**Well-Oiled Machines: Collaborative Work in Robotics**

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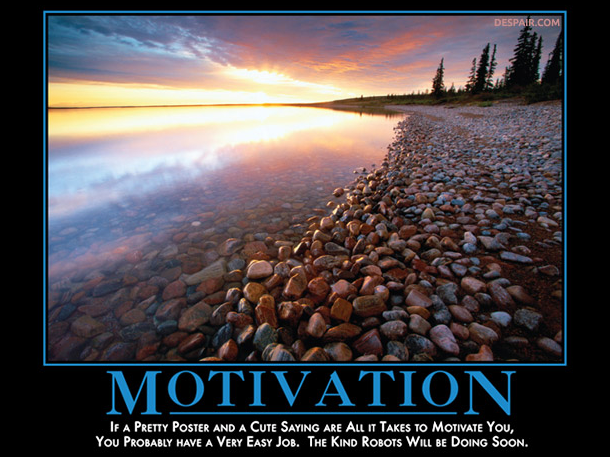
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**Abstract**

This paper explores the benefits and drawbacks of collaboration in robotics education. Robotics programs are growing across the country, but little guidance has been offered so far by research as to how these programs should be structured. The importance of getting it right quickly is paramount in a fast-moving field such as robotics. Most programs involve collaboration in small groups with a competition as the final goal. Some worry that a focus on competition may attract only a small segment of learners, and produce a non-diverse field. Some new programs include collaboration between small groups to achieve larger cooperative goals such as exhibitions. The benefits of collaboration will be discussed including the results of small group work, and the potential for broadening the spectrum of students who engage in robotics. This paper will divide its exploration into four sections: learner, learning context, curriculum, and assessment. Learners are viewed through a constructionist lens and they can be attracted to robotics for different reasons. The learning context of robotics is complex and flowing, and the collaborative nature of the environment produces many complex results for student outcomes. The curricula of robotics programs around the country vary widely, but can be very effective if the learning goal is kept in mind when the curriculum is designed. Assessing learning for collaborative robotics can be aided by several key strategies. Following the consideration of the four perspectives, the implications of the paper will be summarized, limitations will be presented, and areas for further research will be proposed. The author believes that this paper holds important results for the budding field of robotics education, including conclusions about optimal group size, proper teacher involvement, and methods for applying robotics to peripheral subject matter learning.

**The Issue**

The importance of robotics is increasing both in everyday life and in the economy (Kuka Robotics, 2015). As robots are more and more intelligently designed, they are becoming capable of more and more complex tasks. Robots have even replaced human workers in a variety of vocations, with fast food cooks looking to be next (Love, 2014). As is always the case when new technologies disrupt old ways, modern-day Luddites bemoan the loss of jobs and call to ban the new technology. A more productive route would be to ensure that we are preparing ourselves for the changing future by adapting education to the changing times. Some foresight would tell us that if robots are replacing fast food cooks it would be smart to begin training people to design, create, and maintain robots.

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The field of robotics education is an exciting one because it is not already mired down with as many centuries of tradition and custom as our other academic disciplines. In math, for example, new teachers tend to fall into the pattern of teaching the way they were taught(Kennedy, 1999). In robotics this will not be the case because few if any teachers took robotics themselves.

Thanks to the newness of the field, robotics educators find themselves with great freedom. With great freedom, however, comes great responsibility. Many difficult choices must be made when a teacher creates a learning context, curriculum, and assessments for their learners. One of these choices concerns the balance between competition and collaboration in the classroom. It is vital that new robotics teachers heed the lessons coming from the emerging research on robotics education because the early adopters of robotics education will have compounded effects on future learners. It is also vital that robotics educators work to grow the field and generate legitimate and voluntary interest in robotics amongst youth. Without such interest and engagement, we could see an ever-widening gap between those who control robots and those who are replaced by robots.

This paper will investigate the current state of research on the learners, learning contexts, curricula, and assessments surrounding robotics education, with a particular focus on how using a collaboration in the classroom could benefit this and future generations of robotics students by broadening appeal and deepening cooperation skills.

**Learner**

The majority of researchers who study robotics view learning through the constructionist lens. Like constructivists, constructionists believe that knowledge is constructed by the learner in an attempt to make sense of his environment. As Seymour Papert, father of constructionism explains, there is more to constructionism than just that:

Constructionism […] shares constructivism's connotation of learning as "building knowledge structures" irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe. (Papert & Harel, 1991)

If knowledge needs to be built by the learner, there is no better way to educate people than to have them build things. Building a robot is a task that constructionists see as almost ideal. The learner begins with nothing, and uses materials and resources to create a moving entity that can in a sense think for itself. The type of knowledge formed around such a project is quite robust. The builder of a robot will have knowledge that is conditional, meaningful, and experimentally verified. All of this knowledge is constructed by the learner instead of presented to them by an authority figure.

Robotics learners are also creating “public entit[ies]” (Papert & Harel, 1991) because the robots they create are subject to scrutiny by peers, teachers, and sometimes even family and friends. This public nature of robotics creations can be a terrific influence on robotics learners, increasing their accountability, motivation, and pride. On the other hand, some types of public robotics displays have the potential to turn away certain types of learners. This demands careful attention.

Overly competitive robotics can act as a deterrent to certain learners who do not relish competition. Robotics is mostly an elective subject at this point in time, so teachers who want a broad array of learners need to consider incorporating more collaborative, lower intensity robotics projects into their curriculum. Rusk and colleagues engaged girls in a series of workshops and programs that used storytelling, art, and exhibitions. They found that girls were much more interested in robotics when the tasks were not traditional car and racing types of robotics but rather combinations of art and engineering (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007). A good balance will attract both learners who relish competition and those who prefer collaboration. Limiting the appeal of robotics to either group would be a disservice to the field.

To create a healthy field, collaborative robotics must not only attract diverse learners, but it must create environments and contexts conducive to productive learning.

**Learning Context**

The collaborative robotics learning environment is ever-shifting. Unlike traditional school settings where students work in static arrangements for the majority of the class, a robotics classroom is full of motion and negotiation of space. Students bustle to and from the equipment shelves, they slide over to their neighbors to ask for advice, they huddle around the computer screen, and they spread out around a table to watch their robot in action. The complexity of the environment is part of what makes it so vital to study and understand so that facilitators can shape their contexts intelligently.

Collaborative robotics is currently relegated to extra-curricular programs. Few schools offer robotics as a part of the standard curriculum. Though there is shifting opinion towards the usefulness of robotics (Crane, 2015) it remains slow. For the time being, the learning context of robotics is largely voluntary after-school programs, with schools devoting a wide variety of space and resources to their programs (Barreto & Benitti, 2012).

The learning context of robotics is often one that is thought of as lavishly expensive to create. This need not be the case. As in the example set by Rusk et al. there are many ways to engage students in robotics while maintaining low costs. Rusk and her colleagues engaged students in a variety of themed workshops that used some robotics components but also arts and crafts materials. These inexpensive arts materials added creativity to the projects and even expanded the appeal of the workshops. They noted that “many girls have more experience with art materials, and thus they are better able to use art materials as a source of inspiration for creative robotics projects.” (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007) New technologies are constantly emerging to make robotics environments even cheaper. Arduino is a company that offers starter robotics kits for $84.53 (Arduino, 2015). The kit is reusable and can be used by groups of 1-3 students. A Raspberry Pi is another type of robot-controlling computer that can be purchased for $101.35 (RS Components Ltd., 2015). Most robotics environments contain a collection of ‘brains’ similar to the Raspberry Pi or Arduino along with a collection of motors, sensors, and connection pieces that can be used to assemble the physical robots (Hussain, Lindh, & Shukur, 2006). Computers are another key physical component of robotics learning contexts. Computers are used to write programs that are then downloaded onto the robot ‘brain’ and executed by the robot. The sets of robot brain, computer, and mechanical parts that make up the physical piece of robotics learning can be shared by multiple members of the class as most robotics takes place in groups.

Group size is an important factor to consider for a collaborative robotics environment. A Swedish study on robotics found that the optimal group size for collaborative robotics was 2-3 students (Hussain, Lindh, & Shukur, 2006). Working alone has drawbacks such as frequent hold-ups and higher monetary costs to buy more sets. Working in groups too large can be detrimental as well though. Groups that are too big can leave some students out. As group size increases, allocating fair loads of work to each group-member becomes more difficult, and making sure each member is learning everything becomes almost impossible. Denis and Hubert found that a high-quality instructor can have a large impact on the distribution of work in a group (Denis & Hubert, 2001). The way that groups collaborate in a robotics class is an important aspect of the learning context, and also has implications outside of robotics.

Collaboration is an essential element of any robotics classroom. Groups work within their members to achieve their group goals. In some robotics environments, groups even work with other groups to achieve larger class goals (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007). This crucial element of the robotics learning context has intrinsic value. Collaboration is a skill that appears on many educational goal statements and educational design frameworks (P21, 2015). Denis and Hubert coded the conversations of students working together on robotics projects and found evidence of productive collaboration, including both leadership and cooperation behaviors (Denis & Hubert, 2001). The collaborative aspect of the learning context gives robotics an easy path to achieve the learning goal of collaboration, which is a crucial skill in the workplace.

The space of a collaborative robotics classroom should be optimized for constructionist learning. For learners to build their own ideas about robotics, they need options. As Lindh and Holgersson observed, “there needs to be a large space for the pupils to work, they must be able to spread the LEGO material on the ground, “play around”, and test different kind of solutions for each kind of project they face” (Lindha & Holgerssonb, 2007). Without the physical room to experiment and see their options, students will be slower to build meaning from robotics. Though some schools do not have the resources to let students spread out, it is highly recommended by the current research that the learning context of robotics include large flat spaces for each group.

The presence of physical robotics objects is important to the robotics classroom. Using computer simulations of robots is not as effective for learning. This principle has been demonstrated by Mitnik in a study on using robots to learn graphing concepts. Mitnik and his colleagues separated students into two groups. One group used physical robots to complete an activity while the other used a computer simulation of the same activity. The group that used the physical robots showed increased retention, motivation, and collaboration over the control group (Mitnik, Recabarren, Nussbaum, & Soto, 2009). This demonstrates what constructionism suggests –that the physical act of manipulating and constructing robots is important for constructing understanding.

Students need more than just a good space and materials to learn productively, they also need a well-designed curriculum.

**Curriculum**

The robotics curriculum is diverse and unique. Because robotics covers so many fields of knowledge, teachers are free to emphasize different fields within robotics in their classroom. Some teachers use robotics as an experimental tool to learn STEM concepts like graphing (Mitnik, Recabarren, Nussbaum, & Soto, 2009). Others emphasize the interactive nature of robots (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007). Robotics can also be used to learn computer programming concepts. Common to all of these areas of emphasis is the thread of collaboration.

Collaboration adds a larger element of the unknown to curriculum design. In traditional teacher-centered class design, the main unknown is how the students will respond to the information the teacher presents. With collaboration, the domain of the unknown extends to how students interact with each other, how students interact with the robotics equipment, and how students interact with the instructor. Thus, design of collaborative learning environments becomes very difficult and is the subject of continued research (Lowyck & Pöysä, 2001). Amongst this tangle of complex collaboration and multifaceted robotics projects, researchers are trying to tease out what can be gained from a collaborative robotics curriculum, and how best to achieve those gains.

A large study of Swedish students looked at how a LEGO robotics curriculum affected the math and problem solving ability of students. The participating schools were instructed to engage students with the LEGO robotics kits for eight hours per month. No further standardization occurred. Collaborative group sizes differed, and each school implemented the robotics curriculum that they felt would be best for their students. The results of the experiment were that “for pupils in grade 9 before and after the training, we did not find any significant shifts in the mean with regards to mathematics. For the problem solving, there is no significant improvement either” (Hussain, Lindh, & Shukur, 2006). The study seems to present some major issues for robotics instruction, but there are also some issues with the study. First, there was no standardized curriculum, so we don’t know what the schools were actually doing with the students. This is a problem because normal teaching involves beginning with a goal in mind and designing a curriculum to achieve that goal. If no goal of mathematics skills and problem-solving skills was communicated to the participating schools, it seems unremarkable that the students did not improve in those areas. Perhaps most of the teachers had other goals in mind when they used the kits. Second, the required time commitment of eight hours per month seems inadequate to produce any real gains in such complex and specific fields as math and general problem solving. It would have been interesting for the authors to test the actual robotics abilities of the students at the end of the study instead of peripheral skills. Their focus on math problem solving ignores the fact that robotics skills have intrinsic value in today’s economy. The important takeaway from this study is that merely providing learners with a robotics learning context is not enough to see gains on assessments –the curriculum must be intelligently designed with specific learning goals in mind.

Another study asked a similarly peripheral question about robotics: would participation in a robotics summer camp program increase campers’ scientific inquiry skills? Williams and colleagues studied middle school students who attended a two-week long summer robotics program and found that their physics content knowledge improved, but their inquiry skills did not improve (Williams, Ma, Prejean, Ford, & Lai, 2007). The study found that most students engaged in a trial and error process with their groups and failed to use systematic inquiry processes to meet the challenges of the program, which explains the lack of improvement in that skill. The authors noted that there were several issues with the study that call for further research. First, they acknowledged that two weeks is a very short time period. Next, they admitted that the facilitators were not instructed to focus on scientific inquiry methods and consequently rarely addressed them. Further, the researchers found several areas of possible improvement for the program. These include more ‘just in time’ resources for students, more differentiation among students of different skill levels, and facilitators who are better able to stress scientific inquiry and scientific concepts with the learners. Another thing the researchers struggled with was the balance between free exploration and structured tasks. They found that some play time was important for students, especially initially, but then increased structure would have been helpful to accomplish specific learning goals. Though this study has limitations, its results show that robotics programs *can be* an effective vehicle for teaching scientific content if the curriculum is designed with that content in mind.

In a focused study on how a robotics class increases students’ knowledge of robotics, researchers found that students who participated in an after-school robotics program performed significantly better on a written test than a control group of students who did not take the course (Barker & Ansorge, 2007). The test asked questions as specific as “What icons are needed in every ROBOLAB program?” This study did an excellent job of connecting the curriculum to the desired learning goals. The authors’ research is proof that it is possible to design a robotics curriculum that effectively addresses important robotics concepts, especially if those concepts are known beforehand and included in the curriculum.

With the panoply of possible areas of focus for a robotics curriculum, it is helpful to categorize them into different types. Denis and Hubert identify four main types of robotics curricula:

* “a *technocentric* approach aimed at the development of technical situations often close to the industrial world”
* “an approach based on the *creation and exploration of microworlds based on the learner's project”*
* “an approach based on the theory of the *cognitive spectacles* or *computer assisted experimentation*, connected to scientific contents”
* “a *programming or algorithmic* approach” (Denis & Hubert, 2001)

These four types of curricula support collaboration to different extents. The technocentric approach necessitates collaboration because robotics in the workforce is always done in collaborative groups. The microworlds curriculum calls for a pair of students working on the mechanical and programming sides of the robot and collaborating to achieve some complex goal. The third curriculum deals with experimentation. This type of curriculum involves a certain degree of collaboration in that all students are working to measure or find the scientific truth about the same phenomenon. Students usually work in collaborative teams when conducting such experiments, so collaboration is possible, and has even been shown to increase motivation and engagement (Mitnik, Recabarren, Nussbaum, & Soto, 2009). Finally, some classes use robots as a vehicle for teaching computer science concepts. The robots act out computer programs, making physical that which was merely digital. Researchers have suggested curricula that can teach even very complex computer science techniques such as task decomposition through a collaborative robotics framework (Burbaite, Stuikys, & Damasevicius, 2013).

When the curriculum is enacted, teachers require ways to know how successful their curriculum was. That is where assessment comes in.

**Assessment**

One of the main issues with collaborative robotics is the question of assessment. When teams work together on a project there is always the question of how to fairly distribute grades. Several elements of robotics can be used to ameliorate the potential injustices arising from group work.

Small group sizes can make it more difficult for single group members to slack. By using the recommended group size of 2-3 derived from observation of Swedish students (Hussain, Lindh, & Shukur, 2006), teachers can more easily see during class if one partner is doing all of the work. Some schools may struggle to keep group sizes low, however, as smaller group sizes necessitate larger quantities of robotics materials. Given such a hurdle, teachers may have to turn to the other strategies offered below.

Constant teacher vigilance can be a terrific influence on student engagement. Despite the perception of robotics as a laissez-faire classroom environment, research shows that a good facilitator can have enormous effects on the quality of learning that occurs. A teacher who is constantly moving around the room asking questions will likely alleviate any preventable issues of slacking that might otherwise have occurred (Hussain, Lindh, & Shukur, 2006) (Denis & Hubert, 2001).

Another quality of collaborative robotics that makes fair assessment possible is the possibility of dividing the labor into discrete components. Studies show how this often occurs naturally as one student is more inclined to programming while the other prefers mechanical construction (Denis & Hubert, 2001). Additional group members might have roles that facilitate communication between the two other members, or that bring creativity and artistic design to the robot in the case of collaborative projects that involve artistic expression (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007). A thoughtful teacher can use such division to assess learning fairly, and force students to rotate through the various positions if a balance of skills is a goal of the course.

A final resort of the teacher who is trying to ensure equity of assessment is individual testing. Collaborative robotics teaches many skills that are not easily testable with pen and paper, but a clever teacher can find ways to assess the skills that *are* testable. For example, Barker and Ansorge developed an individually administered test which evaluated students’ knowledge of key robotics concepts, both on programming and on mechanics (Barker & Ansorge, 2007). The test included such questions as “In computer programming what is a variable or container icon used for?” and “The rotation sensor works like what on a car?” These questions can give a teacher good information about what the student comprehends. Though they should not be used as the entire grade for a robotics class, they can provide a balancing force to the overall assessment picture that accounts for individual performance.

Individual grades should also be accountable to group performance. In competitive robotics this is usually assessed by the groups’ final ranking or achievement in the final competition. For collaborative robotics, group assessment can take a gentler form, relying on softer achievements like creativity and functionality, which can be judged by the instructor. In extra-curricular settings where there are no grades, assessment on a collaborative project can also come from exhibitions. Though not formal assessments, exhibitions where students display their work to parents and friends can provide an important source of accountability, motivation, and feedback for students (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007).

**Implications**

This essay has important implications both for the field of robotics education and for personal practice. Research in the field of collaborative robotics is making it clear that robotics is not a silver bullet to teach all STEM topics. Study after study shows little to no gains in math or science from robotics programs when those goals are not explicitly communicated to the teachers (Barreto & Benitti, 2012). In other words, just *doing* robotics does not generate knowledge or achievement in peripheral fields. Educators must now decide to what extent robotics is valuable to their institutions. Robots can be used to conduct better scientific experiments, they can be used to teach computer science, they can be used to teach mechanics and other scientific content, but it must be done with a specific purpose in mind or it will only make students better at robotics.

Robotics instructors can learn important lessons from the research discussed in this essay. Group sizes should be between two and three students. Using inter-group and intra-group collaboration can attract a more diverse student pool to robotics programs. Collaboration on artistic and narrative exhibitions can provide similar levels of motivation to competitions. Students need time and space to explore and experiment with robotics kits, especially when first introduced to robotics. After that, instructors should structure the program to achieve desired learning goals. Structure is best provided as ‘just in time’ resources. Instructor involvement still has a large effect on student achievement despite the student-centered design of the class. Attentive instructors can help spread learning to all group members, focus groups on specific learning goals, and prevent frustration.

All of these implications are limited by the fact that robotics education research is in its infancy. Further, individual instructors will be limited by such constraints as space, financial resources, and time, as most extra-curricular programs have tightly limited supplies of each. As research continues, instructors should continue to follow the suggestions of academic studies to enhance their work and create optimal environments for learning robotics.

**Future Considerations**

Based on this literature review there are several areas of collaborative robotics which need further study. As Barreto and Benitti point out in their survey of quantitative robotics studies, there is a dearth of hard data concerning the benefits of robotics for education. Of the ten quantitative studies on robotics that they analyzed, four did not use a control group and most did not use random selection to choose their subjects (Barreto & Benitti, 2012). Clearly robotics education is a budding branch of research that will benefit from increased attention from the academic community.

Another thing currently lacking from the body of research on collaborative robotics is a long-term study on students who use robotics heavily. While the Swedish study found little benefits of an eight hour per month program on peripheral skills (Hussain, Lindh, & Shukur, 2006), it would be interesting to see the results of long-term study of robotics on a randomly chosen group of students compared to a control group. Such a study might give a fairer picture of the benefits of robotics for critical thinking skills.

More research is needed to determine which types of students are currently choosing to learn robotics and which students are not. In an elective subject such as robotics it is important to consider who is being attracted to the subject. If robotics is only attracting academically-oriented boys, that is something that should be remedied. One way to remedy this would be to study various robotics programs around the world and see what types of robotics programs attract more diverse groups of students. Once this is discerned and imitated, more programs can gain diverse followings, which is essential for the success of the field.

**Concluding Remarks**

Advancing technology has made the use of robotics in the classroom both feasible and important. Feasibility has come from decreasing costs of robotics sets. Importance has come from the demand from the technology sector of our economy. With this new supply and demand of robotics programs comes a chance to get it right with a young, flexible new field of education. Using constructionist principles, educators are letting kids get hands-on with robotics and learn by doing, making, and creating. As they do, make and create, there are many questions about the nuances of robotics program design that remain unanswered. Research is starting to catch up with those unanswered questions.

Should students work in groups, and in what sizes? Students should work in groups because group robotics work bolsters students’ collaboration skills (Barreto & Benitti, 2012). Research is pointing to groups of two to three students as the optimal group size (Denis & Hubert, 2001).

Can robotics be used to teach other subjects? Yes, but only when done deliberately. Merely doing robotics will not help with other subjects unless the robotics tasks are designed with other content areas in mind (Barreto & Benitti, 2012).

Can robotics appeal to a broad range of students? Robotics that uses collaboration and creativity to tell stories or display student exhibitions can open the door to students who wouldn’t normally be interested in robotics (Rusk, Resnick, Berg, & Pezalla-Granlund, 2007).

As usual with a new field of study, more questions than answers are generated from the early literature. How structured should projects be? Which robotics system translate into the most benefits for students? What soft skills are gained from long-term interaction with robotics? These questions will all be explored as researchers continue to explore the fascinating topic of collaborative robotics.

A robot is a machine that takes inputs from sensor and executes actions based on that information. Much like the robots they help create, robotics teachers around the country will take inputs from current research and literature reviews such as this paper. They will also observe their classes, taking in information about their specific learners, context, curricula, and assessments strategies. They will process this information and use it to adjust their programs in new and exciting ways. These changes will be followed by more research and studies, and the cycle of improvement will continue. As it does, we can be hopeful that this emergent field of collaborative robotics education will continue to bloom and adapt itself to the research of the past and the demands of the future.

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