophers, …"*
- There are many decades of practice by computer scientists and AI researchers in solving problems across all kinds of application domains. In this process, logic has been expanded and methodologies developed to solve problems using logic.

Building on the work in AI (knowledge representation and reasoning) and the nature of STEM subjects, we developed a logic based approach to integrating the teaching and learning of STEM subjects including computing and AI themselves.

The logic based approach has proven to be effective when we develop integrated curriculum in the context of science at middle school level (called LPK12), data science at high school level (called LogicDS), and chemistry at college level (called iChemistry).

We have carried out a preliminary study of the impact of LPK12 and LogicDS on students' learning and on professional development (PD). Our integrated curriculum has been used by hundreds of students, and in PD for tens of in-service and pre-service teachers.

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Although logic has been universal and, together with grammar and rhetoric, was essential to a classical education, logic in its modern form is rarely covered in the current curriculum. As a result, it is new for us on how to measure students' learning of computing and STEM subjects through logic. A significant effort of ours is to study the development of assessment and to validate it.

In this symposia, we will report the logic based approach, an example data science curriculum based on this approach, a study of the impact of LPK12 on students' learning and the development and validation of an assessment for logic based abstraction.

PRESENTATION #1 THE LOGIC-BASED INTEGRATION FRAMEWORK

The logic based approach consists of the follow components

- Central task: develop a **program** for **computers** to **answer questions** automatically.
- The method of the development of such a program.

The development method consists of three components. The first is abstraction which consists of the following components. a) Questions. The questions can be from any STEM subject. b) Language. For any abstraction (whose definition is in the next bullet), we need a language. One of the most universal languages is *mathematical logic*. c) Abstraction. Once we have a language, we are able to use the language to *abstract* information relevant to our questions. The result is called *abstraction* (or a model). The questions are supposed to be answered from the abstraction through logical reasoning. d) Methodologies. When facing STEM problems, the abstraction is not always straightforward. Methodologies have been developed in STEM areas and explicated in Computer Science and Artificial Intelligence. Examples include

- object-relation methodology to mode information for most questions about this world interesting to people,
- problem decomposition (or divide and conquer), and
- iterative refinement (of the abstraction).

The second is Programming. Abstraction forms a base for programming. By programming, we obtain a program from an abstraction using a particular programming language. Programs are executable by computers automatically. As a result, the program (and the associated abstraction) can be tested effectively (e.g., compared with an abstraction on paper). Computers also provide convenience for debugging the program (and the associated abstraction).

The last component is the program/abstraction is iteratively refined based on tests (experiments) and debugging.

How does the logic based approach integrate computing and a STEM subject? The logic describes the world by objects and relations among them. For any STEM subject, it studies objects and their relationships. These objects and relations can be handily represented by the logic language. The logic based approach provides a straightforward connection between a STEM abstraction and program, and the programming usually makes the learning engaging.

By consensus and standards on STEM subjects, we can also make an argument that logic based approach supports students' learning. In the well known K-12 Computer Science Framework (National Research Council, 2012), the learning of science and engineering involves 8 practices: SP1. Asking questions and defining problems, SP2. Developing and using models, SP3. Planning and carrying out investigations, SP4. Analyzing and interpreting data, SP5. Using mathematics and CT, SP6. Constructing explanations and designing solutions, SP7. Engaging in argument from evidence, and SP8. Obtaining, evaluating, and communicating information. Our approach provides direct support of all of them except SP3. For mathematics, our approach covers its core practices as identified in the Common Core State Standards for Mathematics (Common Core State Standards Initiative, 2011): MP2. Reason abstractly and quantitatively, MP3. Construct viable arguments and critique the reasoning of others, and MP6. Attend to precision.

PRESENTATION #2 DEVELOP A CURRICULUM FOR DATA SCIENCE USING THE LOGIC-BASED APPROACH

Data science is revolutionizing science and industries, and the current job market has shown a strong demand for a workforce fluent in data science (NASEM, 2018; NSTCC-STEM, 2018). As an interdisciplinary subject, data science has its foundations in computing, math, and statistics among others by (NASEM, 2018), providing excellent opportunities for high school students to develop college-ready STEM competencies and prepare their future careers. However, developing an introductory data science course for high school students is challenging due to its foundations in multiple areas. This challenge provides an opportunity to apply our logic-based approach to developing an introductory data science course.

Data in data can be taken as objects and their relations that are interesting to human beings, and are amenable to be represented by logic. The concepts of statistics, a major discipline for studying data, can be precisely defined using logic. For example, population and variables can be defined by basic logic concepts of sets and functions: a ***population*** is a *set* of objects, and ***variables*** are functions mapping the population to values. The frequency of a value of a variable can also be represented logically. Let *P* be the population and $x: P \to V$ be a variable. The ***frequency*** of a value *a* in *V* is the number of individuals of *P* whose value is *a* under function *x*. This can be expressed using *set builder* notation as $len(\{b \in P: x(b) = a\})$ where *len* is a function from sets to their sizes. This representation can be easily translated into a program in programming languages such as R. We have shown how math, computer science, and statistics are unified by logic.

To develop a logic based curriculum for data science, we gathered math, computing and statistics concepts from sources including *Introduction to Data Science (IDS)*, *Bootstrap Data Science curriculum*, *AP Statistics*, *GAISE II*, and *Data 8*: *The Foundations of Data Science*. We then wrote *precise definitions* for these concepts using mathematical logic. Next, we arranged these concepts in a logical sequence, reflecting their progression and interdependencies. We then identified necessary constructs for the mathematical logic language. We next connect statistics and logic to programming in a particular programming language. Each curriculum lesson began with a motivating example (for a concept, logic, statistics or programming) and a question(s) to engage students' curiosity, followed by the concept's precise definition. Examples and exercises were provided to reinforce the understanding. The lesson will end with programming practices. The initial curriculum was piloted in classrooms and refined by working with teachers and findings from the analysis of the data collected from classroom implementation.

PRESENTATION #3 THE IMPACT OF A LOGIC-BASED INTEGRATION OF COMPUTING AND SCIENCE ON MIDDLE SCHOOL STUDENTS' LEARNING

To evaluate the impact of our developed curriculum using a logic-based approach, studies were conducted over two separate periods in 2018 and 2020, in a classroom of a STEM elective course at a middle school in the USA. Middle school students aged 11 to 15 were chosen for the study due to their demonstrated ability to employ logical symbols in relation to abstract concepts, as supported by research by Piaget (1972) and Vygotsky (1987). In 2020, with one teacher leading 317 students ranging from 6th to 8th grade through an 8-week module comprising two 50-minute sessions per week, the experiment encompassed activities including video-based lessons, quizzes, and an online post-test assessing computational and science content. In 2018 the participants were 167 students from grade 6th and 7th with one teacher.

Results from both studies revealed significant improvements in computational thinking among middle school students. The 2018 study shows us that both the 6th- and 7th-grade students showed significant development in their computational thinking skills, particularly in abstraction. The effect sizes, measured by Cohen's d, were large, and the normalized gains were medium. This indicates that the modules effectively helped most of the participating students make considerable progress in abstraction skills. Students were given questions that were specifically developed and validated to measure their abstraction skills. From the student responses of 6th grade students, the effect size index (Cohen's d) is 1.36, and their normalized gain is 0.48. For 7th grade students, Cohen's d is 0.82 and their normalized gain is 0.39. In the 2020 study, we explored different levels of abstraction and programming to better understand how well students learn these skills. Our data and analysis provide a detailed understanding of students' learning of abstraction and programming within the LPK12 framework. Students performed well at the basic level of abstraction. For example, they effectively represented knowledge as LP facts and asked questions using LP queries, both with and without variables. We found that students could build their reasoning process to predict the expected answers from queries. Most students had positive experiences with programming and showed debugging skills, demonstrating their ability to identify and fix errors.

These studies also revealed a significant increase in science knowledge among middle school students in the 2018 study. Most interviewees found the modules interesting, and nearly all believed that computing positively impacted their science learning. Integrating computing tools into the science curriculum made topics more interesting and fostered professionalism and engagement, as confirmed by positive feedback from interviewees.

PRESENTATION #4 DEVELOPING AND VALIDATING AN ASSESSMENT TO MEASURE STUDENTS LEARNING OF LOGIC BASED ABSTRACTION

We are using a logic based approach to integrate computing with STEM subjects for K-12. However, rigorous instruments measuring students' learning of abstraction are still rare. We developed our assessment tools to measure students' learning of abstraction. Our assessment tools included pre- post-tests, surveys, and interviews. The claim is our developed assessment can measure the student learning of abstraction. We validated our assessment tools using the argument-based validation approach proposed by Kane (2013).

The first step is making the interpretative argument which involves defining abstraction, creating a hypothetical learning progression to guide test development and developing a test according to the progression.Three major assumptions were made in this step, that the definition of abstraction aligned with existing literature, the hypothetical learning progression facilitated student understanding, and test scores accurately reflected understanding of learning progression components. We proved our assumptions using theoretical validation and empirical validation which are other two steps of argument based validation. Our definition of abstraction agrees with the description of abstraction by Aho and Ullman (1992), Wing (2006), Sherman and Martin (2015). Our hypothetical learning progression is grounded in constructivism and aligned with NGSS standards.

Empirical validity was supported by data from 317 students, 11 of whom were interviewed, and 118 who responded to an online test. Face validity was confirmed by experts, while reliability was assessed through inter-rater consistency, item-rest correlation, item difficulty, and discrimination. Protocol analysis-based validation through interviews and modern test theory-based validation via Confirmatory Factor Analysis further bolstered the assessment's validity. Overall, the results from both theoretical and empirical perspectives were positive, affirming the effectiveness of the assessment tool in measuring students' understanding of abstraction.

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