Constructionist Collaborative Engineering: PVBOT

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Abstract

This paper describes constructionist collaborative engineering (CCE), a paradigm for teaching high school students to understand science from a complex systems perspective. Constructionism, as originally developed by Papert (1980), is in part a theory of understanding how people learn more effectively by building, programming, creating, and designing their own materials for learning ("objects to think with"). CCE builds on this work by describing collaborative creation by students of solutions to engineering problems using complex systems methods. We present PVBOT (**P**hysical/**V**irtual ro**BOT**ics) as a physical robotics CCE system in which students individually build and program simple physical robots that must work together to achieve a common goal. By doing so, the students come to understand the complex systems perspective of individual agents working in concert to create an "emergent" solution. We explore CCE as a paradigm for teaching the complex systems perspective and discuss the tradeoffs of using PVBOT to teach the complex systems perspective.

Introduction

Complex systems research has become increasingly important for understanding scientific phenomena (Holland, 1995; Wolfram, 2002; Wilensky & Resnick, 1999), and as a result, there is a call for increased research on how to effectively teach students complex systems skills (Jacobson & Wilensky, 2005). As with many disciplines, complex systems science has become increasingly computational, and our research suggests that teaching complex systems skills and computational skills in concert helps students learn complex systems science more comprehensively and more quickly (Berland & Wilensky, 2004, 2005). Just as print literacy opens a lens through which we can look at the world, we describe computational and complex systems literacies as means to not only gain technical skills in these domains, but also the cognitive and social skills necessary to use complex systems as a perspective on science. To that end, we follow diSessa (2000) in his discussion of alternative literacies.

This paper proposes constructionist collaborative engineering (CCE) as a paradigm for teaching complex systems perspectives and a system, PVBOT, built to teach complex systems literacy and computational literacy using CCE. The term constructionist collaborative engineering describes a focus on students building material objects collaboratively. PVBOT is a physical/virtual robotics system in which both students and student-built robots collaborate. Berland & Wilensky (2004, 2005) show that students engaged in collaborative engineering with virtual robotics can also learn certain complex systems literacy skills. Since collaboration between physical robots can be logistically difficult and expensive, there are few studies examining the effectiveness of teaching complex systems literacy with physical robots, though studies have shown significant gains in using physical robotics for related learning tasks (Pollack, Lipson, Funes, &

Hornby, 2001). This work extends on work with VBOT, a collaborative constructionist virtual robotics architecture (Berland & Wilensky, 2004, 2005).

Defining Computational and Complex Systems Literacies

To understand how and why complex systems and computational literacies could be taught with CCE, these literacies must be defined and investigated. In this section, the literacies are both defined with relevant literature and external learning goals.

Computational Literacy

As argued by Papert (1980) and diSessa (2000), computational literacy implies both the ability to use computer software and the ability to create and manipulate computer software (or hardware) to communicate and disseminate ideas. This definition of literacy parallels the generally understood meaning of print literacy; a print literate individual can express oneself in writing. However, the term computational literacy has often been used to describe an impoverished level of literacy in which the learners only master a few standard computer applications. For example, when I was a teacher, I taught a class called "computer literacy," which was designed to teach mastery of Microsoft Word, Excel, and PowerPoint. To distinguish this conventional definition from the richer definition in which students can express themselves with computers, we follow Papert (1980) and refer to it as computational literacy. The expressive and authoring aspects of computational literacy are largely ignored in the pre-collegiate curriculum. We argue that such computational literacy can greatly benefit citizens of our era, because computers shape so much of our interaction and communication.

Complex Systems Literacy

Some have argued that complex systems theory is a new kind of science, one posed to usurp the mantle of scientific explanation from traditional equation-based science (Wolfram, 2002). Scientists use complex systems methods to model phenomena in domains varying from physics (Bar-Yam, 1997) to social interactions (Watts, 2003). Research has shown that modeling with complex systems is more comprehensible to high school students than traditional equation-based science (Wilensky, 1997, 1999; Ioannidou, Rader, Repenning, Lewis, & Cherry, 2003; Centola, McKenzie, & Wilensky, 2000; Wilensky & Reisman, 1998, 2005; Jacobson & Wilensky, 2005). Complex systems literacy skills, however, are still absent from most school curricula.

Complex systems literacy refers to an individual’s ability to negotiate the relationships between “agents”, “aggregates”, and “levels thinking,” in situations such as traffic jams. This terminology is derived from Wilensky & Resnick (1999), who use the example of a traffic jam:

> “Two high-school students were writing a computer program to simulate the flow of traffic on a highway. They began by writing some simple rules for each car: Each car would accelerate if it didn’t see any other cars ahead of it, and it would

> slow down if it saw another car close ahead. They started the program running, and observed the patterns of traffic flow. On the screen, a traffic jam formed. They continued to watch and–much to their surprise–the jam started drifting backward along the highway. 'What's going on?' said one of the students. 'The cars are going forward, how can the jam be moving backward?'"

In this example, the *agents* are the cars in the traffic jam. A traffic jam consists of cars. The traffic jam is a result that emerges from the *aggregation* of cars. Understanding the relationship between the individual cars and the emergence of the aggregation of the cars is called *levels thinking*. Levels thinking is not only the ability to think at both the level of the cars and the level of the traffic jam, but also the ability to concretize the relationship between the two levels. Levels thinking is perhaps the key component of complex systems literacy from our CCE approach, as it is amenable to using computational methods and is useful from the material, cognitive, and social perspectives.

Defining Constructionist Collaborative Engineering

We propose using constructionist collaborative engineering design strategies for helping students develop these different literacies. In the following, we define CCE as an organic hybrid of constructionism and collaborative play,

Constructionism and Engineering

Constructionism postulates that one learns more about an object or a concept by participating in the process of building the object or concept (Papert, 1980). The Logo computer language is an example of a constructionist educational programming environment; it allows learners to see the process of creating from start to finish. In logo computer environments, users program a "turtle" (a virtual agent) with a simple, but full-featured programming language, streamlined for beginners, in which all relevant program code is visible to the user-programmer. Often Logo is used as a mathematics programming environment or a drawing language. However, the Logo programming environment provides an important backdrop for the various projects in autonomous virtual robots. Papert (1980) discusses the Logo computer language in more detail. The turtles can be programmed as autonomous virtual agents. You can use Logo to create simple agent-based simulations and give the agent a fair amount of seeming "intelligence" relatively simply within the environment. Thinking about the relationship between oneself and one's turtle is a common introductory task in teaching with Logo. Constructionism and Logo have been the focus of several encouraging studies of computational literacy. Logo is an example of a constructionist engineering environment because students use it to engineer objects that reflect their current understandings of the world.

Collaboration and Engineering

While constructionism is inherently a theory of social, collaborative learning, it is necessary to elaborate what we mean by collaboration. In CCE, the collaboration is not only people working together, but also people working together towards a common intrinsic goal. Another way to look at voluntary collaboration is as a form of 'play'.

Traditional school curricula rarely involve significant "play" time, and efforts to raise standards for teaching and learning and schools have neglected to target sources of student motivation. A considerable body of research, however, has shown that play can be a powerful academic motivator (Papert, 1980; Vygotsky, 1978; Dewey, 1913; Kafai, 1994; Harel & Papert, 1989). Additionally, there is convincing evidence from both the social and cognitive streams of learning research indicating that learning and transfer are more easily achieved when the students are motivated to work through activities (e.g., Dweck & Elliot, 1983; Ames & Archer, 1988; Pintrich & Schunk, 1996). Schank and Cleary (1994) also show that intrinsic motivation can lead to more personally relevant, stable knowledge acquisition for many students.

Furthermore, studies have also shown that enabling social-help interactions leads to improved cognitive and social functioning (Vygotsky, 1978; Gutierrez, Rymes, and Larson, 1995). Vygotsky (1978) describes the Zone of Proximal Development (ZPD), which is the level at which children can function in a social-help setting as opposed to an individualized one. CCE projects provide students with opportunities to engage in informal social help situations as they work towards a common goal. Gutierrez et al. (1995) show that often the most productive and thoughtful interactions occur in informal spaces within the classroom, outside of the direct view and control of the teacher.

PVBOT: A Constructionist Collaborative Engineering System

In the following sections we describe PVBOT (**P**hysical/**V**irtual ro**BOT**ics), our current approach to CCE. PVBOT is designed to help students develop complex systems and computational literacy by collaboratively solving complex engineering problems.

PVBOT is meant to address not only the use of CCE in teaching computational and complex systems literacies, but also how physical robots can be used for CCE. Physical robots have been used productively for engineering education many times (Papert, 1980; Resnick & Ocko, 1991), and there is a natural affinity of educational robotics to engineering solutions (Hancock, 2004; Martin, 1996a). Though prior research looks promising in addressing our learning goals, there hasn't been significant work in using physical robotics to teach computational and complex systems literacies.

The PVBOT organizing metaphor stems from Braitenberg's “vehicles” (1984). Braitenberg uses virtual, physical, and theoretical educational robotics as a starting point for projects in art, philosophy, electrical engineering, and cognitive science. The book begins with descriptions of how to build (as circuits, thought experiments, programs) a simple set of autonomous robots that either “love” or “hate” light. To love light is to tend to travel towards it. For instance, a “love” robot might be a small, two-wheeled artifact that orbits a lamp. A “love” circuit could simply connect a light sensor to a motor attached to a wheel. As the light sensor sees more light, the motor speeds up, spinning the wheel faster, and sends the robot towards the lamp. PVBOT robots work much like Braitenberg's vehicles, in that they are programmed by simple, real-time sensor/motor pairings. PVBOT builds on the vehicles by adding a common space in which these robots function, a simplified language, and a "sandbox" in which to test the robots.

PVBOT: A Physical Robotics Participatory Simulation

PVBOT is built on top of the NetLogo multi-agent modeling environment (Wilensky, 1999) and the HubNet networked learning architecture used for participatory simulations (Wilensky & Stroup, 1999b). In participatory simulations, participant-students interact in a social space (such as a classroom), while the agents that the participants control interact in a shared virtual environment visible to all participants (Wilensky & Stroup, 1999a). PVBOT is an immersive collaborative robotics modeling and programming participatory simulation designed for use in middle school. PVBOT consists of: 1) an interface through which students build the control system of their personal robot; 2) a physical robot (typically one per student, see Figure 1); and 3) activities for students using the system.

In a PVBOT activity, each student in a classroom designs behaviors for a robot using a PVBOT client (Figure 2). While building circuit-based programs has traditionally been an undergraduate-level activity, recent studies have shown that students can productively use such systems for learning systems-based thinking (see Hancock, 2004). In the PVBOT system, each student’s PVBOT control center corresponds to a physical robot “agent” (Figure 1). The students' individual robots are placed in a "pen" where the robots must work together to achieve a common goal. The students control the behavior of the robot by building "behavior circuits" (programs written in the PVBOT language, as seen in Figure 2). During activities, students can act using PVBOT in several ways: they can build behavior circuits, save behavior circuits, load behavior circuits that they have built onto the robot, share behavior circuits with other users, or load behavior circuits that have been shared.

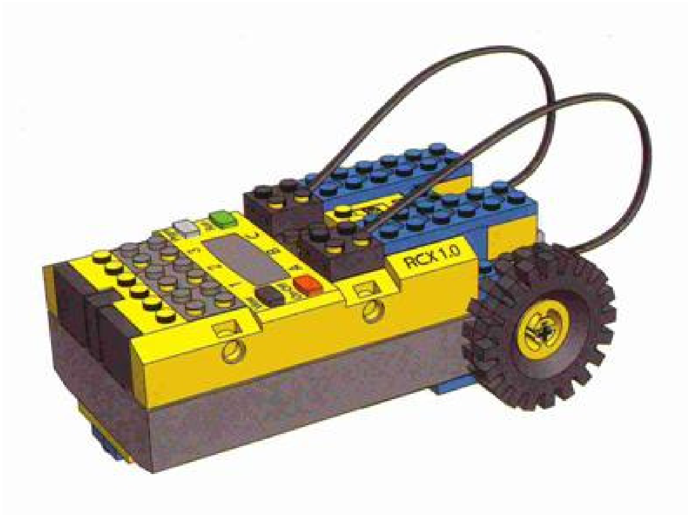

Figure 1 – Mindstorms Physical Robot

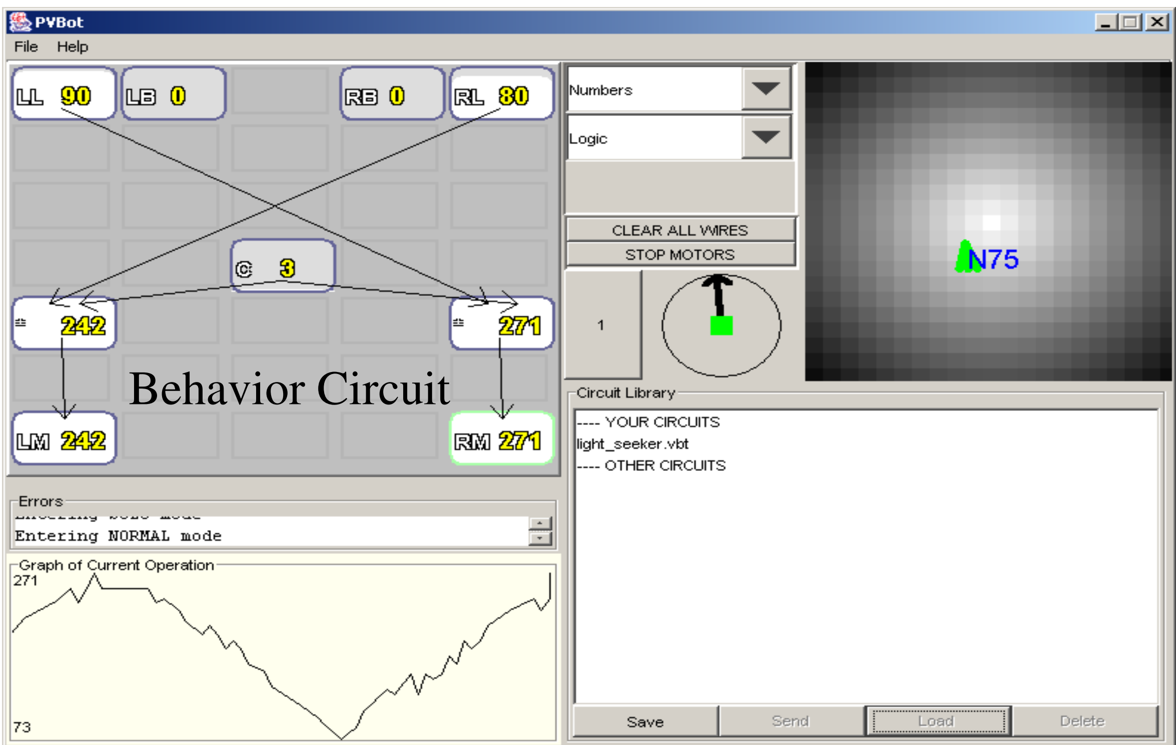

Figure 2 – The PVBOT client interface

PVBOT as a Physical Collaborative Engineering System

A simple PVBOT activity is a physical implementation of the traffic jam described above. Each student programs her robot to optimize traffic flow down a common path. If all of the students simply go full speed, there is a robot pile-up, but if the students take into consideration the robots ahead and behind, the students can make the traffic flow more smoothly. A sample iteration through the activity would involve each student:

1. Building a simple circuit to make her individual physical robot go forward on the path as quickly as possible.
2. Test her robot with the other students robots on a road made of construction paper on the floor.
3. Note the time to get to the end.
4. Build a new circuit that would avoid immediate crashing.
5. Test her robot again with the other robots.
6. Note the time again.
7. Repeat until satisfied.

At first blush, this might not seem especially collaborative, as the student is individually building and testing her robot on a competitive field. However, there are several salient aspects which make it constructionist and collaborative as an activity: the student's robot is only effective when the other students' robots are effective; each student must build circuits which take into consideration each other students' robots; there is a common goal; the solution is complex in the sense that each agent in the system must work together to have the system work at all. Students iterate programs until engineered complex solutions become robust with respect to the range of behaviors in the class.

Discussion

Due to our pilot studies with VBOT (Berland & Wilensky, 2004, 2005), there is evidence that teaching computational and complex systems literacies using CCE is a productive approach. Specifically, we found that students engaged in CCE using VBOT were likely to be engaged with fellow students, more likely to do well on questions using complex systems logic (than students not using VBOT), and at least somewhat able to communicate using computational and complex systems language. However, there are several important unresolved issues in using these approaches. The most obvious problems are the lack of longitudinal data and the lack of significant research in using physical robotics to teach complex systems literacy. As this paper is concerned with designing such a system for gathering such evidence, we hope to resolve that issue in the near future. There are other unresolved issues, as well, and hopefully investigating them will shed light on how to better design this system.

In the near future, we are beginning a study to investigate these issues in more depth. Several classroom implementations with both VBOT and PVBOT are planned. With this larger data set, we will address the following issues:

1. There is no comprehensive study of the relative affordances of comparative physical and virtual environments in constructionist learning.

As discussed earlier, virtual and physical environments have both been used to success in constructionist research and otherwise. Although there have been several studies of the relative affordances of virtual and physical environments (see Sharlin, Watson, Kitamura, Kishino, & Itoh, 2004 for a review of research on tangible interfaces), that work has not been explicitly both constructionist and empirical.

Rod Brooks (1993) defines the parameters for robot intelligence as an adaptive relationship between the "brain" and "body" of an autonomous agent. Simulated robots, however, have only a virtual "body." Brooks (1992) finds that while "artificial life" has no physical "body", virtual robots often interact with virtual environments in many of the same ways that physical robots interact with physical environments. As Brooks (1992) shows, every agent is both a product of and constrained by its environment. The complexity of an adaptive creature often relates to the complexity of its environment.

2. As the field of complex systems is young, there have been few comprehensive collaborative constructionist studies of complex systems literacy.

Even though there is significant work using constructionism to teach complex systems literacy (such as Wilensky & Resnick, 1998), the field's youth leaves many un-addressed topics. For instance, there has been relatively little research concerning the use of physical systems in teaching complex systems literacy. While this gap is being addressed by researchers such as Abrahamson, Blikstein, Lamberty, and Wilensky (2005), there remains much work to be done in this field.

3. While some research has shown a relationship between computer and complex systems literacy, there is little evidence that these literacies are mutually beneficial.

Research shows us that by teaching students to use computer programming to do complex systems science, computational literacy and complex systems literacy can be mutually reinforcing (Wilensky & Resnick, 1999; Wilensky, 2001). Our pilot studies also suggest that there are correlations between complex systems and computational literacy in students using PVBOT (Berland & Wilensky, 2004, 2005). The work, however, is preliminary, and further research is needed to conclusively show that students use computational literacy skills to complete complex systems related tasks, and vice versa.

4. There have been no comprehensive studies on the use of physical robots in teaching complex systems literacy.

Robots are a natural fit in complex systems research. Complex systems events involve many similar elements doing simple tasks that, together, create some emergent phenomenon (Wilensky, 2000; Holland, 1995). Similarly, it is common for robotics research to use several simple robots that collaborate in the creation of a phenomenon (see Parker, Schneider, and Schultz, 2005 for a variety of examples). Despite these parallels, and despite that robotics are commonly used to teach computer and mathematics literacy (Resnick & Ocko, 1991), robotics, as a field, has only recently begun to be addressed in complex systems research (Pollack, Lipson, Funes, & Hornby, 2001). Furthermore, there is little research using robotics to address complex systems literacy.

5. There has been little research in understanding the spread and flow of information in collaborative constructionist environments.

Research on social networks has recently made significant progress about transmission of information around small groups (Brown & Duguid, 2002; Watts, 2003). As of yet, few studies have applied it to constructionist learning environments, even though constructionist learning often involves collaboration and the sharing and distribution of information. The present study aims to demonstrate the value of collaborative learning in small social learning networks research and constructionist research.

6. PVBOT provides an untested model for collaborative programming environments.

Since the advent of the personal PC as a learning tool, collaborative programming has been evaluated several times as learning method (e.g., Papert, 1980; Tiffin & Rajasingham, 1995). Recently, new programming methods, such as "extreme programming," have been used in collaborative programming research (Beck, 1999). The present study provides a new framework for simple collaborative programming in complex environments.

Summary

As science-making drifts towards complex system ways of understanding, and as society drifts towards the increased ubiquity of computers, we will find these literacies necessary to remain informed citizens and scientists. However, the path to learning this content is not self-evident, even for those who believe in their importance. To that end, we have defined constructionist collaborative engineering as a means to achieve these literacies, and shown how PVBOT could be used as a system to teach those literacies through constructionist collaborative engineering.

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