Using LEGO robotics in a project-based learning environment

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Abstract
The use of robotics as an educational tool is growing in popularity. Advances in technology have resulted in the development of generic robotic construction kits for use in grade school (K-12) environments. For many teachers, this requires a conceptual shift away from the idea of learning from technology, often found in traditional multimedia computer-assisted instruction, toward a viewpoint of learning with technology in a project-based learning environment. In this learning context, rather than trying to assess students’ performance outcomes using a measurement instrument, it may be more informative to examine the observable intermediary states children produce during their problem-solving process. This type of observational record cannot easily be described in text and still photos, nor does such a medium allow the richness of expression afforded by digital video and audio. In this paper, we introduce the benefits of exploring new LEGO robotic technologies for learning. We describe various LEGO robot construction tasks undertaken by middle-school children in a project-based learning environment, highlighting sample products of their work. Finally, we describe how teachers in a classroom setting can use digital video effectively.

1. Introduction
The use of robotics as an educational tool is growing in popularity. Advances in technology have resulted in the development of generic robotic construction kits for use in grade school (K-12) environments. Recent examples of these new technologies for children are LEGO® MINDSTORMS® robot construction kits and LEGO® ROOBOLAB™ icon-based programming software. Such technology allows children to create autonomous robots that can solve fairly sophisticated tasks such as locating and removing objects from a defined space. The design of the LEGO robotic products has its roots in the research of Seymour Papert (1980) and his colleagues at the MIT Media Laboratory. An important outcome of Papert’s research was the development of a constructionist learning/teaching environment that provides children the possibility to interact with technology on a number of different levels (concrete to abstract).

Robotics provides children with the opportunity to test the results of abstract design concepts through concrete, hands-on robotic manipulatives (Druin & Hendler, 2000). For many teachers and educators, this requires a conceptual shift away from the idea of learning from technology, often found in traditional computer-assisted instruction, toward a viewpoint of learning with the technology that is consistent with the “Mindtools” approach to problem-solving advocated by Jonassen (2000). This Mindtools approach is well suited to the project-based learning (PBL) environment in which the problem drives the learning (Hung, 2002). In a PBL environment, students often discover they need to learn new knowledge and continuously revise existing knowledge before they can begin solving problems.

In the PBL context, rather than trying to assess a student’s performance outcomes using a measurement instrument, it may be more informative to examine the observable intermediary states children produce during their problem-solving process. This type of observational record cannot easily be described in text and still photos, nor does such a medium allow the richness of expression afforded by digital video and audio. In this paper, we introduce the benefits of exploring new technologies for learning in the form of LEGO robotics. Students use the LEGO (Mindstorms for Schools) Team Challenge Kit #9790 (LEGO, 1999a) in conjunction with a programming environment called ROOBOLAB. We describe various LEGO robot construction tasks undertaken by middle-school children. We then demonstrate the end products of their work—autonomous robots solving problems. Finally, we demonstrate how teachers and students in a classroom setting can use digital video as a tool for assessment purposes and as an opportunity to share their ideas within a broader based learning community.

2. Project-based Learning (PBL)
Designing a robot to do even a simple task can place extensive demands on students’ creativity and problem-solving ability (Druin & Hendler, 2000). Building and programming autonomous robots is an ideal context in which to situate a PBL experience. In the PBL environment, students work collaboratively to understand the problem as they construct viable solutions (Lui & Hsiao, 2002). Successful PBL questions lead to projects that are related to authentic situations, which have pragmatic meaning for students (Brown, Collins, & Duguid, 1989). A guiding question or problem usually sets the stage and the project context allows for a multitude of design paths. Students can collaborate over an extended period of time during a problem solving activity. The result of this collaboration is the construction of an artifact that can be presented to a wider classroom audience. The production of an artifact, that is readily sharable with a larger community of learners, encourages students to make their ideas explicit. According to Penner (2001), having students make their ideas explicit to larger communities of learners allows students to experience science concepts in a meaningful, personalized context.

In general, PBL (see Figure 1) is characterized by five processes: (a) engagement, (b) exploration, (c) investigation, (d) creation, and (e) sharing. Underlying these five processes is an iterative analytical evaluation of the students’ problem-solving approaches and solutions.

![Figure 1. Modified diagram taken from](http://www.qescnet.qc.ca/worksheets/pbl#2)

- **Engage**
- **Explore**
- **Investigate**
- **Create**
- **Share**

**EVALUATION**

From a teaching perspective, a number of aspects are important for assessment and evaluation of students’ work in a PBL context: (a) students should understand the process of how they got to where they are and where they want to go; i.e., the problem-solving choices they make; (b) students should be able think about the outcomes of their work; (c) this can done through combination of a written logbook, verbal explanation, or video demonstrations; and, (c) the project guidelines must include some
levels of criteria that students can work toward at various points during the PBL process (see the www.qesnrecit.qc.ca/workshops/pbl/assess.htm for examples of PBL rubrics that can be used).


3. Engaging the Learners as Robot Designers in a PBL Environment

The objective was to conduct a pilot study of children’s problem-solving approaches to building and programming LEGO robots using new curriculum materials in a PBL environment. Two different middle schools were involved in the pilot study. Students at each school were sorted into collaborative teams of two or three. The students were asked to record their problem-solving approaches in a reflective logbook during the building and programming of their group’s robot. Video was used extensively to record various stages of robot construction. The video also included student explanations of their project development steps and problem-solving processes.

The PBL environment, resources, and overall guiding project question was introduced to the students:

**Using the LEGO MINDSTORMS kit and ROBOLAB programming language: How would you design and build an autonomous robot that is capable of removing 5 soda-pop cans from a specified area that is one meter in diameter?**

The PBL resources and overall question are provided as part of the LEGO ROBOLAB Team Challenge kit (LEGO, 1999a; LEGO, 1999d) and associated teacher resources (LEGO, 1999b; LEGO, 1999c); however, these resources were modified to fit the context of the school and classroom environment in which they were used. Given the complexity and open-ended nature of the task, a semi-structured instructional PBL environment was necessary to complete the project within a given time specification (total time 25 hours). Therefore, the PBL environment was configured into three incremental sections: (1) building an Acrobot as a simple introduction to the kit and programming language, (2) exploring the advantages and disadvantages of various chassis designs for speed, power, durability, and maneuverability, and (3) applying skills learned in both chassis design and programming to solve as many levels of the CanDo challenge as possible (there are four levels). Each section allowed the students to gain the necessary knowledge required for the completion of the subsequent section.

4. Acrobot

The first section involved the students becoming familiar with various pieces of LEGO robotic kits. For example, students needed to become familiar with the small LEGO RCX unit, sometimes referred to as the LEGO Brick (see Figure 2). This brick contains the CPU and input/output connections to control the robot actions. The ROBOLAB (see Figure 2) programming language the students use is a visual icon-based environment (Portsmore, 1999). Programs are transferred from the desktop to the RCX via infrared link.

![Figure 2. (a) The RCX and (b) example ROBOLAB program code.](image)

To facilitate student familiarization with the robotic kits and programming language, the students were directed to build the Acrobot robot (see Figure 3). The building of this specific robot allowed for a quick and simple introduction to topic areas, such as team configuration, programming, specialized LEGO sensors (e.g., touch and light), and construction practices.
Once the Acrobot was built according to the instructions provided, students were asked to identify common weak points in the robot's construction and what methods they would use to strengthen it. The following excerpts from student log books are typical examples of their understanding and problem-solving process:

"The wheel on the front looks like it would fall off on impact when crashing into solid objects because it looks like a weak attachment. I added an extra wheel in the front and built under the robot to make a piece of LEGO go across part of the two motors and attached the end to the pieces next to it giving it more strength.

Grade 7 Student"

"This structure does have weak points. One of them is the back wheels. They will fall off easily because there is no type of bracing to keep the wheels on. I would brace the back wheels to the main structure at the bottom and brace the front to the RCX, using elbow pieces. Then I'd strengthen the back by adding a few other pieces to connect the back together.

Grade 7 Student"

"I think this structure has common weak points because the blocks can't always hold. If you build a robot and drive it into the wall, chances are the robot will break. You will need to make it stronger. I added braces to the wheels on the bottom making the wheels fall apart less and I added braces to hold the 2x2 connectors on. When we made the Acrobot, we had to make sure it flipped in both directions. The Acrobot’s center of gravity changed when we added weight to the back end. We had to add weight to the front end to move the centre of gravity back to the center of the robot so it would flip again.

Grade 7 Student"

The next two sections describe the major elements of the student’s design and development work. Video is used to record the students’ explanations and help further their understanding of mechanics and the tasks their robots are performing.

5. Chassis Designs

Through preceding trials, we found that even students from the "LEGO generation" had difficulty building structurally sound chassis. Students often do not have a solid understanding of how they might utilize gear reduction and other mechanical advantages to build a robot for speed, power, durability, or maneuverability. Consequently, the second step in the PBL environment was orchestrated to give the students the opportunity to construct, evaluate, and compare various chassis designs. Student groups were assigned the task of building, testing and evaluating specific chassis designs from the Subassembly Constructopedia (LEGO, 1999d). The designs in the Subassembly Constructopedia are incomplete, requiring the students to use their own ingenuity and creativity in completing the chassis in the form of a working robotic vehicle. Additionally, as part of the PBL environment, the students were asked to demonstrate and talk about their chassis designs with their classmates. The sharing of design features, advantages, and disadvantages with classmates proved valuable for the students, particularly when it came time to design their final team challenge robot. The following are examples of student chassis evaluations for three different chassis designs: (a) Backup and Turn Chassis, (b) Hill Climber Chassis, and (c) Two-Wheeler Chassis.

5.1 Back-up and Turn Chassis

The differential incorporated into this particular single-motor chassis design proved an interesting challenge for students. However, as evidenced in the video clip (see Figure 4), the Grade 9 student in the group was able to explain the basic workings of the mechanism, forces, and gears as well as demonstrate an understanding of the weaknesses of their design. The following written explanation, from a Grade 8 student, demonstrates a fairly sophisticated understanding of the gears and forces at work within their chassis design:

Our robot has a force advantage. The driving gear is made to form a gear train that changes the direction of the force. The differential in our chassis allows both back wheels to move independently of one another. Our robot can turn even though it has only one motor. To do this we back it up. The left wheel will stay still and gets locked in place with a ratchet so it will always turn to the left. Then we can move it forward in a different direction.

Grade 8 Student
5.2 Hill Climber Chassis

The students assigned the Hill Climber Chassis were faced with a definite construction challenge. This particular chassis design utilizes a complex gear-train system in order to greatly increase the power of the robot. The following written reflection and verbal explanation (see Figure 5), both by the same Grade 8 student, demonstrate an understanding of the gear/force relationships at work within this particular chassis design.

Our robot has the greatest force advantage. A small pulley wheel, which is attached to the motor, has an elastic band around it attached to another bigger pulley wheel giving it a force advantage. Attached to the axle of the larger pulley wheel is a worm gear, which turns a gear wheel—giving it a huge force advantage. On the other end of the axle of the gear wheel is another gear wheel (confused yet?) It is part of the gear train that eventually turns the wheels.

Grade 8 Student

5.3 2-Wheeler Chassis

In this example of a student evaluation of a specific chassis design, the physical movement of the robot and turning of the gear-wheel mechanisms helped to clarify the students’ understanding of the inherent concepts. In their verbal explanation (see Figure 6), these grade 7 and 8 students use actions and visual movement to aid in their explanation and understanding. The students’ written reflection is not as conceptually rich as is their explanation on the video.

The advantages of the 2-Wheeler chassis are many. The slower movement of the robot enables it to travel uphill, without falling down. The robot has one motor per wheel. The smooth surface of the skid at the bottom of the robot contributes to smooth and short turning. The device makes very small and short turns, which is an important factor in making sure the robot does not crash into anything. The robot has lots of durability and power. With 2 motors the device is open to more abilities. The disadvantages of the 2-Wheeler chassis are few. The wheels are driven by a chain (elastic band), which increases friction and slippage and causes the robot to move more slowly. Being made from LEGO, the robot can also break easily. This gets very irritating when you are trying to make the 2-Wheeler chassis more complex. The last disadvantage is it requires lots of small pieces.

Grade 7 & 8 Students
6. CanDo Team Challenge

At this stage in the PBL environment, students were required to employ previously gained knowledge to solve a fairly sophisticated task. The CanDo challenge requires teams of two to three students—builders, programmers, parts specialists, communicators/journal keeper—to design, build, and program a robot to remove randomly-placed, weighted soda-pop cans from within a circle that is about one meter in diameter.

The student problem-solving approach for the CanDo challenge is highly open-ended; thus, there is a need to provide some degree of structure. Teams were color coded for organizational purposes. The following challenge levels were to be attempted by each team:

- **Level 1:** The robot starts inside the circle and removes the cans from the circle.
- **Level 2:** The robot starts inside a house adjacent to the circle. The robot is pointed facing the circle. The robot enters the circle and removes the cans.
- **Level 3:** The robot starts inside a house adjacent to the circle. The robot is pointed facing away from the circle. The robot enters the circle and removes the cans.
- **Level 4:** The robot starts as in Level 3, but must play a sound each time a can is removed from the circle.

The levels were organized hierarchically to reflect an increasing level of difficulty. Video was used to record the individual team’s accomplishments at various levels. Team members were asked by the teacher to explain the design features of their robots and why they made certain choices during their design process. Video segments depicting examples of CanDo challenge work are located on our Web site.

The use of video in a PBL environment provides a rich representational paradigm for students to articulate their problem-solving processes and demonstrate their final solutions. In this sense, the video provides an additional source of information for both students and teachers to evaluate problem solving. In the context of assessment and evaluation in this PBL environment, other information sources include still photos, logbooks, and programming code. The additional information provides teachers with the opportunity to evaluate students’ abilities from a variety of perspectives. For example, a student who struggles academically, performed exceptionally well throughout the robot construction and programming task. The video clips in Figure 7 show this student explaining his problem-solving approach to the Level 4 challenge.

The student's problem-solving ability was most evident when he worked with concrete objects (motors, gears, structural components) used in the construction of the actual robot. Interestingly, the student appeared able to bridge his strength in one area (working with concrete objects) to a related yet fairly abstract area, computer programming. The bridging process was aided by the graphical nature of the programming environment. Figure 8 shows an example of program code written by the
Notice that the icon-based programming code (ROBOLAB) uses a representational approach that often provides one-to-one mapping between the virtual screen object (e.g., motor) and the actual concrete object (e.g., LEGO motor). Such a programming environment appears to enhance the ability of students to understand the relationships between concrete and abstract concepts. Compare the program code in Figure 8 with the program code in Figure 9, written by the same student, to solve the more difficult Level 3 challenge.

The code shown in Figure 9 reflects a higher level of problem solving that one would expect to see as the difficulty of task increases. In this case, the pictorial representation of code shows the nonlinear nature of the program's execution. The programming solution generated by the student reflects the complexity of the problem. Writing a program requires defining the problem, designing an algorithm, coding a possible solution, and debugging the program. At the same time, the student must keep in mind the functioning physical structure of the robot. These skills are often associated with logical reasoning and complex thinking skills (Jonassen, 1996). In Figure 10 we can observe how the student's programmed solution functioned for the Level 3 challenge.

Teams also kept reflective logs that clearly showed their own unique understanding of the challenges and successes they faced in solving each level of the CanDo task. Another example depicting how students were able to use video effectively to articulate their problem-solving process was clearly exhibited by the team's robot design in Figure 11. The team designed a robot with a removable plow, so their program could be downloaded easily (i.e., update robot control).

In this case, the students' concrete problem-solving skills were excellent, as was their ability to demonstrate their knowledge. On the other hand, their written explanations were not as rich.

In summary, the CanDo team challenge was shown to be an effective learning exercise in the context of the PBL environment. The multilevel organization of the challenge provided the necessary task structure while still allowing the students an opportunity to pursue an open-ended individualized approach to problem solving. Students were encouraged to work at their level of ability from the basic understanding in Levels 1 and 2 of the challenge to more complex problem solving required for Levels 3 and 4. All students in the class were challenged at their level of understanding.

7. Final Analysis
The often quoted phrase 'learning by doing' is never more appropriate than in a PBL environment designed to teach students how to build autonomous robots. Such a learning context is highly student-centered as opposed to teacher-centered. Designing a robot to do even a simple task can place extensive demands on students'
individual creativity and problem-solving abilities. At the same time, the learning context allows students to work in a constructionist, collaborative learning environment that promotes the sharing of ideas. Furthermore, Kafai & Resnick (1996) suggest that this type of constructionist learning environment is well suited to learning in a digital world because it requires the learner to produce artifacts (in this case, a robot) that can be shared with a larger audience.

Although students could express their thinking through a variety of sources (audio/video, written logs, physical construction, and computer programming), it was the use of video, as part of the PBL assessment and evaluation process, that appeared to be the most valuable element for both the teacher and students. For students, it provided a feedback mechanism that helped them assess their progress. The use of video also encouraged them to further solidify their learning because of the necessity of having to publicly explain various elements of their problem-solving process.

From the teacher’s perspective, the video provides a valuable additional source of information for assessment purposes. The video recordings nicely supplement the reflective logs by allowing the students to further elaborate on their reasoning for pursuing a specific course of action, especially for those students whose verbal skills are stronger than their written skills. This was shown in the sections on chassis construction and during various levels of the CanDo challenge. Furthermore, video clips provide an artifact that can be shared with a larger audience (other classes, parents, community stakeholders).

The current project only begins to explore the potential of how robotics and video can be effectively used in a PBL environment. The design of similar instructional projects calls for the development of creative teaching techniques in a student-centered learning context.

8. References


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Running a project-based robotics classroom often raises new and different issues than those found in more traditional classrooms. Here are some tips for classroom management. Project Rules. Set clear expectations for students.Â In a project-based class, failure is inevitable. An idea that seems good at first turns out to be a dead-endâ€™or an outright disaster. As the upset students sit amid the ruins of their project, praise them for taking a risk and point out the positive aspects of their plan. Help them see what they have learned about which designs do and donâ€™t work. Remind them that everyone in the class will have a design fail at some point in the year. Enforce the project rules to make sure that they get no jeering or other negative response from the other students. Joyful learning, offer hands-on, fun activities in an attractive learning environment, feeding students interest and curiosity.Â As stated by [28], educational robotics is an effective tool for project-based learning where STEM, coding, computer thinking and engineering skills are all integrated in one project. Educational robotics is rich with opportunities to integrate not only STEM but also many other disciplines.Â In this paper the concept of using robotics as an educational tool and the features of Lego Mindstorms have been described. In the 21st century learning context, engaging students with technology is an important pedagogy to gain attention and increase motivation among students. It is evident that the use of robotics will improve the studentsâ€™ problem solving and algorithmic skills.