Scaffolding Children's Robot Building and Programming Activities

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Abstract. Since 2001 the School of Information Technology and Electrical Engineering (ITEE) at the University of Queensland has been involved in RoboCupJunior activities aimed at providing children with the Robot building and programming knowledge they need to succeed in RoboCupJunior competitions. These activities include robotics workshops, the organization of the State-wide RoboCupJunior competition, and consultation on all matters robotic with schools and government organizations. The activities initiated by ITEE have succeeded in providing children with the scaffolding necessary to become competent, independent robot builders and programmers. Results from state, national and international competitions suggest that many of the children who participate in the activities supported by ITEE are subsequently able to purpose-build robots to effectively compete in RoboCupJunior competitions. As a result of the scaffolding received within workshops children are able to think deeply and creatively about their designs, and to critique their designs in order to make the best possible creation in an effort to win.

1 Introduction

This paper describes the RoboCupJunior activities implemented by the School of Information Technology and Electrical Engineering (ITEE) at the University of Queensland. RoboCupJunior aims to engage 10 to 17 year old children in robot building and robot programming through structured challenges and competitions. The University of Queensland has organized two competitions (in 2001 and 2002) featuring the three RoboCupJunior challenges of Dance, Rescue and Soccer. The competitions themselves have been structured to account for age and opportunity differences, and to provide an environment where learning continues to take place.

The most significant efforts, however, have been placed in the development of appropriate workshops to introduce children and teachers to the RoboCupJunior program and the associated technology – most notably the LEGO® RCX™ and ROBOLAB™ products. In order for the workshop initiative to achieve this goal extensive efforts have been made to ensure that workshops teach children the fundamentals of robot building and programming in an engaging and meaningful way. The teaching methods incorporated in ITEE robotics workshops are outlined in this paper.

The robotics workshops provided by the School of Information Technology and Electrical Engineering have proven to be incredibly successful with over 2200 chil-

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dren across 60 schools in Queensland participating. Teachers, children, school administrators and government bodies have embraced the initiative. The success of the workshops is primarily due to their ability to provide the necessary robotics education to support children's robot building activities. Queensland students are the current (2002) world champions in the soccer challenge. Furthermore, Queensland students were winners in every challenge at both age levels in the Australian championships in 2002. Queensland's successes in both national and international RoboCupJunior competitions are testament to the success of the initiative.

The development of the workshop program has been guided by the knowledge that many children require scaffolding in their robot building endeavors. Scaffolding allows children to acquire the knowledge they need to become independent robot builders and programmers. This paper discusses the workshop development process, the underlying theoretical model, the practical implementation of this model, and the improvements which have been made based on student and teacher feedback. Empirical data from both workshops and RoboCupJunior competitions is used to explore the extent to which the initiative has provided children with the scaffolding they require to become successful robot builders and programmers.

2 Background

The ITEE Robotics Workshop initiative is guided by the belief that the most powerful way to learn about technology is to become a creator of technology. One of the most effective means by which children can create technology is to develop an understanding of the dynamic and programmable properties of that technology. This is an idea that has been advocated by many in the past 20 years. Papert, in his landmark work Mindstorms [9] recognized that computer programming as an educational activity had great potential as a vehicle for the acquisition of useful cognitive skills such as problem solving and reflective thinking. Other researchers have also identified the importance of allowing children to experience the unique dynamic and programming properties of computers and in doing so allowing children to become creators, not just consumers, of computing activities [11], [5], [15].

Researchers at MIT continued the work of Papert [9], continuing his vision of computing in which children explore ideas by constructing their own computer programs. Resnick and his group at the MIT media lab based their research on this philosophy. They started with the development of LEGO/Logo [12] which combined the LEGO® Technic™ product with the Logo programming language providing children with an environment where they could build and program robots.

Robot building and programming is a natural – and exciting – extension of computer programming activities. Through building and subsequently programming robots, children are building agents which they can program to perform a wide variety of different behaviors. This process allows children to directly see the consequences of their programming activities – the resultant robot behaviors. In this robot building process children have become empowered as they purposefully create robots to achieve a specific function. Researchers are currently exploring classroom technologies that enable children to learn from construction. Many researchers have identified that technology which supports children becoming involved in design projects provides rich opportunities for learning [4], [6], [8].

The final assumption that underpins the Robot Workshop initiative revolves around the importance of scaffolding for children in their robot building endeavors. Vygotsky, a prominent development psychology, was the first to advocate that complex forms of thinking have their origins *social* interactions [2]. Scaffolding – a process whereby important activities are modeled through cooperative dialogues between a skillful tutor and a novice – is an important feature of social collaboration that fosters cognitive growth [2], [14]. Subsequently, guided participation model form the foundation of the ITEE robotics workshops. Within this model, the workshops provide structured learning activities that are carefully tailored to the children's abilities. Tutors are available to provide helpful hints and instructions, to monitor the children's progress. The tutors gradually reduce their levels of support as the children become more confident and competent.

RoboCupJunior is an excellent context within which children can be introduced to the field of robotics [7], [16]. The RoboCupJunior robotics competitions provide an additional level of importance to the robot building activities of children. Through the competition children are able to work in teams to create competitive robots. This competitive environment motivates children to work of creating robots that are skillfully able to complete specific tasks.

2.1 RoboCupJunior Australia

RoboCupJunior is a project-oriented educational initiative that organizes local, regional and international robotic events for young students [13]. Within RoboCupJunior three team challenges have been developed:

- **Soccer:** 2-on-2 teams of autonomous mobile robots play games in an 1800mm x 1200mm field. The soccer challenge in the Queensland RoboCupJunior competition is open to the senior participants, aged between 14 and 18 years.
- **Rescue:** Robots race to rescue victims from artificial disaster scenarios, varying in complexity from line-following on a flat surface to negotiating paths through obstacles on uneven terrain. For the Australian competition, the robot is required to find its way to a hazardous area – following a contrasted line – to rescue the victim. The challenge is open to the middle school entrants, aged from 10 to 15.
- **Dance:** One or more robots perform to music, in a display that emphasizes creativity of costume and movement. Within the Australian RoboCupJunior competition the Dance challenge is split into two age categories, junior (10 - 12yrs) and senior (13 - 18yrs).

Children between the ages of 10 and 18 produce a robot or robots to compete in one or more of these three challenges. Australian RoboCupJunior competitors primarily use, but are not limited to, the LEGO® MINDSTORMS™ robot construction environment to create their robots. The LEGO® MINDSTORMS™ Kits provide children with an environment in which they can create and program robots. The LEGO® products are comparatively inexpensive and most importantly reusable, allowing children to easily work through create-improve-demolish processes.

2.2 Robot Building with LEGO

At the core of the LEGO® MINDSTORMS™ Kit is the RCX™ brick. The RCX brick is an autonomous microcomputer embedded in a LEGO brick (seen in Figure 1) that can be programmed to serve as the "brain" of any LEGO construction [1]. The RCX is programmable, microcontroller-based brick that can simultaneously operate three motors, three sensors, and has an infra-red serial communications interface [10].

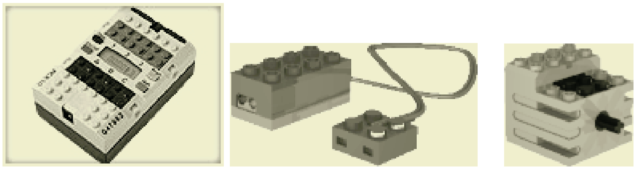


Fig. 1. The LEGO RCX Brick, a light sensor and the motor that children use to build robots.

The key elements necessary for using the RCX are the RCX brick itself, an infra-red transceiver, and a personal computer. Additional components, such as motors, sensors, and other building elements, in combination with this base system allow the creation of functional autonomous robotic devices [10]. LEGO provides an array of analog sensors capable of measuring light intensity, rotation and touch as well as a DC motor (see Figure 1). Within a LEGO MINDSTORMS kit there are also gears, wheels, axles and bricks which in combination with the other elements provide a comprehensive robot-building environment. All of the LEGO parts are self contained units allowing users the opportunity to create robots without the having to machine their own structures or design electronics components. LEGO MINDSTORMS provides both children and adults with opportunities to develop robots that move, think, and react.

2.3 ROBOLAB

ROBOLAB is a software development environment designed for use in the programming of RCX-based creations. The programs created using ROBOLAB can be downloaded to the RCX using the infrared transceiver. The RCX can then run the program independent of the computer.

The ROBOLAB software development environment is predominantly used within the ITEE robotics workshops. ROBOLAB is an iconic programming environment. The icons represent actions that the robot may perform as well as programming structures such as loops and decision statements, and commands. Users construct programs by selecting, placing and connecting icons in a ROBOLAB diagram.

ROBOLAB has a number of levels to accommodate the varying abilities of students. Pilot is the basic elementary section and Inventor is designed for use by more advanced students. While both use icons to represent commands or structures, within the Pilot section the number and order of icon options is restricted to ensure the success of the user.

The second category is Inventor. Inventor has been designed to meet the needs of students in the middle and upper grades of school. This category allows the users access to all of the ROBOLAB programming icons. As a result, students have the freedom to design programs of their choice.

3 Robotics Activities Coordinated by ITEE

The School of Information Technology and Electrical Engineering offers a number of robotics activities to schools. Three-hour robotics workshops are conducted during school terms to provide children interested in robotics the knowledge necessary to independently create their own robots. Due to demand, the workshops have been expanded to include groups of teachers and student teachers. For the past two years ITEE has also offered three-day summer camps designed to provide children with a greater understanding of the LEGO robot building and programming process. These workshop and camp activities culminate with the annual RoboCupJunior Queensland competitions. In addition to these activities, teachers, school administrators and government bodies have actively sought the advice of ITEE robotics staff with respect to robotics curriculum issues. ITEE has provided assistance though a consultation process. Each of these activities is discussed in detail in the following sections.

3.1 Robotics Workshops

The University of Queensland's School of Information Technology and Electrical Engineering has been running robotics workshops since 1995 [17]. In 2001, these workshops were redesigned specifically for the RoboCupJunior initiative. They are open to school children and operate during the school terms. The workshops are three hours long. During the workshops students build a robot and then spend time programming the robot to perform simple tasks. Due to demand, the workshop program has been extended recently to include teachers and student teachers.

The workshops are designed to allow students to work at their own pace through the building and programming processes. Students work in pairs for most workshops, however when workshop numbers are large they may work in groups of three. Each pair or group of three are provided with a computer with the ROBOLAB software installed, an RCX brick and an infra-red transceiver, as well as motors, sensors, and general LEGO bricks. Experienced tutors are available to answer questions and provide support. There are usually two tutors who participate in each of the workshops.

There are two levels of workshops: beginner and intermediate. Beginners are defined as those students who have not used ROBOLAB. These students work through activities which outline the fundaments of the ROBOLAB environment and guide them through the creation of simple programs. Intermediate students, those who have already participated in a beginner's workshop or who have used the ROBOLAB programming environment elsewhere, are given more complex activities to complete.

3.1.1 Workshop Participants

Workshop and summer camp participants are school children between the ages of 10 and 17. Children usually come to the workshops as a school excursion. Over the last year approximately 2200 students from 60 different schools have attended the robotics workshops. Participants are predominantly from schools in the Brisbane metropolitan area, but participants have also attended from Northern NSW, North Queensland and some rural areas. Both public and private schools have attended the workshops; however the majority has been public schools.

Approximately 60% of students who attend the robotics workshops are from primary schools and are aged between 10 and 12. For the primary schools workshops generally include between 25 and 30 students. Workshops for older children who attend secondary schools usually comprise between 10 and 15 students. Students are predominately volunteers who have a keen interest in robotics. They are accompanied by teachers and mentors and these adults are encouraged participate as well.

Although both boys and girls attend the robotics workshops generally there are a greater number of boys in attendance. Boys make up approximately 60% of participants from the co-educational schools that participate.

3.1.2 Robot Building

During the ITEE robotics workshops participants are required to build the specified robots and subsequently program it using specially designed worksheets. The robot that the participants use in their programming exercises is a differential drive robot (wheel-chair configuration) has two motors (a motor driving each wheel), two light sensors which are capable of reading levels of light intensity. Both of these sensors are trained onto the ground and the light intensity measured is that reflected from their own light source.

Students are initially directed to the website ITEE RoboCupJunior website http://www.itee.uq.edu.au/~robocup/junior/, which contains the build instructions for the LEGO™ robot that is used in the workshops. This robot takes between 45 to 90 minutes to build depending on the robot building skills and experiences of the participants. Workshop attendees construct a robot that has been designed by the workshop tutors making this process one of "build-by-numbers". This strategy has been put in place for two reasons:

1. Evidence from early workshops which allowed children to construct their own robots suggested that children could easily spend the three hours playing with the LEGO™. By providing the children with a robot "recipe", they move on to programming tasks more readily.
2. The robot used in the workshops is a structurally sound design. The robot is robust enough to survive falls and collisions. In addition, from building such a robust LEGO structure it is intended that children learn some of the principles of sound LEGO construction.

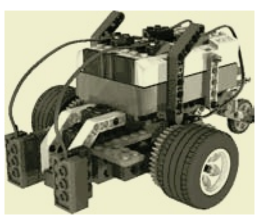


Fig. 2. The robot that participants build in the ITEE robotics workshop.

Figure 2 depicts the robot that children construct in the workshop. The build instructions are pictorial. This enables children with limited LEGO™ construction experience to successfully construct a robust robot. Each step in the build instructions shows the LEGO™ piece as it is about to be placed, with an arrow indicating its destination. The next image shows the piece in position. Where possible an additional illustration depicts the intended destination of those pieces just connected. Colored backgrounds are used to separate differential the required parts, the steps, and subassemblies. There is no text describing new parts.

On completion of the workshop robot, children then move on to robot programming activities. Children generally create programs for their robots for the remainder of the workshop. They generally spend approximately 90 minutes creating programs for the robots. These activities are described to children in a series of worksheets.

3.1.3 Worksheets

All of these worksheets use ROBOLAB at the Inventor 4 level. This level provides access to all available icons, but requires the users to manually connect added icons. The worksheets are designed so that by progressing through the worksheets the children gradually build up knowledge of how to get their robot to produce certain behaviors. The purpose of the worksheets is twofold:

1. to describe the development environment and its associated syntax; and
2. to scaffold the novice programmer by guiding through the creation of simple programs.

Each worksheet introduces a concept or a syntax requirement. The format of the worksheets is such that they provide step-by-step instructions of how to construct a particular program. The description is text-based and is supported by an image of what the program should look like at that step. Figure 3 below provides an example of a worksheet activity.

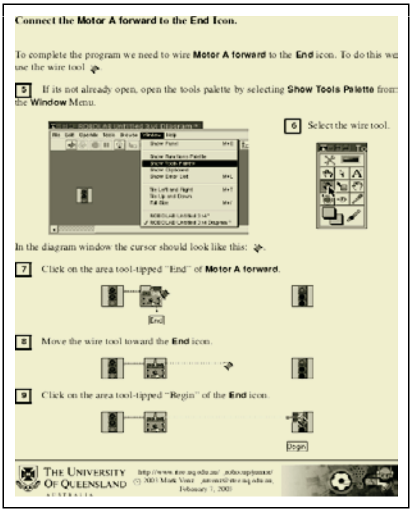
Children who are new to the ROBOLAB development environment participate in the introductory workshop. While there are nine worksheets in all, during an introductory workshop students have only to complete the first five worksheets. By the end of these five worksheets, the students have been shown how to use ROBOLAB to program their robot to turn a motor on and off, travel in a straight line, turn 180 degrees, stop when a dark color is detected and consistently follow a dark line. The children in Figure 4 are attendees at introductory workshops.

A second intermediate workshop is available for children who have completed the beginner's workshop or who have had previous experience with ROBOLAB. During this second workshop children are given the opportunity to explore programming concepts related to structured programming. They complete worksheets 6 to 9. By the end of the intermediate workshop children are able to create loops, program robots to deal with decisions, use variables and apply their knowledge in construction of their own line following program.

3.1.4 The Evolution of ITEE Robotics Workshops

The ITEE Robotics workshops have evolved over the last two years. Improvements made have been in response to issues identified by teachers, students and tutors. There has been a gradual refinement of workshops to meet the needs of participants. The processes outlined above are the result of this refinement.

Over the past two years the robot construction instructions have improved considerably. These improvements are based on feedback received from children. The first series of robot build instructions used both pictures and text. While using these instructions the children were often observed asking questions that they would have



Connect the Motor A forward to the End Icon.

To complete the program we need to wire **Motor A forward** to the **End** icon. To do this we use the wire tool.

5 If its not already open, open the tools palette by selecting **Show Tools Palette** from the **Window** Menu.

6 Select the wire tool.

In the diagram window the cursor should look like this:

7 Click on the area tool-tipped "End" of **Motor A forward**.

8 Move the wire tool toward the **End** icon.

9 Click on the area tool-tipped "Begin" of the **End** icon.

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Fig. 3. The robotics worksheets provide step-by-step instructions on how to complete a particular programming task.

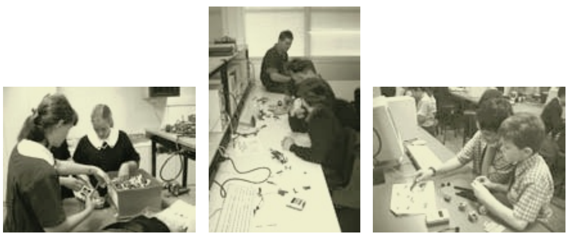

Fig. 4. Robotics workshops engage children aged between 10 and 17 in robot building and programming activities.

known the answers to if they had read the text. In response the children's failure to read the important text associated with images, the second generation robot construction instructions primarily contained images. An image of the parts needed for each step was shown in a table above each step. A textual description of the parts and how many were needed was also given. Questions arising from these build notes where primarily about which part was required. These questions were answered by tutors referring children to the text accompanying the parts table.

The final version of the build instructions contains images only. The only text in these instructions is sequence numbers and size information. As mentioned, these notes have added a step which shows the LEGO™ piece as it is about to be placed, with an arrow indicating its destination. The number of queries during the construction of the robot has decreased dramatically. The most common question asked is "How did you make those pictures?"!

The programming worksheets also went through a development cycle. The first version only contained one worksheet. This worksheet asked the students to program the robot with a number of exercises. The worksheet familiarized participants with the development environment and introduced them to concepts of actions states, program looping, binary decisions and message passing. It also introduced the concept of multitasking and described how to make the robot react to sensor readings. Observations suggested that these worksheets were far too complicated for the children. For the most part students ignored the text. When challenged by a problem, they would consult the tutors, before they would search the text for clues. Exercises which had no example program were generally avoided. Observations indicated that the participants had no real understanding of the ROBOLAB environment or programming on completion of the workshop session. The participants were generally unable to create their own programs without assistance.

Based on these observations, the programming worksheets were changed dramatically. The second worksheet was greatly simplified. Children were given more detail on how to use the ROBOLAB development environment and provided greater detail about the ROBOLAB syntax. The second set of worksheets provided ROBOLAB iconic solutions to each of exercise, and an explanation of the principles underlying the solution. Observations of these students showed that the worksheets had only partially helped them use the ROBOLAB environment.

The third set of worksheets reverted to a more text based approach, but covered the description of the environment and solutions to the exercises by progressing step by step through the exercises with supporting images. Again the bulk of the text in the worksheets was ignored. Information hidden in the text was not found. Empirical evidence suggests that after completing the worksheets in these early workshops only about 1/3 of participants could use the light sensor effectively.

Within the current worksheets each exercise is now a separate worksheet. Each worksheet introduces a concept or a syntax requirement. Again the worksheets provide a step per action, but each step is accompanied by an image of what the program should look like at this stage. The order of the exercises was also changed with the introduction of using the light sensor in the third worksheet. In earlier iterations, use of the light sensor was the final concept covered by students in the workshop. This final set of worksheets covers less programming information than earlier worksheets, instead concentrating on the functionality of key icons, and focusing on how to use the ROBOLAB development environment. The new worksheets are based on observations across many workshops. They have been designed to prevent students from encountering the programming difficulties common in earlier workshops.

3.2 RoboCupJunior Queensland Competitions

The RoboCupJunior Competitions provide a strong motivation for children to build robots, and to critically think about their robot creations. The competitive aspects encourage the children to think deeply and creatively about their designs, and to critique their designs in order to make the best possible creation in an effort to win.

However, the competition is more than motivation – it is a great educational opportunity. The competition is a gathering of student minds; an opportunity for students to share their ideas. Students are keen to share, and are usually ready to offer advice. This was first observed during the 2001 competition, where some of the teams that fielded non-functional robots at the start of the competition had robots that functioned well by the end. When asked how this had come about, the students responded that they had received assistance from other students: their competitors.

In 2002, inter-team interaction was encouraged further by the complete exclusion of adults from the team setup and practice areas. Teachers and parents were invited to sit in the stands and observe, rather than actively participating in the setup of the robots. The students quickly tired of climbing the stairs to the stands, and started asking other students nearby. Social interactions built quickly, and inter-team sharing flourished. Figure 5, a photograph taken at the RoboCup 2001 competition, gives a feeling for the interest and excitement generated during the competition.

Fig. 5. The soccer quarter finals of RoboCupJunior Queensland 2001 held at the University of Queensland.

3.2.1 Observations of Robots Built for Competition

All but one of the teams used LEGO™ and the RCX™ brick to build their robots. The exception was the team from Brisbane Grammar School with the custom design that won the 2002 championships. Despite the explicit nature of the building and programming instructions provided in the workshops, no teams arrived with the workshop design for the construction or programming. All of the teams had taken it upon themselves to come up with completely new designs, or to significantly customize the workshop design. There was a notable contrast between younger and older robot builders. The younger team (aged 10 to 13) would typically build an initial base, and then add components to fix problems rather than re-designing the whole robot. Older teams were more able to see the benefit in going back to the design phase and re-considering their first steps.

Programming the RCX was predominately performed using ROBOLAB, with a number of teams also using NQC [13]. Dance robots, in both primary and secondary divisions, used highly linear programs. Rather than using a loop with a counter, students would cut and paste long strings of commands to form a long line of motor control elements with timer elements to set the duration of each motion. There was almost no use of sensors or sensor programming. Rescue robots, on the other hand, tended to be programmed with a linear sequence of behaviors. The students would first run a line following behavior, followed by a search behavior. Soccer produced the most diverse range of programming styles, and included the most examples of the use of NQC. Many students used a state based style, where a single behavior would execute for a fixed amount of time, or until certain sensor conditions were met, before moving to another behavior. Others used multi-tasking to execute parallel behaviors that would compete for control of the robot based on competency measures, in a similar style to the subsumption architecture [3]. A robot programmed in this manner was the runner-up to the world champions in the 2002 competition.

4 Future Improvements

Further research is being conducted into the impact on robotics activities on children's ability to independently build and program robots to achieve particular goals. A full usability study of the ROBOLAB™ development environment is being undertaken to highlight usability issues which both support and hinder the programming efforts of students. In addition, in the next year workshop participants will be observed and recorded as they work through programming tasks in an effort to gain an in-depth understanding of the concepts which cause the most difficulties. While observations of children using the current worksheets indicate that children are having success programming their robots during the workshops, further studies will be undertaken to evaluate the degree to which children are able to use this knowledge at a later date.

In the coming year minor improvement may be made to both the robot construction notes and the programming worksheets. The tutors are currently exploring ways in which the build notes could include three dimensional vector models of the robot and animated steps in the construction process. Such improvements are possible in an interactive web-based environment. While the worksheets are fundamentally sound, minor improvements in the ways certain processes are explained may be made. The tutors are also in the process of developing three additional intermediate worksheets which cover GOTO statements, as well as the programming concepts of multitasking and event handling.

5 Conclusions

Over the past two years, the School of Information Technology and Electrical Engineering at the University of Queensland has been involved in delivering robotics tuition and providing a competitive format to further this educational process, to school communities across Queensland. The robotics workshops and summer camps initiated by ITEE have provided opportunities, which may not have otherwise been available, for a wide range of children to develop knowledge and skills in robot building and programming. This scaffolding has helped students who have gone on to compete in RoboCupJunior Dance, Rescue and Soccer competitions. These competitions have been successful in creating a community of children avidly interested in building robots, sharing ideas and striving to "do it all better next year".

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