Educational Robots and Computational Thinking

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Abstract. In 1969 Seymour Papert developed the idea of Logo programming and Turtle robots. His thesis was that people learn according to the mental models available to them. He envisioned the potential of the computer to make students active learners, constructors of their own knowledge through the process of programming. The floor Turtles are devices the students can program and use to explore ideas and the world around them. The Logo approach was not simply writing code, it was about developing a student's thinking skills, problem solving and other sustainable learning traits. A 2006 seminal paper by Jeannette Wing prompted renewed interest in what is now called computational thinking. This paper examines this new perspective and how they relate to the theory and practical use of Turtle type educational robots.

Keywords: Computational Thinking, Roamer, Educational Robots, TRTWR, RiE, Teaching with Robots, Logo, Seymour Papert, Turtles, Jeannette Wing.

1 Introduction

In 2006, Jeannette Wing, President's Professor of Computer Science at Carnegie Mellon University, delivered a seminal paper to the Association of Computer Machinery [1]. Wing stated that thinking processes and disciplines used by computer scientists would benefit students of all subjects. The paper inspired computer scientists and educators and has led to growing interest around the world to promote the idea to schools. These proponents cite work with educational robots as a means of engaging students in what is called Computational Thinking (CT) [2]. This paper reviews this trend from the robotic educator's perspective.

The paper explores the pre-history of the current CT movement, which is intimately involved in the work of Seymour Papert – the founding father of educational robotics. It goes on to examine the claims made by proponents of CT and summarises their ambitions and the challenges they are striving to overcome. A critical analysis of this work presents a few cautionary comments and then reviews the synergies between the ideas of CT and those of the Educational Robotic Application (ERA) Principles [3]. It illustrates these with example activities and suggestions that may help the development of successful CT strategies that can advance the objectives of both educational roboticists and educational computer scientists.

2 Papert, Logo and Turtles

In the late sixties and early seventies Seymour Papert developed the idea of Logo as a computer language for young children. He also invented educational robots when he developed the Turtle as a real-world device that children could control with their Logo programs. Papert had worked with Jean Piaget exploring how children learn mathematics. He shared many of Piaget's notions of genetic epistemology and he believed that anything was simple to learn if you could assimilate the idea into your collection of mental models [4].

Papert recalled how, as a 2 year old child, he had become fascinated by automobiles, particularly differential gears. Brought up in the South African bush, where keeping cars going was a major challenge, this was a hands-on familiarity. In short, he loved playing with gear systems. Years later he was able to quickly grasp some powerful mathematical ideas, which bemused most of his contemporaries. He realised that this was because he could relate these ideas to his knowledge of gear systems. "*My thesis could be summarised as: what gears cannot do the computer might. The computer is the Proteus of machines. Its essence is its universality, its power to simulate"* [5].

Papert saw the Turtle robot as an "object to think with" [6]. He thought of it as a transitional object, an idea he borrowed from clinical psychology [7]. This relates to how we form relationships with the physical world, how we project our thoughts, imaginations and emotions into objects and how they trigger thoughts and help create thinking patterns. He called this process body syntonicity. Children imagine how they would navigate around, for example a square. They transfer this experience into a program that made the robot draw a square. In this way, they made contact not simply with facts about squares, but the essential structure of geometric shapes.

Papert cited the Piaget's psychogenetic theories and related these to the Bourbaki mathematical concepts as the roots of Logo [8]. He hypothesises a process in which mental structures emerge from student's experience. Children learnt by using Logo and Turtle as tools to explore environments (microworlds) rich with ideas.

George Polya was another major influence on Papert. Polya had noticed that many of his students had acquired mathematical knowledge, but did not have the ability to solve mathematical problems. In his classic book "How to Solve It" Polya introduced a heuristic approach to problem solving used by mathematicians [9]. This was a fledgling attempt at trying to do more than teach factual knowledge. The mathematics teaching community reacted enthusiastically. In the foreword to the new edition Professor Ian Stewart remarks that the 1980 yearbook of the National Council of Teachers of Mathematics in the USA had been "*marinated in Polya sauce*".

3 Computational Thinking

In her 2006 paper Wing states: *"It [Computational Thinking] represents a universally applicable attitude and skill set everyone, not just computer scientists, would be eager to learn and use"*. She goes on to claim, *"Computational thinking is a fundamental skill for everyone, not just for computer scientists. To reading, writing,* *and arithmetic, we should add computational thinking to every child's analytical ability"* [1].

What is meant by computational thinking continues to be debated and with an increased intensity. The 2014 English National Curriculum for computing opens "*A high quality computing education equips pupils to use computational thinking and creativity to understand and change the world*" [10]. It is not our intention to attempt a strict definition. We are more interested in "the sense" of its meaning, particularly where it relates to educational robotics. Journalist John Naughton refers to abstraction, decomposition, heuristics, and iteration [11]. Felleisen and Krishnamurthy argue that imaginative programming is crucial [12]. Table 1 summarises the key ideas of CT [13].

Table 1. Computational Thinking Concepts and Competencies

CT Concepts	Competencies
Abstraction	Dealing with complexity through reducing unnecessary detail
Algorithm	Identifying the processes and sequence of events
Decomposition	Breaking complex artefacts, processes or systems into their component parts
Generalisation	Identifying the patterns and commonality between artefacts, processes or systems
Logical Analysis	Applying and interpreting Boolean logic
Evaluation	Systematically (through criteria and heuristics) make substantiated value judgements

The statement that CT is not programming appears persistently in the literature. In England, the government's launch of the "Year of Code" has provoked an adverse reaction. Clive Beale Educational Director of Raspberry Pi Foundation, stated, "*...code alone was not what computing is about. Computing could be a creative discipline bringing in other subjects as music and art*" [14]. Professor Mark Guzdial, from Georgia Tech, makes the point while it may not be the aim it is the means [15].

4 A Cautionary Note

The CT literature is enthusiastic. David Hemmindinger points out that some of the claims made by the CT community are also the provenance claimed by other disciplines [16]. He wisely warns against some of the more zealous claims made in favour of CT.

It is not the first time a discipline has endeavoured to promote its thinking skills and processes as a general approach beneficial for all of K-12 Education. In 1970s England, a grassroots inspired initiative transformed the teaching of woodwork and metal work (Industrial Arts) into Design and Technology (D&T). It was not sufficient to make things, it was important to design them. It was realised that the design process offered a universally applicable intellectual discipline and problem solving process. Every manmade thing is subject, consciously or subconsciously to the design process. This includes web site design and the development of the most sophisticated software and computer-based projects. The impetus of the D&T movement saw the subject introduced in several countries. In 1994 it led to the International Technology Educators Association (ITEA) launching the Technology for All Americans project [17]. Advocates like Dr. Ronald Todd, director of Project Update[1], passionately espoused ideas that are remarkably similar to those made by the CT Community [18]. The potency of this is illustrated in "The Fleet Circus Project", run in a small primary school in Lincolnshire, England, it shows an exemplar D&T project [19]. This cross-curricular work saw the students design and build a series of circus automata, many of which were computer controlled.

As a fervent believer in this approach, Dave Catlin had salutary experience trying to persuade the administrators of science teaching in Montgomery County, Maryland of the potential D&T offered. They made it clear that their interest lay in getting science students to think like scientists. To become a mathematician you need to think like a mathematician, to become an artist you need to adopt the thought processes of the artistic fraternity. Teachers of those subjects justifiably believe in the mental processes of their disciplines. This is not simply a "turf-war". Lave and Wenger's work on communities of practice clearly shows that you acquire the attributes of a profession by engaging in its practices [20].

We can draw a number of lessons from these histories. The first Hemmindinger has already identified – developing the thinking skills is the goal shared by all subjects. Just as with the original Logo ideas, programming provides the opportunity to engage students in activities with the potential to develop those skills. But, it needs to be done from within the discipline. Felleisen and Krishnamurthy suggested the way forward was to align CT with mathematics – an accepted core subject [12].

We need to consider carefully how explicit we need to be about the mental processes. Papert's belief was that the structures would emerge from exploring suitable microworlds, with appropriate tools. This raises an issue beyond the scope of this paper, but something worth further investigation – the difference between experts and novices – see Bransford et al [21]. The expert's mental structures are internalised and as Lave and Wenger demonstrate they gradually emerge from exposure to a variety of relevant experiences. CT is such a structure and you cannot simply "bolt it on" to a novice. Vygotsky's defined the zone of proximal development (ZPD) as the difference between a child's independent problem solving performance and their performance guided by more capable peers [22]. Papert noted that students' ability to solve problems improved when Polya was the guide [23]. Stewart points out simply implementing the heuristics is not enough; they require the interpretation of experience. Polya used heuristics not as rigid rules, but as a set of guidelines, backed up with sound praxis. But he was an expert: a more capable peer. The Fleet Circus Project was successful because the teachers used the design process as a loose guide. Others, who systematically followed the design process, have failed. It is like trying to be an artist by "painting with numbers". The problem is, many teachers have yet to internalise CT. They do not qualify as more capable peers.

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[1] UPDATE (Upgrading Practice through Design and Technology/Engineering Education) was a K-6 effort across six states, with the intent of using D&T as a means of integrating science, math, and technology for elementary students

5 Computational Thinking and Educational Robots

In his blog, John Naughton stated that many UK schools taught Logo programming enabling children to control a Turtle robot to carry out complex manoeuvres. He then said, most of those schools gave up teaching Logo [11]. However, the teaching of Logo and controlling of Turtles never stopped. For over 30 years the use of educational robots, disguised as programmable toys or control technology, has been standard practice in UK primary schools. This work has not taken place in the hallowed halls of academia, but in classrooms. The protagonists of this effort have been dedicated teachers working with a few specialist companies and robots like Roamer, PIP, Pixie and BeeBot. Together they have accumulated practical experience of dealing with the issues discussed above. The ERA Principles (Table 2) were empirically derived from this work [3].

Table 2. Summary of ERA Principles

Technology	Student	Teacher
Intelligence	Engagement	Pedagogical
Embodiment	Sustainable Learning	Curriculum and Assessment
Interaction	Personalisation	Equity
		Practical

These principles provide a framework to judge the value of educational robots and robotic activities. They afford a means of supporting future design efforts and provide a set of tools for correlating data in the long-term e-Robot Research Project [24]. The Principles usually work together in a variety of ways. We now present four sample activities, which we will use to explain the relevant ERA Principles and illustrate how they relate to CT ideas.

What Did I Do? This is a simple activity for 5 year olds. The robot has a specific behaviour which demonstrates all its basic movements and actions in a sequence. The students' task is to describe what they see. At this age students generally do not have the language to describe the robots actions. Typically, they resort to their imaginations inventing non-standard units to describe how far the robot moves.

In the Dog House Students turn their Roamer robots into "dogs". This task involves science (observing and studying dog behaviours and habitats), mathematical modelling (describing the behaviour in a way that it can be programmed) and programming, testing and debugging. It also involves D&T and art and crafts and is typical of many cross-curricular opportunities educational robots offer. This type of task is open-ended – the students are not making a dog, but a machine that makes people 'think' dog [25].

Spacecraft Rescue A spacecraft has crash-landed in a ravine. The Rescue Team has to send their robot to recover it. The students design a structure that the robot can transport to the site. The structure has to be capable of lifting the spacecraft, loading it onto the robot which then transports the spacecraft and the structure back to base. Materials used, manufacturing processes and travelling are all costed. The challenge is to complete the task as economically as possible. The programming involves older students in basic vector analysis [26].

Going Round the Bend Turtle robots turn on the spot because both their wheels turn in opposite directions at the same speed. In this task students create a behaviour where the wheels drive independently. This allows students to make the robot move in curved paths. This is an activity in practical calculus.

Most teachers feel under pressure to deliver good test scores. If CT helps them do that then it complies with the **ERA Practical Principle** (which concerns issues relating to teacher buy-in). In this case, buy-in is satisfied through the **ERA Curriculum and Assessment Principle (CAP)**, which states: "*Educational Robots can facilitate teaching, learning and assessment in traditional curriculum areas by supporting good teaching practice".* Felleisen and Krishnamurthy were criticized for "hiding CT in mathematics" [14]. Their response based on "14 years in the trenches of outreach" was that this was essential to get teacher buy-in. This agrees with our 30 year practical experience with robotics. However, as Table 3 illustrates, with educational robots it is possible to reach a wider audience than the maths teachers. Educational robots provide a well-trodden route for CT to reach schools.

Table 3. Relationship of CT Concepts, student activity and curriculum subjects for the Dog Activity. A similar correlation can be made for all the sample activities.

CT Concepts	Student Activity	Related Subjects
Abstraction	What are the essential features of a dog?	Science/Art
Algorithm	Defining what the robot dog will do	Mathematics
Decomposition	Creating a design specification for the dog	Design Technology
Generalisation	How do dogs behave in their environment	Science
Logical Analysis	Not applicable in this activity	
Evaluation	Does my robot dog meet my design criteria?	Design Technology

"Good teaching practice" is a key phrase in the CAP definition. Good practice is exemplified in the Fleet Circus Project, but how do you capture and propagate that? It has been proposed that Assessment for Learning Methodologies (AfL) offers a resolution to this problem [27]. The Spacecraft Rescue illustrates how application of these methods can help resolve the expertise-problem highlighted by Professor Stewart [28]. It provides an effective way to scaffold activities and support non-expert teachers with the contextual knowledge essential to this sort of endeavour.

The **Sustainable Learning Principle** (SLP) resonates with many of CT ideas. Another phrase used to describe this principle is Lifelong Learning. SLP skills are transferrable from task to task and discipline to discipline. They fall into four broad categories: cognitive, emotional, personal and social. The CT Concepts in Table 2 are cognitive aspects of SLP. Generally, programming is a solitary process, whereas working with floor robots is normally done in groups. They include the social aspects of SLP and as a consequence the personal and emotional facets. This connects CT with powerful learning paradigms associated with such social learning environments.

Derived from an analysis of hundreds of different robotic activities the **Pedagogical Principle** identifies several distinct elements that combine to make up an activity. With a specific outcome, Round the Bend is a *focussed task*. It involves *mathematical modelling* and provides the students with the opportunity to engage in *inductive thinking* and *experimentation* with an authentic problem. Understanding the nature of PPs helps the developer create activities with structure and support necessary to meet the **Practical Principle** and provides an analytical tool for research. Such elements are essential if the aims of CT movement are to be realised.

Robots have a history of **Engaging** students, dealing with **Equity** issues and enabling activities to be **Personalised** to suit the needs of students [29]. CT must address these issues if it is to be useful in K-12 education.

The **Embodiment** Principle states *Students learn by intentional and meaningful interactions with educational robots situated in the same space and time.* A straw poll of over 250 teachers who frequently use robots indicates a belief that there is at least a valuable qualitative difference in the experience of a real compared with virtual robots. In this sense, educational robots offer a concrete way of engaging CT. While programming is currently the main way students interact with robots. We will see tangible computing, HCI and HRI playing an increasing role. **What Did I Do?** shows how CT concepts like *Abstraction* and *Decomposition* can be engaged without programming. As Wing asserted, CT goes beyond computer science and is a general skill. The **Intelligence Principle**, predicts that behaviours beyond the Logo paradigm can and will be invented. Ensuring these behaviours engage CT will add value to educational robots.

6 Conclusions

Educational robots have grown out of ideas that represent a prehistory of CT. There is a strong correlation between the ERA Principles and the ideas embraced by CT. CT and Educational Robotics have a natural symbiotic relationship and can work together to offer exciting educational opportunities for K-12 Education.

Barr and Stephenson called for the larger computer science community to help the CT cause by providing suitable materials and taking advantage of opportunities to work with K-12 administrators [2]. Educational robots offer a substantial set of tried and tested materials that meet the need for CT resources. Robot activities bring a practical maturity that can help CT theory become a successful practice. These present teachers with the opportunity to help students develop their CT skills while meeting their obligation of delivering the curriculum and aiming for high test scores.

On the other hand, the interest and energy represented by the CT movement represents an opportunity to further the aspirations of the educational robotic community. In the USA and UK CT currently has the attention of policy makers and administrators. The educational robot community should grasp this opportunity by forging links with this movement.

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