

A Constructionist Approach to Teaching with Robotics

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Abstract

This paper presents four case studies representing the use of LEGO robotics materials and MicroWorlds EX Robotics programming by learners from five years old to mid-career postgraduate educators representing a variety of communities and prior school success. The robotics examples presented are more whimsical, playful and gender neutral than the traditional “battlebots” and vehicles dominating much robotics instruction.

Nearly two decades of using robotics in a constructionist context as inspired by Seymour Papert led the author to propose a new pedagogical theory, “A good prompt is worth 1,000 words.” When the four critical factors in this approach are in place, learners are able to develop projects more sophisticated than those resulting from traditional curriculum and instruction.

During the conference presentation, video of the case studies and similar student projects will be presented in order to illuminate the powerful ideas contained within this paper. This work provides provocative ramifications for the successful teaching of robotics and implications for all teaching.

Keywords

Robotics, constructionism, Seymour Papert, school reform, Reggio Emilia, project-based learning

Introduction

LEGO robotics has enjoyed a reasonable level of popularity in classrooms over the past twenty years. The flexibility, durability, ease-of-use, familiarity and brand recognition of LEGO construction materials have made enormous contributions to the viability of robotics in education. Without LEGO’s contributions to the educational marketplace robotics would remain the domain of science fiction or post-graduate education.

Robotics involves aspects of mechanical and electrical engineering as well as computer science. A working robot required both construction and programming. Therefore, a variety of student expertise, interests and learning styles are supported. Teachers otherwise reluctant to learn or teach computer science are often attracted to the tactile (hands-on) nature of LEGO robotics. Such hands-on activities often facilitate minds-on programming, complete with its requisite problem solving, debugging and mathematical thinking.

Principles of robotics engineering are neither the primary or secondary objectives of using robotics materials in K-12 education. Robotics principles may be learned at ages younger than previously anticipated, but such understanding is incidental to the use of robotics as material for constructing knowledge. (Papert and Franz, 1987) The sorts of learning made possible by robotics activities are often greater than the sum of its parts. A variety of school subjects are integrated while serendipitous connections to powerful ideas and forms of creative expressions are commonplace in the pedagogical approach described in this paper. The case studies presented represent a departure from traditional teaching practice.

Five Ways to Use Robotics in Education

There are at least five general approaches to the use of robotics in education. Each approach has its own objectives and requires different levels of teacher intervention.

Robotics as a discipline – Robotics is taught as its own discipline. Popular school age robotics competitions, such as the FIRST LEGO League, are examples of this approach.

Teaching specific S.T.E.M. concepts – Robotics may be used to teach physical science concepts such as: simple machines, force, torque, power, friction, mechanical advantage; computer science concepts of programming, debugging and feedback; mathematical concepts of fractions, variable, arithmetic operations, etc....

Thematic units – Students build and program robots to model machines and systems such as airports, factories, amusement parks or a city. The hope is that traditional school subjects and concepts are experienced or embedded in these themes.

Curricular themes – Robotics is used as a medium for solving specific problem connected to a formal curriculum topic. An example might be, “Identify a problem in Sub-Saharan Africa and build a robot to solve that problem.” The realism of the solution may be subordinate to thinking about the nature of the problem.

Freestyle – Robotics materials and computer programming are used as construction material as part of a student’s intellectual laboratory and vehicle for self-expression. The learner may use the materials to make anything they wish. Powerful ideas are experienced within the context of the activity.

Constructionist Approach

A detailed discussion of Papert’s theory of constructionism is beyond the scope of this paper. However, the following case studies are based on the principles that knowledge is constructed and the best way to ensure learning is through the deliberate construction of something shareable outside of one’s head. (Ackerman, 2001; Papert, 1993, 1991; Papert et al., 1991; Stager, 2002; Stager, 2007; Turkle & Papert, 1991)

The role of the teacher is to create the productive context for learning, including material organization, scaffolding, consulting, collaboration and anticipating forthcoming needs of each student. Teaching is subordinate to learning and the teacher is available to seize teachable moments and collaborate with students, rather than direct activity.

Four Case Studies of Robotics Projects

Ballerina

A five year-old kindergartener in an underperforming school expressed interest in being a ballerina. While this is hardly a unique aspiration of young girls, I suggested that she might be able to build a LEGO ballerina. “Anna” quickly set off to build a spinning mechanism as the core of her ballerina. She then took great care in creating a dress out of a paper napkin decorated with colored markers and made hair for the ballerina out of pipe cleaners. Such creative expression is consistent with Papert’s “computer as material” (Papert & Franz, 1987) metaphor, Reggio Emilia’s use of mixed media as a vehicle for personal expression (Topal, et al., 1999) and the Piagetian notion of “objects to think with.” (Papert, 1980a) It also contributed to an awfully cute robot.

Since a ballerina needs choreography, I showed Anna how a touch sensor could be used as a switch telling a Logo program to do something new. She decided that two touch sensors could be used and programmed to make her ballerina spin left or spin right. While one switch might have been sufficient for changing direction, holding a button in each hand felt more consistent with commanding the ballerina robot as if it were a marionette.

The entire project took two or three morning sessions to complete.

Anna was justifiably pleased with her creation and it became a favorite project of her older classmates. In a video clip captured during the project, the school principal asks Anna “And you did this with your computer?” at which point, the little girl confidently makes a modification to her Logo program with a nonchalance unusual for five year-olds speaking with adults. Also on video you can see Anna whistling and spinning her head synchronously with the ballerina while working its controls. This is a demonstration of the syntonetic body geometry on which Logo’s turtle graphics system is built; a learner makes sense of the world and powerful geometric ideas by relating such concepts to their physical motion.

Teddy Bear

A group of third grade students from an affluent private girls school worked with me for four consecutive mornings (approximately three hours per session). A consensus was reached for teams of students to work on inventions one might find at a state fair. One group of girls decided to bring a teddy bear to life by making it dance.

Once I made an incision in the bear’s torso, the girls set about building a skeletal system capable of making the bear dance. Three to five students approached the task with great enthusiasm and focus. An immediate challenge was translating the rotational motion of a motor into the up and down movement required for dancing limbs. The constraints of the stuffed bear’s limbs helped constrain the arms and legs and approximate dancing gestures.

As in other robotics projects, bugs required problem solving and alternative strategies while each successful breakthrough led students to set more complex challenges or grander theories to test. The dancing teddy bear was no exception.

Having achieved mechanical animation, the girls asked if the bear could also be “taught” to sing. As quickly as I was able to tell them that the LEGO programmable brick was capable of playing a simple single-note melody, one student rushed off to the music classroom to borrow a piece of sheet music.

Armed with the sheet music, a new challenge emerged. The expertise of team members capable of reading music was called upon. Then the musical notes and rests had to be converted to numerical values representing frequency and duration and programmed via MicroWorlds. The singing was added to the dancing procedure and a new Logo superprocedure was downloaded to the RCX brick functioning as the bear’s attached brain. Once the singing was satisfactory, their main program would need to be modified to sequence singing and dancing.

When asked to sing, the music played so quickly that the folk melody was barely perceptible. Faced with this bug, the girls needed a solution. One student noticed that the melody sounded correct, but too quick. Since there is no knob for adjusting musical speed on the computer or RCX, a programming solution would be necessary. The girls collaboratively arrived at a solution. They needed to multiply each of the duration values by a constant, hence slowing down the melody. (They may have experimented with increasing both variables, pitch and duration, before realizing that only one needed to change.)

Isolating the correct variable and multiplying it by a constant is a nice piece of mathematics for eight year olds, especially when you consider that it is during that grade level that most children are tortured by the rote memorization and recall of multiplication tables. These students demonstrated a working understanding of multiplication, variable, music notation, computer programming and both the physical science concepts and affective skills gained during robotics projects.

Phonograph

The next project description is of a robot built and programmed by incarcerated fifteen year-old who like most of his peers, was diagnosed with a variety of learning disabilities. He also had a poor record of school success in addition to truancy.

This teenager was inspired to recapitulate the invention process of Edison by creating a working phonograph without access to Edison's work, life experience or laboratory. The student's primary motivation was not to construct a phonograph, but to build "something hard, something nobody has ever done before." This is a remarkable stance for any young person, even more impressive when you consider this student's prior poor academic experiences. Constructing a sophisticated robot was a way to assert his competence as a learner in a school setting just different enough to inspire such innovation. It is also critical to understand that the phonograph was the first robotics project ever engaged in by this at-risk learner.

Young Edison's "school" was the alternative high tech constructionist learning environment Seymour Papert and I created inside of a state prison for teens in Maine, USA. The Constructionist Learning Laboratory (CLL) provided a computer per child, a rich variety of material with which to construct and sufficient time to work on substantive projects. Having been liberated from curriculum and assessment requirements by the Governor and Secretary of Education, the CLL was able to put the needs, interests and talents of severely at-risk students ahead of a traditional, albeit arbitrary, scope and sequence.

The robotic phonograph is an important example of a constructionist approach to robotics and the use of LEGO materials. The student used non-LEGO elements, constructed an invention from a simple prompt and developed the vocabulary for talking about his work. He *became* Edison and invented the phonograph for himself. In the process he came to understand gearing, computer control, transforming vibrations into sound and the satisfaction that accompanies a sound engineering effort. The narration demonstrates his understanding of gear ratios, the use of a microscope and even an appreciation of margin of error in his description of the device. The student learned about gearing, sound amplification, magnification and a host of other big ideas valued by educators concerned with traditional notions of curriculum value such concepts. (Stager, 2007a)

Project goals were intrinsic to the learner, There was no hidden curriculum or expectation that by building a phonograph each student will demonstrate an understanding of X or Y curricular objectives. No attempt was made to institutionalize this student's experience by compelling his classmates or future classes of students to build a robot phonograph. Young Edison's teachers had confidence that the use of such materials in the type of constructionist learning environment created would lead to the development of powerful ideas – even if some of those ideas were impossible to predict or the finished product imperfect. Best of all, the invention was original, conceived, constructed and programmed by a student.

Adult professional development

Robotics not only captures the imagination of children, but also provides a terrific context for educators to explore the power of learning technology in a playful, tactile and non-threatening fashion. For more than a decade I have employed the same pedagogical strategy for "teaching" robotics to teachers. The approach employed is similar to the way in which I introduce robotics to children. Adults are asked to form project teams of two to four. However, since professional development time is in shorter supply than classroom time, brainstorming project ideas is a luxury one can rarely afford. Frankly, adults in a workshop or graduate course are less likely than children to share their imagination or whimsy prior to experience with new technology.

Therefore, I begin my adult workshops by asking each team to pull an open-ended project idea "out of a hat" and immediately get started trying to solve the challenge stated on the sheet they chose. Each project sheet contains a one line prompt and an extension problem for more ambitious teams. Other craft materials and props useful in the challenges are available in the classroom.

Prompts might include:

- Build a robot card dealer that deals a hand of playing cards
- Invent a machine to walk a dog

Create a robot capable of playing a song on a xylophone or percussion instrument

Design and program a working chairlift or gondola

Construct a machine capable of blowing soap bubbles

Extension activities might be to have the chairlift drop a paratrooper on command or attach the bubble machine to a moving vehicle. The whimsical nature of these challenges makes the activities more gender neutral and respectful of a plurality of personalities and learning styles. (Bers, 2007; Rusk & Resnick, et al. 2008; Resnick, 2006; Resnick & Ocko, 1991)

Adults are encouraged to stop working and visit with other teams in order to learn from their colleagues and share expertise. Children do not need such reminders since they routinely explore the work of their peers, a phenomena called “collaborations through the air” by Yasmin Kafai. (Kafai & Harel, 1991; Kafai 1995; Kafai & Resnick 1996) Throughout the project development activity, participants are asked to remove their teacher hats and think about thinking – their thinking and that of their colleagues. Possible lessons and implications for teaching practice are discussed after participants experience the successful, if novel, learning adventure.

Repeatedly teachers in conference workshops, Pepperdine University graduate program orientations (Cannings & Stager, 2003; Stager, 2005) and most recently a project to teach Brooklyn, New York middle school science teachers to integrate robotics into their curriculum marvel at their successful work in an unfamiliar domain free of didacticism.

Commonalities

In most cases, I introduce robotics to the class by showing them the motors and sensors that are part of the LEGO RCX materials. I explain how to turn on the RCX brick, the sensor inputs and the motor outputs. The class is shown the infrared tower used to transmit programs from the computer to the programmable brick and that is about it. That five-minute presentation is about the extent of the formal robotics instruction. Two sets of pictorial engineering reference materials, one created by Fred Martin (Martin, 1995) and the other by MIT Media Lab students (The Art of LEGO), show students how various structures are built with LEGO and are made available in the classroom. A two-page MicroWorlds EX Robotics programming reference is also provided for students or workshop participants.ⁱⁱ

In all four cases presented, students of all ages, socio-economic status and academic achievement were able to invent, construct and program extraordinarily complex robots **the first time** they used the materials. How can this be true? A learner might be unable to create projects of similar sophistication after having completed a formal robotics curriculum lasting a year or more?

A teacher impressed by the ingenuity of a successful student project may be inclined to institutionalize a particular activity. It would be a mistake to require every student to build his or her own phonograph or add “dancing teddy bear” to the curriculum. Such pedagogical practices are found in science curricula that require every student to repeat identical experiments for decades and in the robotics teachers who come to tell me how their class “just built the traffic light.” In 1987, LEGO published several step-by-step tutorials designed to help people learn to use LEGO TC Logo. Nearly two decades later, what were once provided as mere examples have been chiselled in stone as sacred curriculum.

Learning cultures built upon the principles of this paper’s pedagogical approach require educators secure in their knowledge that with each project triumph or “bug,” the community gets smarter as the collective student expertise increases.

In each case there was no direct instruction, no model plans, no step-by-step instructions, no online tutorials, no formal assessment, no extrinsic motivation and no online access. After close to twenty years of teaching children and adults about and with robotics, learner after learner has been able to create impressive machines without traditional teaching. Such counterintuitive results required the construction of an explanatory theory.

Emergence of A New Pedagogical Theory

My experience suggests that the successful project development described in this paper's four case studies is based on four critical factors:

A good prompt

a personally meaningful and motivating question, challenge or prompt

Appropriate materials

availability of an assortment and ample quantity of construction materials allowing a learner or team of learners to build something they're proud of and leave it assembled long enough for others to admire to learn from it.

Sufficient time

quality work takes time and students deserve an opportunity to experience a level of project "completeness" and the satisfaction that comes from accomplishing one's goals

Supportive culture

a non-coercive, collaborative, non-competitive environment facilitates risk taking, inspires reflection, stimulates inquiry and rewards creativity

When these four factors are present, students are capable of exceeding their own expectations and learning a great deal along the way.

This pedagogical approach is not restricted to robotics or computer science. However, the number of disciplines, modes of interaction and individual learning styles expressed within such projects makes robotics particularly compelling. Teachers observing students working in the contexts described or while assuming the role of students themselves begin to see robotics as a learning lens for reflecting on their own practice.

A Good Prompt is Worth 1,000 Words

"A good prompt is worth 1,000 words," is the way I describe the open-ended learner-centered approach to teaching with robotics. While each of the four critical factors appear simple and self-evident, traditional schooling too often creates significant obstacles to creating the productive context for learning about robotics and more importantly, learning *with* robotics. This is not an excuse for not teaching robotics or for limiting the intellectual potential of students.

More importantly, these four critical factors may have implications for all project-based learning and challenges the hierarchical approach to curriculum typically employed by schools. In other words, when these four factors are present, students may learn more than is traditionally expected of them.

Students served by a constructionist approach grow in ways beyond the typical goals of a robotics project. An at-risk student raises their personal educational standards when in a rich environment that places their talents, needs and expertise ahead of standard curricular requirements. Anna's ease and confidence in speaking with an authority figure, like the principal, may be the result of the collegial stance I maintain while teaching children with robotics materials. Robotics provided a gateway to literacy for another at-risk teenager who wrote documented his invention process in a class newspaper and shared the results with a corporate CEO via the first letter he ever wrote,

Students not only encounter powerful ideas, but they are empowered as well. To critics suggesting that childhood innocence is robbed or creativity sapped by children using computers, the robot ballerina and dancing teddy bear are active antidotes to concerns over passive screen watching. (Cordes and Miller 1999) Children who may have urged parents to buy them an expensive mechanical toy now are empowered by the means of production to invent their own

fanciful high-tech plaything. Math, science and engineering are brought to life with an artist's aesthetic.

Broader Implications For Schooling

The examples presented serve as a challenge for educators to create the productive contexts necessary for learning across various knowledge domains and disciplines. A constructionist approach to robotics expands student potential over more traditional instruction and justifies the investment of time, resources and energy required to introduce a new medium for knowledge construction.

The lessons from the specific vignettes presented are less about how a young girl transfers knowledge constructed through the act of building a robot teddy bear to another school subject than what educators can learn about learning from careful observation of a student's experience. Three lessons for educators of all subjects and ages may be distilled.

Memories are Made of Project-Based Learning

The pedagogical approach called project-based learning (PBL) affords students an opportunity to solve authentic personally relevant problems in a context in which they make connections between different disciplines and employ a variety of skills. Effective PBL experiences may precipitate a need for structural changes in scheduling, curriculum and assessment while teachers recognize that the richest learning emerges from an environment adhering to the principle of "less us, more them." ⁱⁱⁱ

When Ideas Go to School, They Lose Their Power

The four critical factors described earlier may appear simple, but are deceptively difficult for schools to realize. This failure may result from exterior pressures on "schooling" or a lack of understanding of learning in general or specifically, the subtleties of project-based learning. Many teachers yearning for the benefits of project-based learning perceive an inability to change expectations, their role or the context of the classroom in the ways required by the four factors. These "yearners" (Papert 1993) compromise by skimping on time dedicated to a project, limiting collaboration or narrowing the objective of the project. For too many schools, project-based learning means any non-lecture-based activity. Little more than an illusion of freedom is created when students are allowed to explore for a short time before being expected to produce the "right answer."

Much ado about challenges

One example of new pedagogical wine in old bottles is "Challenge Based Learning." (CBL) Apple Computer is the primary advocate of what they consider a new pedagogical approach, even if CBL bares an uncanny similarity to time-honored notions of project-based learning. (Apple 2008) CBL errs in what Papert might consider instructionist ways with its overreliance on teacher-specified topics, rubric-constrained parameters and a narrow range of experiences, including virtually no computation. The CBL emphasis is on information retrieval, synthesis and presentation like most school activities.

Paradoxically, it is the very enormity of the CBL prompts that constrains the potential for authentic learning. Asking students to solve problems that may not be solvable by the collective efforts of the world's smartest people for generations, is not an authentic context for learning. As a result, the range of experiments, paths of inquiry, tinkering and even complexity are sacrificed. When faced with impossible challenges, limited resources, insufficient time and looming assessment, students respond in a rational fashion. They produce digital movies, posters, presentations and other forms of "reports" containing the politically correct and overly simplistic conclusions their teachers expect. Sentimentality is substituted for intellectual depth.

Children are certainly competent and capable of making genuine intellectual and creative contributions to the world. They can and do solve important problems. Some play make beautiful

music or exhibit athletic prowess. It is however foolish to expect children to solve the world's problems, like famine, global warming or improving "the air that you breathe." Even if this critique of CBL is a bit harsh, computer use in the majority of its challenges is quite inconsequential, particularly when compared with the sorts of activities advocated by members of the constructionist community.

Curriculum

Curriculum should neither be coercive nor exploitative. When asked about the changes in schooling required to support project-based learning, Papert replied, "Well, first thing you have to do is to give up the idea of curriculum. Curriculum meaning you have to learn this on a given day. Replace it by a system where you learn this where you need it. So that means we're going to put kids in a position where they're going to use the knowledge that they're getting. So what I try to do is to develop kinds of activities that are rich in scientific, mathematical, and other contents like managerial skills and project skills, and which mesh with interests that particular kids might have... I imagine the learning environment of the future as we've given up the idea of there being curriculum that says you have to learn this at the seventh of May in your eighth year.... Kids will work in communities of common interest on rich projects that will connect with powerful ideas." (Papert GLEF 2001)

Assessment

Another enemy of constructionism is the perceived need for assessment and the public's increased demand for measurement. Newer pedagogical strategies, such as rubrics, appeal to some educators as a form of alternative assessment since numerical grades are replaced by seemingly more subjective criteria. However, "The Trouble with Rubrics," (Kohn 2006) demonstrates how rubrics preserve the coercive elements of traditional grading schemes, reduce student motivation and curtail possibilities for serendipitous learning.

Any attempt to test, measure or quantify what a student knows is intrusive and disrupts the learning process. There is no substitute for teachers really knowing their students and assuming a responsibility for investigating their thinking, as exemplified by the preschool teachers of Reggio Emilia. Such teacher researchers make each child's thinking visible so it may benefit the learner, their peers, parents seeking demonstrations of progress and teachers responsible for creating the next intervention required to propel student thinking and learning.

Much of the success experienced by children in Papert's "prison project" (Stager 2007a; Papert 2000) was possible because of our exemption from all state assessment and curriculum requirements. "I think that this project allowed some of them [students] to get a new sense of themselves as learners -- that learning is something valuable, that setting yourself a goal and working to achieve it is something which some of them have never seen before in their lives. They've never known anybody who works over time for the achievement of some goal. So you can change their view of life." (Papert in GLEF 2001)

Educational innovation remains elusive without a willingness to challenge, revise or even abandon curriculum and assessment. The quest for better forms of assessment and curriculum may distract educators from creating productive contexts for learning in which students may achieve more than they or their teachers are capable of anticipating.

"For those of us who want to change education the hard work is in our own minds, bringing ourselves to enter intellectual domains we never thought existed. The deepest problem for us is not technology, nor teaching, nor school bureaucracies. All these are important but what it is all really about is mobilizing powerful ideas." (Papert 1998)

Kid Power

Schools remain plagued by Dewey's century-old criticisms of school's overreliance on curriculum and scarcity of authentic experiences. (Papert 1998a) Papert suggests that the computer and kid power, the fundamental building blocks of constructionism, allow children to drive learning rather

than be the passive recipient of teaching; shift agency to the learner; and introduce powerful ideas to even young children without losing their power. (Papert 1998a)

“We have to look at different kids differently. The most common element with all kids is that they start off as enthusiastic learners, but by the time they have been in school for a few years they have stopped being enthusiastic about learning. The learning instinct is strangled. That makes their lives poorer. It makes society poorer. It makes the economy rigid and inflexible. It makes for a more rigid society all around.” (Papert in Bennahum 1996)

The children responsible for the learner-centered robotics projects described earlier were engaged in sophisticated knowledge construction unconstrained by the curriculum or adult preconceptions of final products or measurable achievement along the way. Other domains may be explored with different tools and material in a similar spirit if educators assume a constructionist stance. The computer remains the protean material for making, learning and doing.

Children have a remarkable capacity for intensity. It is incumbent upon educators to leverage this gift in order to support children in exceeding their potential. Too often, our focus on achievement, assessment and curriculum coverage creates an artificial ceiling. Having the courage to behave as if learning is natural and children are competent liberates students and teachers to achieve in powerful ways and at a level previously unimaginable.

References

Ackerman, E. (2001). *Piaget's constructivism, papert's constructionism: What's the difference?* Paper presented at the 2001 Summer Institute, Mexico City.

Apple (2008). "About Challenge Based Learning." Retrieved June 1, 2010, from <http://ali.apple.com/cbl/>.

Bennahum, D. S. (1996). "School's Out: Interview of Seymour Papert." *Meme 2.13*. Retrieved June 1, 2010, from <http://memex.org/meme2-13.html>.

Caldwell-Edmonds, C. The concept of emergent design [web site] *The concept of emergent design* [web site] Retrieved June 20, 2003, from <http://www.techlearninglink.org/Emergent%20Design%20and%20Decentralized%20Models/Emergent%20Design.htm>.

Cannings, T., & Stager, G. (2003). Online constructionism and the future of teacher education. Paper presented at the ICT and the Teacher of the Future - Selected Papers from the International Federation for Information Processing Working Groups 3.1 and 3.3 Working Conference, Melbourne, Australia.

Cavallo, D. (2000a). Emergent design and learning environments: Building on indigenous knowledge. *IBM Systems Journal*, 39(3&4), 768-781.

Cavallo, D., Papert, S., & Stager, G. (2004, June 22-24, 2004). *Climbing to understanding: Lessons from an experimental learning environment for adjudicated youth*. Paper presented at the Sixth International Conference of the Learning Sciences, Santa Monica, California.

Cordes, C. and Miller, E. (1999) *Fool's Gold: A Critical Look at Computers in Childhood*, Alliance For Childhood, <http://www.allianceforchildhood.net/>.

Dunn, S., & Larson, R. (1990). *Design technology : Children's engineering*. New York: Falmer Press.

Edwards, C., Gandini, L., & Forman, G. (Eds.). (1998). *The hundred languages of children: The Reggio Emilia approach - advanced reflections* (Second ed.). Westport, Connecticut: Ablex Publishing.

Forman, G., & Fyfe, B. (1998). Negotiated learning through design, documentation and discourse. In C. Edwards, L. Gandini & G. Forman (Eds.), *The hundred languages of children: The Reggio Emilia approach - advanced reflections* (Second ed.). Westport, Connecticut: Ablex Publishing.

Gandini, L. (1998). Projected curriculum constructed through documentation - progettazione: An interview with Iella Gandini. In C. Edwards, L. Gandini & G. Forman (Eds.), *The hundred languages of children: The Reggio Emilia approach - advanced reflections* (Second ed., pp. 120-121). Westport, Connecticut: Ablex Publishing.

Gardner, H. (1998). Foreword: Complementary perspectives on Reggio Emilia. In C. Edwards, L. Gandini & G. Forman (Eds.), *The hundred languages of children: The Reggio Emilia approach - advanced reflections* (Second ed., pp. 7). Westport, Connecticut: Ablex Publishing.

GLEF (2001). Seymour Papert on Project-Based Learning. Expert Interviews. Edutopia, George Lucas Foundation.

Harel, I. (1991). *Children designers: Interdisciplinary constructions for learning and knowing mathematics in a computer-rich school*. Norwood, N.J.: Ablex Pub. Corp.

Harel, I. (1993). Who is a constructionist? Keynote address at the international logo conference. Kew, Australia: unpublished.

Kafai, Y., & Harel, I. (1991). Learning through design and teaching. In S. Papert, I. Harel & MIT Epistemology and Learning Group. (Eds.), *Constructionism: Research reports and essays, 1985-1990*. Norwood, N.J.: Ablex Pub. Corp.

Kafai, Y. B. (1995). *Minds in play: Computer game design as a context for children's learning*. Hillsdale, N.J.: L. Erlbaum Associates.

Kohn, A. (2006). "The Trouble with Rubrics." English Journal **95**(4): 12-15.

Miller, G., Church, R., & Trexler, M. (2000). Teaching diverse learners using robotics. In A. Druin, Hendler, James (Ed.), *Robots for kids: Exploring new technologies for learning*. San Francisco: Morgan Kaufmann.

Papert, S. (1980a). Computer-based microworlds as incubators for powerful ideas. In R. Taylor (Ed.), *The computer in the school: Tutor, tool, tutee* (pp. 204-210). NY: Teacher's College Press.

Papert, S. (1980b). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books.

Papert, S. (1984). Computer as mudpie. In D. Peterson (Ed.), *Intelligent schoolhouse: Readings on computers and learning*. Reston, VA: Reston Publishing Company.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer*. NY: Basic Books.

Papert, S. (1998). "Technology in Schools: To support the system or render it obsolete." Milken Exchange on Education Technology. Retrieved June 1, 2010, from http://www.mff.org/edtech/article.taf?function=detail&Content_uid1=106.

Papert, S. (1998, June 2). *Child power: Keys to the new learning of the digital century [lecture transcript]*. Paper presented at the Eleventh Colin Cherry Memorial Lecture on Communication, Imperial College, London, UK.

Papert, S. (2000). What's the big idea? Toward a pedagogical theory of idea power. *IBM Systems Journal*, *39*(3&4), 720-729.

Papert, S. (2005). Beyond wires and boxes: Technology as a tool for educational transformation, *Presentation at COSN's K-12 School Networking Conference*. Washington D.C.: Consortium on School Networking.

Papert, S. (Ed.). (1991). *Situating constructionism*. Norwood, NJ: Ablex Publishing Corporation.

Papert, S., & Franz, G. (1987). Computer as material: Messing about with time. *Teachers College Record*, 89(3).

Papert, S., Harel, I. (1991). *Constructionism: Research reports and essays, 1985-1990*. Norwood, N.J.: Ablex Pub. Corp.

Rathjen, D. (1988). *Lego crazy action contraptions: A lego inventions book* New York: Klutz Press.

Resnick, M. (1993). Behavior construction sets. *Communications of the ACM*, 36(7).

Resnick, M. (2006). Computer as Paintbrush: Technology, Play, and the Creative Society. In Singer, D., Golikoff, R., and Hirsh--Pasek, K. (eds.), *Play = Learning: How play motivates and enhances children's cognitive and social--emotional growth*. Oxford University Press.

Resnick, M., Bruckman, A., & Martin, F. (2000). Constructional design: Creating new construction kits for kids. In A. Druin, Hendler, James (Ed.), *Robots for kids : Exploring new technologies for learning*. San Francisco: Morgan Kaufmann.

Resnick, M., & Ocko, S. (1991). Lego/logo: Learning through and about design. In S. Papert, I. Harel & MIT Media Lab Epistemology and Learning Group. (Eds.), *Constructionism: Research reports and essays, 1985-1990*. Norwood, N.J.: Ablex Pub. Corp.

Resnick, M., Ocko, Stephen. (1991). Xylophones, hamsters and fireworks: The role of diversity in constructionist activities. In S. Papert, I. Harel & MIT Media Lab Epistemology and Learning Group. (Eds.), *Constructionism: Research reports and essays, 1985-1990*. Norwood, N.J.: Ablex Pub. Corp.

Resnick, R. and Silverman, B. (2005) Some reflections on designing construction kits for kids, *Proceeding of the 2005 conference on Interaction design and children*, p.117-122, June 08-10, 2005, Boulder, Colorado.

Rusk, N., Resnick, M., Berg, R., and Pezalla-Granlund, M. (2008). New Pathways into Robotics: Strategies for Broadening Participation. *Journal of Science Education and Technology*, vol. 17, no. 1, pp. 59-69.

Stager, G. (2002, June 18, 2002). *Papertian constructionism and at-risk learners*. Paper presented at the 2002 National Educational Computing Conference, San Antonio, Texas.

Stager, G. (2005). Towards a Pedagogy of Online Constructionist Learning. Paper presented at the *2005 World Conference on Computers in Education*. Stellenbosch, South Africa.

Stager, G. S. (2007). *An investigation of constructionism at the maine youth center*. [Doctoral Dissertation] The University of Melbourne, Melbourne.

Stager, G.S. (2007) *Towards the construction of a language for describing the learning potential of computing activities*. Paper presented at the EuroLogo 2007 Conference, Bratislava, Slovak

Taylor, R. (1980). *The computer in the school: Tutor, tool, tutee*. NY: Teacher's College Press.

Topal, C.W., Kong, E. and Gandini, L. (1999) *Beautiful Stuff!: Learning with Found Materials*. New York: Sterling Publishing Company.

Turkle, S., & Papert, S. (1991). Epistemological pluralism and the revaluation of the concrete. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 161-191). Norwood, NJ: Ablex Publishing Corporation.

ⁱ A collection of the open-ended robotics challenges may be found at <http://www.stager.org/lego>

ⁱⁱ The two LEGO engineering documents and MicroWorlds EX reference sheet are available for download at <http://www.stager.org/lego>

iii Articles about effective project-based learning may be found at
<http://stager.org/articles/goodpbl.pdf>