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MATHEMATICAL EMBODIMENT THROUGH ROBOTICS ACTIVITIES

A Dissertation APPROVED FOR THE

DEPARTMENT OF INSTRUCTIONAL LEADERSHIP AND ACADEMIC

CURRICULUM

BY

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ABSTRACT

This naturalistic phenomenological study looked at the emergence of mathematical understanding in middle school students as they engaged in open-ended robotics activities. The study chronicled the mathematics they used, the mathematics they perceived themselves to be using, and the opportunities for the embodiment of mathematics understandings as they engaged in meaningful open–ended problem solving activities using robots. In addition, the study sought to understand how the students cooperatively organized their efforts and negotiated meaning as they solved complex tasks.

The robotics activities portrayed in this study exemplify rich tasks that appear accessible to students of varied abilities. This accessibility potentially may provide an avenue for addressing equity issues in education, such as those related to gender, minority status, and learning disabilities. The accessibility of the robotics activities is also important since robotics activities have the potential to provide a meaningful context for the study of mathematics in a transformative mathematics curriculum. In this study, the students' choices influenced the complexity of the mathematics that emerged from the activities. Robotics seems to exemplify an appropriate use of technology to create meaningful, open-ended, problem solving activities. Further research is required in order to adapt these types of robotics activities into the in-school context as part of a transformative mathematics curriculum.

Chapter 1

INTRODUCTION

> *The computer is the Proteus of machines. Its essence is its universality, its power to stimulate. Because it can take on a thousand forms and can serve a thousand functions, it can appeal to a thousand tastes.* (Papert, 1980)

Rationale for the Study

With the advent of handheld calculators in the early 1970s, and later personal computers in the 1980's, the discourse regarding technology in education has become increasingly dominated by computing devices and their potential to support educational aims. One thread of this discourse has revolved around the use of such devices to engage students in meaningful, open-ended problem solving activities. The computer language *Logo* is an excellent example of the promise of computing devices in education. Since its inception in the 1970s, the *Logo* programming language has attracted educators as a learning tool conducive to developing open-ended learning activities.

Seymour Papert (1980) stated that *Logo* was designed as an outgrowth of two fundamental ideas: first, that it is possible to design computers so that learning to communicate with them is a natural process for children, and second, "...that learning to use computers can change the way they learn everything else (1980, p. 8)." In other words, Papert envisioned that *Logo* would fundamentally change education by encouraging active, rather than passive, learning strategies and creating an invigorated culture of learning in the classroom. In subsequent years, educators have explored *Logo* extensively as a learning vehicle for students, particularly with elementary age students.

In the last decade, Papert's vision has been reiterated. Kaput (1992) suggests that general purpose programming languages such as *Logo* serve as tool-makers through which students can build and have access to independently constructed tools to analyze problems. More recently, Yelland (1995) asserted that *Logo* could be used to promote higher-order thinking skills, develop flexible and creative thinkers, and strengthen problem-solving abilities, while McClees and Fitch (1995, ¶ 3) averred that:

> To teach mathematics and programming, Logo is the best tool available. To teach problem-solving, it is one of the best available. Specifically, Logo was designed to be a world for exploring fundamental math concepts, for teaching programming, and for teaching powerful analytical concepts, such as sequencing, iteration, and structure (breaking large problems into smaller ones). If you can think in those terms, you can also analyze the world around you. (p. 11).

One feature of early *Logo* activities that was eclipsed by the advent of newer and increasingly more powerful personal computers is the floor "Turtle." This was a device directed via wires linked to the computer that maneuvered on the classroom floor according to the instructions programmed in *Logo* by students. The turtle was essentially "dumb" in that all processing was performed by the personal computer with directions generated through the execution of a *Logo* program being relayed through the attached tether. The key to successfully directing the turtle was the necessity for children to alter their perspective from self to this mechanical "other" and use it as an "object to think with" (Papert, 1980, p.11) to move and explore in a three-dimensional meso space (Berthelot & Salin, 1994); despite being effectively floor bound. As personal computers became powerful enough to support sophisticated graphical user interfaces such as Windows or MacIntosh, the lumbering physical turtle retreated into the micro space of the computer monitor screen; replaced by a two-dimensional simulacrum.

The introduction of newer and more powerful personal computers and, especially, small powerful microprocessors such as the Lego® Mindstorms™ RCX brick and the Handy Board has, in effect, allowed the return of the Turtle. No longer tethered to a computer by a cable, they are able to accommodate the integration of a large number of effectors (i.e., motors and servos) as well as a variety of digital and analog sensors such as light, touch, temperature, range finder, and interrupt counters (encoders). However, *Logo* is no longer the pre-eminent programming language for these microprocessor-directed turtles. Instead, it has been replaced by variations of the *C* programming language more suited to the technical background and proclivities of those adults who first took an interest in the power and potential mobility of these microprocessors for robotics. The bias towards *C* seems to be a result of a confluence of the familiarity with *C* on the part of those adults, primarily due to the widespread commercial application of *C* throughout business and industry, and lack of awareness of (or discounting of) the capabilities of *Logo*. While it may be arguable that the change from *Logo* to *C* has possibly resulted in a gain in power and flexibility from the adult perspective, it can be reasonably asserted that this has come at the expense of accessibility for younger users and their teachers.

The implications of this shift in programming language for education are unclear and raise a number of questions. First, as numerous studies have affirmed, *Logo* is acknowledged for its potential to be used in open-ended problem solving activities with students. However, *C* has no similar track record. The reason is that it has not been studied outside the computer science community and, until the development of the Mindstorms™ RCX and Handy Board processors; there has not been sufficient interest or incentive to do so within the education community. Second, many in the education community consider *Logo* to be a dead issue. This is sort of a "been there, done that" attitude resulting from the misapprehension of Papert's vision for *Logo* and the resulting misapplication of *Logo* within the curriculum. Many school districts adopted a computer science approach to *Logo*; teaching it as a traditional course in programming, in and of itself, instead of as a powerful tool for the exploration of non-programming-oriented concepts. Finally, considering standards-driven school curriculum, it is not clear how thinking and problem solving skills developed through *Logo*-type environments translate into curriculum objectives and objectively measurable performance improvements on standardized tests.

Purpose of the Study

Middle school is an especially fertile time for students to explore robotics activities as they transition from concrete to formal operators (Piaget, 1964). In mathematics, moving into formal operations involves important transitional thinking strategies including controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning, conservation of solids and conservation of volume (Inhelder & Piaget, 1958, Renner et al, 1976). In addition to Piaget, process and enactivist approaches to learning suggest the potential of robotics activities for students' mathematics learning. Theory and research arising from these approaches to learning emphasize the emergence of understanding from a fertile, open-ended inquiry environment.

Robotics is a potentially rich source of meaningful activities that has connections with Whitehead's process philosophy and postmodern ideas about learning. Yet, robotics activities have not begun to be used in ways that fully take advantage of the technology to create rich activities that enable the emergence of mathematics understanding. Others have commented on the potential contributions of technology in mathematics learning. Schwarz (1999, p.101) notes, "Technology even makes possible the addressing of traditional content in more profoundly interesting and challenging ways." Yet research has scarcely begun to address the potential contributions of technology in developing rich, contextual learning activities that go beyond the familiar computer-mathematics software duality for simulation or drill.

The purpose of the present study is to explore the emerging mathematical understandings and approaches to learning of middle school students as they engage in robotics activities. The study will focus on self-selected middle school student members participating in robotics activities. In particular, I will address the following questions:

1. What mathematical understandings emerge as students engage in robotics activities?
    a. What mathematics are the students using?
    b. What mathematics do they perceive they are using? Do their perceptions change in the course of the activities?
    c. What are the opportunities for mathematical embodiment in robotics activities?
2. How do students working cooperatively organize their efforts and negotiate meaning as they solve complex, open-ended robotics tasks?

The results of this study will be used to inform speculation on how complex, meaningful, open-ended activities involving robotics might have an effect on educators in their practice, specifically with the goal of improving mathematics education. In particular, the findings may inform ideas about rigorous, relational mathematics curriculum (see Doll, 1993), rich in interconnections and potential for personal meaning-making, cooperation, interest, and technology use.

Context of the Study

The mathematical activity that I describe in this study occurred at the suburban middle school where I had formerly been a mathematics teacher. I had also taught the site's Technology Education courses. It was in my capacity as the Technology Education teacher that I first became involved in Botball. I was the school's first Botball team sponsor and originator of the robotics activities program at this school.

The school sponsor of the Botball team during the time of this study was one of the site's special education teachers, Ms. Nickerson. All of the activities in this study took place in her classroom with the exception of the intermural robotics competitions. I had worked closely with this teacher over the past several years since leaving to complete my graduate work at the university in the same town. All robotics activities described took place after school hours with the exception of the Robotics Clusters, which occurred during school hours.

The school is a public middle school, grades 6-8, of approximately 750 students located in the suburb of a large southwestern city. Of the four middle schools in the district, this school is one of the most diverse, has a greater proportion of free and reduced lunches, and is considered less affluent than the other middle schools. The student population is predominantly White, (as is the community), English speaking, and largely lower middle class. The school has the greatest socio-economic range of the middle schools in the district and has a number of ethnically diverse students mainly of Hispanic, Native American, African American, and Asian American backgrounds. For this study, the voluntary participant pool was predominately Caucasian and male; although it did include three female students, two of whom classified themselves as multiracial, as well as one Native American male and one Hispanic male. The organizational structure of the Robotics Club enacted a problem-centered approach to learning as described below.

Problem-Centered Learning

Problem-centered learning involves a significant problem being posed, either by the teacher or students, and student collaborative engagement with the problem in cooperative groups (Wheatley, 1991, 1999). Each group's proposed solutions are then shared with the whole class, which serves as a community of validators. The social norms are established to create a community of discourse where the students have ownership of the process and are responsible to each other to explain and justify their reasoning. The teacher's role is to be nonjudgmental in that she or he ceases to be the sole arbiter of appropriate solutions. Instead, the viability of the proposed solutions is determined through class discourse (Wheatley and Reynolds, 1999). The robotics activities in this study meet all the criteria of problem-centered learning, as listed above, in that the problems were posed either in the context of a robotics competition or designed by the students themselves. The students collaboratively addressed the problems and likewise, they collaboratively determined their solutions. A key aspect of problem-centered learning environments is providing students significant and challenging tasks, replete with problem solving potential.

Rich tasks

Problem-centered learning includes providing students with rich tasks. As informed by Wheatley and Reynolds (1999) and described by Doll's (1993) notion of richness, rich tasks are potentially meaningful to students; consist of significant, open-ended problems; are replete with patterns; allow for student decision-making; promote peer discussion and communication, and allow for multiple levels of meaning to be constructed. Moreover, rich tasks are problematic in that they are open-ended tasks for which no known procedure or solution is available. The students participating in the robotics activities are engaged in rich tasks posed either in the context of an inter-school robotics competition or by the students themselves.

Significance of the Study

Suggesting the potential of robotics activities for students' mathematics learning are theory and research in process and enactivist approaches to learning that emphasize the emergence of understanding from a fertile, open-ended inquiry environment. The enactivist perspective as articulated by Varela, Thompson & Rosch (1991) views cognition as "the enactment of a world and mind on the basis of a history of the variety of actions that a being in the world performs" (p. 9). The body and mind are seen as indistinguishable and structurally coupled with the environment. Individual and environmental structures co-emerge, or are brought forth, in interaction with each other (Reid, 2002). Likewise, cognition is inseparable from other activities and viewed as embodied. As Seitz (2000) puts it, "We do not simply inhabit our bodies; we literally use them to think with" (p. 23). In other words, the embodiment of cognition means that cognition arises or emerges from the interaction of an organism, in our case human beings, with its environment (Varela et al., 1991, Núñez, Edwards, and Matos, 1997; Núñez, 1999; Thelen, 2000). Edwards (1998) extends notions of embodiment into education. In her view, education is seen as providing environments that afford learners opportunities to embody concepts, i.e., to kinesthetically and intellectually interact with the environment designer's (e.g., the teacher's) construction of conceptual entities. The robotics activities described in this study may be a potentially rich source of meaningful opportunities to embody mathematical concepts much like Edwards proposes. However, robotics activities have not even begun to be used in ways that fully take advantage of the technology to enable the embodiment and emergence of meaning.

The next chapter discusses the theoretical perspectives that informed this study and the areas of research that are apropos to the inquiry. First, the influence of process philosophy and notions of complexity on curriculum theory is surveyed. Next, notions of the nature of learning are discussed. Finally, studies of the influence of technology on learning are reviewed.

Chapter 2

RELATED PERSPECTIVES

Thought can only live on grounds which we adopt in the service of a reality to which we submit. (Polanyi, 1966)

Theoretical Perspectives

A number of theoretical and research perspectives inform this study. Ideas of meaningful activities originate in Whitehead's process philosophy (1929) and emerge in postmodern conceptions of learning. Theory and research in process and enactivist approaches to learning emphasize the emergence of understanding in a fertile, open-ended inquiry environment. The robotics activities described in this study are proposed as a potential source of such activities for mathematics learning.

Curriculum Theory

Whitehead (1929) portrays life as essentially periodic, and so too, education. What he describes as the periodicity of education is a continual cycling or "rhythm" involving three stages of mental growth: romance, precision, and generalization. In the romance stage, novelty holds sway and knowledge is asystematic, ad hoc, in ferment. Intuition, excitement, and exploration are limited only by the teasing, tentative emergence of previously unrecognized relationships. The ferment of the romance stage provides fodder for the transition into the precision stage. As Whitehead notes, "Education must essentially be a setting in order of a ferment already stirring in the mind: you cannot educate mind in *vacuo*" (1929, p. 18).

Whitehead characterizes the precision stage as the "grammar stage." Here knowledge is evaluated and extended systematically according to content domain wisdom and methods. Precision "proceeds by forcing on the students' acceptance of a given way of analysing the facts, bit by bit" (p. 18). Further, he notes that precision is barren without romance paving the way, "...unless there are facts which have already been vaguely apprehended in their broad generality, the previous analysis is an analysis of nothing" (p. 18). The acquisition of additional facts in a systematic way provides a means for both a disclosure and an analysis of the subject matter of the romance stage.

The generalization stage is both an ending and a beginning. It is an ending in that the germination of an idea or concept during the romance stage has been examined and extended through the precision stage and is now matured, a fruition ready to be applied in some way. It is a beginning in that it may lay the groundwork for new ideas or concepts, a new romance phase, an awakening interest in a new area.

Whitehead asserts that a lack of attention to the rhythm of education and, in particular, limiting its concerns solely to the precision stage "...is the main source of wooden futility in education" (p.17). Precision devoid of a precursor romance stage leads to decontextualized, less meaningful knowledge. He warns that an emphasis on precision in education misconceives the whole problem, in other words, that emphasis misperceives the nature of learning. The ferment of the romance stage gives rise to the discipline of the precision stage. Precision culminates in the maturation and application characterizing the generalization stage. The cycle renews with a return to the ferment once again as interests are modified or changed. Whitehead's description of the rhythm of education presages the contemporary discourse on complexity. His description of the continuing rhythm of education evokes contemporary descriptions of self-organizing, complex-adaptive systems.

More recently, Doll (1993) describes learning as self-organization, a process where learning and understanding come through dialog and reflection:

> In this frame, where curriculum becomes process, learning and understanding come through dialog and reflection. Learning and understanding are made (not transmitted) as we dialogue with others and reflect on what we and they have said—as we "negotiate passages" between ourselves and others, between ourselves and our texts. Curriculum's role, as process, is to help us negotiate these passages; toward this end it should be *rich, recursive, relational and rigorous.* (p. 156)

From this perspective, challenge and perturbation give rise to organization and reorganization. Since this process of challenge, perturbation, organization and reorganization is taking place within the individual, the outcome is not determined. The educational stage can be set, so to speak, but it is individuals in interaction with their context that co-create the script and bring forth the play.

In Doll's framework, self-organization or reorganization is a response to a perturbation or problems in the system, in this case, the individual learner. This idea of perturbation echoes Piaget's concept of disequilibrium as a precursor to accommodation. However, Doll asserts that not all perturbations lead to reorganization. Instead, there may be a period of chaotic behavior that may lead to either reorganization or degradation. For reorganization to occur, further environmental conditions must be present. Doll echoes Whitehead's notion the necessity of the romance stage in asserting that the learner must know the conceptual terrain well enough to engage it with confidence, to be playful with it. More importantly, the learning environment must provide for the representation of multiple perspectives. As Doll describes it, reorganization:

> ... requires a curriculum rich in diversity, problematics, and heuristics, as well as a classroom atmosphere that fosters exploration... Perturbation will trigger self-organization only when the environment is open enough for multiple uses, interpretations, and perspectives to come into play. (1993, p.164)

Environments such as those described by Doll provide fertile conditions for the reorganization necessary for learning to occur. From the standpoint of complexity, this reorganization occurs at critical bifurcation points in the dynamic, chaotic interactions emerging from the perturbation(s). Without these reorganization/bifurcation events, self-organization cannot take place and meaningful learning is precluded. As a self-organizing process, learning is not about the known or traveling well-trodden paths. Instead, learning is about engaging and experiencing the ferment; exploring the unknown.

Doll identifies four key aspects of curriculum to support self-organization/reorganization: *Richness, Recursion, Relations, and Rigor* (Doll, 1993). *Richness* "...refers to a curriculum's depth, to its layers of meaning, to its multiple possibilities or interpretations" (p. 176). It requires a delicate negotiation between the amount of indeterminacy, disequilibrium, chaos, and lived experience on the one hand and curricular aims on the other. If there is too much of the former, the curriculum loses its coherence. If there is too much emphasis on the latter, self-organization, and hence, the opportunity for meaningful learning is lost. *Recursion* refers to the capacity for reflection, or looping back of one's thoughts. This looping back of one's thoughts is necessary for meaning to be constructed. In Doll's view, reflection is essential in distinguishing recursion from mere repetition and the source of its creativity. *Relations* has two aspects, pedagogical and cultural. Pedagogical relations are those processes within the curriculum that give the curriculum its richness and depth. The emphasis is on the actions and interactions in the classroom. Cultural relations are the context within which the curriculum is embedded, how it interconnects with the remainder of the world. In this light, curriculum emerges and unfolds from within the process rather than being imposed by external authority (Fleener, 2002). *Rigor* (Doll, 1993) involves purposely looking for different alternatives, relations, connections, and interpretations; to continue the exploration, to accept indeterminacy. It also involves identifying hidden assumptions and negotiating the passage between those assumptions to construct meaning.

Doll's curriculum matrix, grounded in process philosophy and chaos theory dynamics, has implications for ideas about learning. Evolving from Piagetian constructivism, postmodern learning theories also are foundational for considering the impact and potential of technology, in general, and robotics, in particular, on student mathematics learning.

Learning Theory

Constructivism's modern roots can be traced, at least along one dimension, to Piaget's theory of knowing. Piaget looked at knowing from a biological perspective and described it in terms of adaptation. Just as organisms must adapt to achieve a fit with their environment, Piaget viewed knowledge as arising from a person's mental or physical activity to achieve a fit. It is this goal-directed activity that gives knowledge its organization by assimilating (or adapting it) into viable knowledge structures which he called 'action schemes' through a process called equilibration (Glasersfeld, 1995). As Piaget observed, "The mind organizes the world by organizing itself" (1937, as quoted in Glasersfeld, 1995, p. 57). These cognitive structures are developed by means of reflective abstraction, i.e., built up via "...a process of interiorizing our physical operations on objects" (Noddings, 1990, p. 8).

Von Glasersfeld (1995) called his form of constructivism "radical" for several reasons. First, the term "radical" acknowledges Piaget and his radical notion that cognition is rooted in biological function rather than impersonal, universal and ahistorical reason. Second, to distinguish it from other forms of what he calls trivial constructivism (i.e., by implication not grounded in Piaget), which merely hold that our ideas are individual mental constructions. And finally, "For the very reason that radical constructivism entails a *radical* rebuilding of the concepts of knowledge, truth, communication, and understanding, it cannot be assimilated to any traditional epistemology." (p.19). In this light, radical constructivism has two basic principles (a) knowledge is not passively received but built up by actively cognizing individuals and (b) the function of cognition is adaptive and serves to organize the experiential world, not discover ontological reality.

Lakoff and Núñez (2000) point out that this organizing and understanding of our experiential world is metaphorical in nature. They describe two types of metaphors: *grounding* metaphors that allow one to project from everyday experience and *linking* metaphors that allow the conceptualization of knowledge in one area in terms of understanding developed in another area. If human knowledge is experiential and metaphorical in nature, it is also immersed in context (Davis, 1997). It cannot be extracted or set apart. It is embodied. Davis describes contextual and embodied understanding in terms of understanding as action or enactivism.

> As such, we are constantly and inevitably enacting our knowledge; we are continuously knowing, as determined by our structures and situation. However, much of this knowing is not, and may never have been formulated in explicit terms. Much of what we do and know, in other words, is unformulated: we just do it; we just know it. ...Knowing is doing, and all doing arises from a rich and ongoing history of structural coupling with a complex and active environment. (1997, p. 193)

Polanyi's notion of tacit knowledge is in consonance with Davis' perspective on embodiment with respect to his assertion that, "...we can know more than we can tell." (1966, p. 4). The implication for the construction of meaning, then, is that the opportunity to do or show more than what can be said (or written) is essential for meaningful learning to take place. A related implication is that educational contexts need to be more open so that the written and spoken word are not the only privileged means of acquiring or demonstrating understanding. Conversely, absent opportunities for embodiment, it becomes difficult to construct meaningful understandings of mathematical concepts. Lakoff and Núñez note:

> It is of special interest that the neural circuitry we have evolved for other purposes is an inherent part of mathematics, which suggests that embodied mathematics does not exist independently of other

embodied concepts used in everyday life. Instead, mathematics makes use of our adaptive capacities—our ability to adapt other cognitive mechanisms for mathematical purposes. (2000, p. 33)

Geometry is one area of mathematics where embodiment is critical to understanding and, yet, the opportunities to embody are markedly lacking in typical education settings. For example, Berthelot and Salin (1994, p. 74) describe three ways in which we experience our space:

1. Micro space is the intimate space of interactions that can be affected without moving; e.g., a book/notebook, a desk or personal computer. It is space mainly composed of objects and it is difficult to distinguish distance from spacing.
2. Meso space is the intermediate space of domestic moves and interactions through choice of position. Moves within this space are mastered using intellectual representations of the space. A classroom would be an example of this space. The distance concept is more developed and measured in small units
3. Macro space consists of areas so large that information can only be obtained through successive moves. It is built of a collection of local views connected through travel. Distance measures are correspondingly larger.

Berthelot and Salin (1994) noted in their studies of elementary school students that lack of experiences in meso and macro spaces inhibited the construction of meaning in micro space; the space where students typically operate in the classroom. Conversely, students can act as if they have micro spatial conceptions of, say, a rectangle. Yet, if called upon to use their notion of a rectangle in a different space, they are unable to recognize, utilize or access corresponding manifestations at that spatial level.

Reynolds and Wheatley (1997) point out that concepts such as length, capacity, weight, mass, area, volume, time, temperature, and angle are ideas humans use to make sense of their environment and meaningfully communicate with each other, and they are, in effect, expressions of the spatial sense Berthelot and Salin describe. Reynolds and Wheatley (1997) assert that students' constructions of spatial ideas need to be developed in more natural settings where they can develop their own ways of comparing and measuring. Typical activities designed for efficacy in a classroom setting are activities essentially limited to micro space and Berthelot and Salin note that, "...if you limit yourself to micro spatial interactions, it is impossible to organize teaching processes which help pupils construct good space geometric models by effective interactions with space" (1994, p. 77). Dehaene (1997) points out that spatial competence correlates strongly with success in mathematics. Spatial competence is also closely tied with imagery. Lakoff and Núñez concur that imagery has a special function, being both perceptual and conceptual in nature. Imagery provides, "a bridge between language and reasoning on the one hand and vision on the other" (2000, p.31) and is kinesthetic as well as visual. This suggests that opportunities for embodiment are essential for the development of the spatial competency necessary to support the imagery that is critical to mathematics success. Moreover, it further suggests that cognition and understanding is dynamically related to our operations among and within cognitive space and these dynamic spatial operations are barely tapped in traditional educational contexts.

How can technology support efforts to engage students in the "romance" of learning and embodiment of mathematics? Are there ways or activities that offer promise for developing students' dynamic spatial operations? Seymour Papert (1980) has offered a vision of technology infused learning environments that could fundamentally alter the way we learn and address these challenges.

Technology and Mathematics

Seymour Papert has long heralded technology in the form of microcomputers and the programming language *Logo* that he developed at the Massachusetts Institute of Technology as a vehicle for the transformation of education. A protégé of Piaget, he asserts that *Logo* environments are uniquely suited to the construction of mental structures, a brand of constructivism that he calls constructionism. Papert describes the learning process in almost Whiteheadian terms. His description of his love of learning evokes Whitehead's romance of education, his endless hours of playing and manipulating the gears calls to mind the precision stage of learning. Eventually, when he sees multiplication in terms of gear ratios, this transition from play into formalization suggests the precision stage. Papert further echoes Whitehead and complexity theory when he expresses delight that a system (i.e., gears) could be lawful and comprehensible without being rigidly deterministic.

Papert makes a number of assertions for computers and *Logo* as a synergistic force in education based on two fundamental ideas: that it is possible to design computers so that learning to communicate with them is a natural process, and that learning to use computers can change the way everything else is learned (1980, p.8). In his view, the combination of personal computers and *Logo* serves as (1980, p.4):

1. A carrier of powerful ideas
2. The seeds of cultural change
3. A novel environment to help people form and explore new relationships
4. The instrument for the challenging of current beliefs and assumptions about learning

Papert's goal is to use the personal computer–*Logo* combination to help with the construction of inclusive computational cultures, namely *Logo* environments. "There is a world of difference between what computers can do and what society will choose to do with them" (1980, p. 5). For him, computers can appeal to and accommodate a thousand tastes and personalize learning. Moreover, the learning experience is more than purely cognitive. Learning is very personal and cannot be assumed to be repeatable for others in exactly the same form. Computers and technology can act as transitional objects to translate body knowledge into abstract knowledge (i.e., to translate embodied understandings into more generalized forms of understanding). As such, technology is a tool that "...instantiates the living bond between finite human being and environing world" (Blacker, 1993, Making Connections section, ¶ 19) and provides a way of revealing or opening up of the conceptual or contextual environment to new possibilities.

Papert emphasizes that students' intellectual structures are not built from nothing. Instead, children appropriate for their own use what they find at hand—a *bricolage* of models and metaphors suggested by the surrounding culture (1980) and the expanded context, the new possibilities that technology can provide.

> But to say that intellectual structures are built by the learner rather than taught by a teacher does not mean that they are built from nothing. On the contrary: Like other builders, children appropriate to their own use materials that they find about them, most saliently the models and metaphors suggested by the surrounding culture. (p.19)

His ultimate concern is the interaction of technological and social processes and how they influence the construction of ideas about human capacities. The *Logo* environment becomes a vehicle for Piagetian learning which to Papert "is learning without curriculum" (1980, p. 31). In this environment, computers become "objects to think with," in which there is an intersection of cultural presence, embedded knowledge, and the possibility for personal identification" (1980, p.11). He is concerned with how a culture, a way of thinking, an idea comes to inhabit a young mind. The child is in control of the process. Through programming the computer to think, they problematize and explore how they themselves think and, in so doing, become epistemologists (p.19).

Overview of *Logo* Research

Since its inception in the 1970's, the *Logo* computer programming language has attracted educators to its potential as a learning tool. Seymour Papert (1980) stated that the computer language *Logo* was designed as an outgrowth of two fundamental ideas; that it is possible to design computers so that learning to communicate with them is a natural process for children, "and that learning to use computers can change the way they learn everything else (p. 8)." In other words, Papert envisioned that *Logo* would fundamentally change education by encouraging active, rather that passive, learning strategies and creating an invigorated culture of learning in the classroom.

In subsequent years, educators have explored *Logo* extensively as a learning vehicle for students; particularly with elementary age students.
In the last decade, Papert's vision has been reiterated. Kaput (1992, p. 520) suggests that general purpose programming languages such as *Logo* serve as tool-makers through which students have access to and can build independently constructed tools to analyze problems. More recently, Yelland (1995) asserted that *Logo* could be used to promote higher-order thinking skills, develop flexible and creative thinkers, and strengthen problem-solving abilities.

Much has been claimed for *Logo*, but does it really fulfill Papert's vision? Some have called the efficacy of *Logo* into question. Subhi (1999) notes that there has been considerable debate in the past decade about the benefits of *Logo* for children in general. So what does the research record say about *Logo*? Are Papert's claims supported? What trends have emerged from the record?

Logo Research Trends

With respect to learning theory and *Logo* environments, it seems clear that *Logo* is consistent with constructivist notions of learning. Researchers are actively studying many aspects of *Logo* and it is apparent from the research and even the most casual Internet search that there are some educators actively using *Logo* in the classroom. As far as the demographics of *Logo* use is concerned, there is a paucity of information. There doesn't seem to be any evidence that *Logo* is being employed in any significant way in the U.S. educational system. In my own experience, I was the only teacher in my district at the middle school level using *Logo* in the classroom. My district was a large suburban school district consisting of 3,600 students in four middle schools. The district dropped *Logo* from the middle school computer education curriculum over four years ago. Moreover, the *Logo* that had been taught had only been taught from a computer science/programming perspective, which was at odds with what Papert advocated. Recently, *Logo* has resurfaced in the Technology Education curriculum in our state with the incorporation of Lego Dacta activities. However, it is employed in a manner more consistent with cookbook-like, programmed learning than the constructionism of Papert.

Likewise, the answer to the technological obsolescence question is similarly unclear. The original *Logo* involved using Apple computers programming physically real electronic turtles wired to the computer. Students actually programmed the turtle's movements about the classroom. With the advent of sophisticated graphics user interfaces in Macintosh and Windows personal computers, the turtle became a virtual object or objects to be manipulated by students. This move away from actual physical turtles arguably meant that the original learning context Papert intended for *Logo* had been lost. However, with the advent of Lego Dacta and the Mindstorms autonomous processor this trend away from interaction with a physical turtle could be countered. Interestingly, I could find no *Logo* studies involving these potentially powerful educational tools; perhaps because of their relative novelty.

A second trend with respect to the *Logo* studies reviewed is that almost all were directed at elementary age students. Older students are all but totally ignored. Few studies can be found addressing *Logo* and learning involving middle school or junior high students. Even fewer are directed at high school students. Of the studies I reviewed, only one involved middle school students (Edwards, 1991) and two involved ninth and tenth grade students (Cope & Simmons, 1991, Olive, 1991). As a former middle school teacher who used *Logo* in the classroom, I believe that *Logo* and *Logo*-type environments have numerous and largely unexplored applications to engage students who are beyond the primary level. The apparent lack of research interest is dismaying, especially given the length of time that *Logo* has been available.

Third, a similar and equally disconcerting omission is made with regard to pre-service and in-service teachers. I could locate only two studies on *Logo* in which teachers were the participants. One (Schibeci, 1990) addressed using *Logo* to help pre-service and in-service primary education teachers to change their views of themselves as learners and the extent that they were able to develop problem-solving strategies in the context of a course in "cultural mathematics" designed to explore the nature of mathematics. The second study (Hoyles & Noss, 1992) attempted to address what a viable pedagogy looks like in a *Logo* context.

The lack of studies involving *Logo* could be a clue as to why *Logo* use is not more widespread. Perhaps schools of education are not providing their graduates with any experience in *Logo*. My guess is, probably not. Absent this experience, my surmise is that the only teachers who ultimately employ *Logo* in the classroom are either technophiles who seek out *Logo* and recognize its value for their teaching or those teachers fortunate to be employed in a district or site where *Logo* has already established a foothold. It is unclear as to why the existing research has focused almost exclusively on students and ignored educators.

A fourth trend emerging from the review has to do with the type of *Logo* studies conducted. The preponderance of the studies reviewed was qualitative in nature. And, from some of the commentary I was able to obtain (Bracey, 1989), this is apparently a reversal of the quantitative trend of *Logo* studies from the 1980's. According to Bracey, Papert rejected much of the previous *Logo* research mainly because it asked overly simplistic questions like "What is THE effect of THE computer on cognitive development? (p. 14)" or focused on programming skills and ignored the effect of context of the learning environment or the effects of *Logo* on the construction of students' cognitive structures. Clements and Meredith (1993) point out that many of the studies presumed that mere exposure to *Logo* and mathematical concepts was all that was required for children to gain understanding. Moreover, Clements and Meredith assert that *Logo* detractors ignore four important issues:

1. Researchers do not know how to measure all that is educationally valuable. Traditional studies manipulating one variable use measures that do not fit with meaningful education reform.
2. *Logo* possesses the power to significantly enhance the educational experience when an active, constructivist approach is taken to the learning process.
3. There is no single best method of assessing the effects of *Logo*. Multiple measures and perspectives must be examined.

4. Mediated *Logo* environments enrich many different aspects of students' lives. Few educational environments have consistently shown the breadth of scope, mathematical, cognitive, social, and emotional effects that *Logo* has.

In several studies, students were given minimal introduction to *Logo* and largely left to their own devices, sort of the pedagogical equivalent of handing an aircraft manual to a novice pilot and expecting her to fly you to Los Angles after reading it. Unsurprisingly, the results minimized the contribution of *Logo*. Clearly, many of these early studies were conducted from a behaviorist or cognitive, rather than constructivist, perspective. This has gradually changed throughout the 1990's.

Most of the qualitative studies throughout the 1990's were traditional case studies undertaken from an empirical, modernist perspective. But as the decade continued, more studies began reflecting a constructivist perspective more in consonance with Papert's ideas for *Logo*. This progression can be seen in many of the studies involving Clements (1989, 1990, 1991, 1995, 1997, 1998, 1999) where the types of questions asked have increasingly reflected more of a constructivist framework. Other studies took more of a situated cognition perspective (Yelland, 1994, 1995). This trend appears to reflect the increasing crossover of post-modern educational discourse into the research agenda. However, none of the studies I reviewed reflected what I would term an enactivist perspective.

Another interesting trend was that several studies noted that *Logo* environments seemed to be more encouraging for female students. Yelland (1994) noted that children's problem-solving strategies may be gender related. In her study involving student pairs, she noted all female pairs made more, but more accurate moves with their turtle and interacted more often with each other than all male or mixed gender pairs. Certain task weightings, such as accuracy over speed, favored female pairs. By the end of the study, however, the all female pairs were able to move the turtle in the quickest and most accurate manner. She emphasized the need for teachers to understand that the criteria and type of task selected in problem-solving exercises may adversely affect the performance of some students and that performance based tasks should consider samples collected over a period of time.

In terms of topics, most of the studies reviewed addressed the effects of *Logo* on mathematical understanding, principally geometric understanding, although other mathematics topics were explored. *Logo* has been proposed as useful in teaching mathematical concepts such as measurement or geometric figures. Clements *et al.* (1989, 1990, 1993, 1995, 1997, 1998) and Clements (1991, 1999) noted problem-solving strategies similar to Kapa in the methods elementary students used. Commanding the *Logo* turtle to move helps students focus on intervals as units of length, rather than discrete points. The visual feedback provided by the turtle facilitates students' recognition that successive moves of forward 20, forward 70 and back 30 could be replaced by one move of forward 60. Students using *Logo* readily and easily verify this conclusion and they are provided with immediate and visual feedback.

Clements and Sarama (1997, 1998) explored the effects of *Logo* on algebraic thinking, concluding that *Logo* can provide an entry into algebraic thinking but their ability to generalize may depend on the depth of their experience and the instructional support given them in making the generalization. They also note that concepts like variables and functions are integral to *Logo*. It provides an environment in which their use is natural and part of normal *Logo* activities. The authors go on to observe that technologies such as *Logo* are less a pedagogical tool and more a mathematical tool.

Steffe and Wiegel (1994) looked at the effects of cognitive play via *Logo* microworlds on mathematical learning. They identified three types of student activities in the microworlds context: cognitive and mathematical play, teacher-directed mathematical activity, and independent mathematical activity. They noted the importance of teacher directed activity for initiating transformation of a situation from cognitive play into mathematical activity. Also noted was social interaction as an important factor between students, as well as, between teacher and students. Teacher-introduced constraints successfully encouraged students to select their mathematical schemes in novel situations and through their acting, the situations correspondingly changed and new possibilities for action emerged in the context of *Logo* microworlds.

Subhi investigated the impact of *Logo* on mathematics achievement and creativity for gifted third graders' in Amman, Jordan. Two-hundred seventeen students were randomly assigned into groups; half of which were given 45 minute *Logo* workshops twice a week over a period of three months and half attended a similar number of mathematics computer assisted learning (CAL) sessions. He found that the *Logo* programming environment improved gifted children's mathematics achievement and creativity. In contrast, the CAL groups scores on achievement and creativity decreased from pre to post test scores with the repetitiveness of CAL cited as a factor in creating frustrated and bored students. Subhi noted that the ability to monitor one's own thinking may also be positively affected by problem-solving in a *Logo* environment and that the students may benefit from the consistent visual feedback on their programs and thinking that *Logo* provides.

Kapa (1999) explored whether *Logo* environments increased problem-solving control, planning ability and sharing processes in comparison with individual learning for fifth grade students. His study compared two groups; one working with *Logo* and another with a word-processing program. Three levels of planning strategy were observed (in order of sophistication from least to greatest); trial and error, step-by-step (i.e., working from the details to develop a general plan), and holistic planning (i.e., top down, working from a plan to develop the details). He concluded that *Logo* improved problem-solving with significantly more students in the *Logo* group developing holistic problem-solving strategies than in the word-processing group. Like Subhi, Kapa noted that, "One of the key features that characterizes problem-solving in a *Logo* environment is the added awareness of every step taken while solving a problem due to immediate feedback. Within a problem-solving-based *Logo* environment students become explicitly aware of their problem-solving processes and their planning strategy" (1999, p.79).

With regard to the educational uses of *Logo*, Clements and Meredith/Sarama (1993, 1997) proposed several implications. First, that merely exposing students to *Logo* is not enough. Teacher mediation is required to provide structured tasks, clarify and extend the ideas of students as they develop. With mediation, *Logo* can provide the tools students need to evaluate their own ideas and learning. A second implication, mentioned by Clements and Sarama, is that *Logo* is potentially important for populations at-risk in mathematics, such as females and minorities. Several studies have suggested that *Logo* is beneficial to these groups because it may allow the students to have a sense of mastery over their environment, builds upon their responsiveness to visual and auditory cues, and supports collaborative learning. Another implication is that mathematics classes should revise and expand their traditional activities so that children are required to use higher-level thinking. In other words, higher-level thinking should extend beyond students' encounters with *Logo*.

A number of observations can be extracted from a review of *Logo* research conducted by Clements and Meredith (1993):

1. *Logo* enhances mathematics achievement. It hasn't been determined whether any type of exposure leads to increased achievement, based on test scores.
2. *Logo* can help children learn higher levels of geometric thinking. Primary school students, after using *Logo*, see shapes as created by actions and can explicitly mention properties of shapes, indicating the development of descriptive thinking.
3. *Logo* students are more accurate in measurement tasks.
4. *Logo* enhances the understanding of variables for students from the primary grades to high school.
5. *Logo* may increase problem-solving ability, especially when teachers actively mediate their students' problem solving.
6. The act of debugging *Logo* programs provides students with valuable experience in using their monitoring skills. Students learn to extend self-monitoring of problem-solving beyond *Logo* environments.
7. Students with *Logo* experience are more likely to interact with peers, engage in group problem-solving, and receive peer social acclaim, especially "loners". Social interaction is facilitated.
8. *Logo* students talk more about learning than non-*Logo* students.
9. Students working with *Logo* are prone to help and teach one another.
10. Students in *Logo* environments are more likely to be self-directed, show pleasure at discovery, and accept responsibility for their actions.

However, along with the benefits, Clements and Meredith also note some of research-based cautions regarding *Logo* in education:

1. Mere exposure to *Logo* is insufficient. Thoughtfully structured tasks are required to precipitate the construction of mathematical concepts.
2. None of the studies reviewed reported mastery of mathematical concepts investigated.
3. Without mediation or guidance from educators, student misconceptions can persist.
4. Some studies showed no significant difference between the *Logo* and control groups. Moreover, some studies showed limited transfer or generalization outside of the *Logo* environment. For example, students may create one idea of a variable in *Logo*, and use a different conception in math class, not recognizing the similarities.
5. Some students may rely excessively on visual cues and not work analytically.

Summary of Logo Research

Clearly, the implementation of Papert's vision has been problematic. *Logo* has been around for almost thirty years now, yet it remains controversial, and numerous studies since its advent have been inconclusive (Palumbo, 1990; Scott, Cole and Engel, 1992; Clements and Sarama, 1993) although more recent reviews of the field have been more positive (Clements and Sarama, 1997):

The results of these studies have not been spectacular. In almost every case of a significant difference, the students using a computer orientation performed better than the control students. However, about the same number of studies reported no significant differences. (Begle, 1979, p. 118)

A review of research almost a decade later causes one to have mixed feelings about the impact of computer use on mathematics education in the 1980s. Recent research findings do not support a definitive case for computers in mathematics education. (Redekopp, 1989, p. 169)

Some researchers report significant gains and even dramatic learning changes for as many as 10% of students. Others, though, reveal mixed results or no significant differences between Logo and control groups. (Clements and Meredith, 1993, p.264)

The areas that have caused the most discussion have been related to the issue of cognitive gains, both in general problem-solving skills and in mathematics achievement, and in relation to the transfer of specific skills. These aspects will no doubt continue to be debated for some time. (Yelland, 1995, p. 866)

> Depending on the environment in which it is embedded, Logo can constitute a trivial enterprise or a variegated educational experience. We claim that few educational environments have shown as consistent benefits of such a wide scope, from the development of academic knowledge and cognitive processes to the facilitation of positive social and emotional climates. (Clements and Sarama, 1997, p. 36)

That these statements reflect reviews of studies done over a span of more than 25 years is an indication that *Logo* has yet to gain a firm footing in education. As a result, its acceptance into mainstream education culture has been lukewarm. Indeed, many educators consider *Logo* and *Logo* environments to be a dead issue (Kozburg, 1996) and some school districts (including my former district) have removed *Logo* from their curriculum. "Most people haven't heard of Logo. Those people who know about it often have a view that is stuck back in the early 1980s" (Temple, 1998, ¶ 2). The basic reason appears to be twofold: the mixed research record undercuts the positive aspects of *Logo* environments and the attempted assimilation of *Logo* into the education establishment through the computer science/programming perspective.

> An examination of computer use in schools today reveals that students' interactions with computers are largely teacher-directed, workbook-oriented, for limited periods of time, and confined to learning about the machines themselves or about programming languages.

> Further, computers are located in separate labs and not integrated into the standard curriculum. "Doing computer" in school is thought of as an exciting activity in and of itself. This separation is reflected in the often asked question: "Does what children learn with the computer transfer to other work?" The present separation of computers from other curricular areas is reflected too in arguments about whether computers might even be bad for children. (Franz and Papert, 1988, p. 408)

As the above statement shows, many of the research arguments of the eighties remained the arguments of the nineties and are likewise extant today. Such as the nature of the cognitive and social-emotional benefits of *Logo* environments and whether there are significant academic and transfer of learning benefits. While the former have become more established, the latter remain problematic, I believe there may be several reasons for this: (a) The research provides conflicting answers depending on which study is examined. At times, it almost seems like there is a *Logo* version of the perennial Apple versus PC superiority argument going on. (b) Computer technology has changed so rapidly during the same period that implementing *Logo* was lost in the maelstrom of schools adapting to changing technology requirements and managing equipment rapidly becoming obsolescent (Clements and Swaminathan, 1995). (c) The emergence of post-modern perspectives on learning has called the outcome of many older studies into question (Agalianos, 1996; Bruce, 1998; Bopry, 1999; Travers and Decker, 1999; Shaffer and Kaput, 1999, Rosow, 2000; Solomon, 2000; Fleming and Raptis, 2000). (d) A countervailing conservative trend of back-to-basics and the re-emergence of traditional perspectives of what it means to know and demonstrate knowledge of mathematics (Hu, W., 1997; Dixon, Carnine, Lee, Wallin, & Chard, 1998; Schoen, Fey, Hirsch, and Coxford, 1999; O'Brien, 1999) and, (e) Not many colleges of education require technology fluency beyond basic email, word processing, and building rudimentary web pages; or have faculty that employ or model it significantly in the classroom themselves, much less introduce their students to *Logo* environments in a meaningful way (Northrup and Little, 1996; Persichitte, Tharp, and Caffarella, 1997; Moursund and Bielefeldt, 1999, Schrum, 1999; Hornung and Bronack, 1999; Willis, Thompson, and Sadera, 1999; Whetstone and Carr-Chellman; 2000, Bielefeldt, 2001; Brown, 2001; Ferguson and Mahoney, 2001).

If Davis and other enactivist theorists and educators are right, it is not enough for students to program the procedures and observe the results on the computer screen. Action/enaction and opportunities for embodiment are required. A piece is missing from Papert's technological vision that this study addressed. The next chapter discusses the design of this study.

Chapter 3

CONTEXT AND METHODOLOGY

What we learn is determined by what we know. (Reid, 1996)

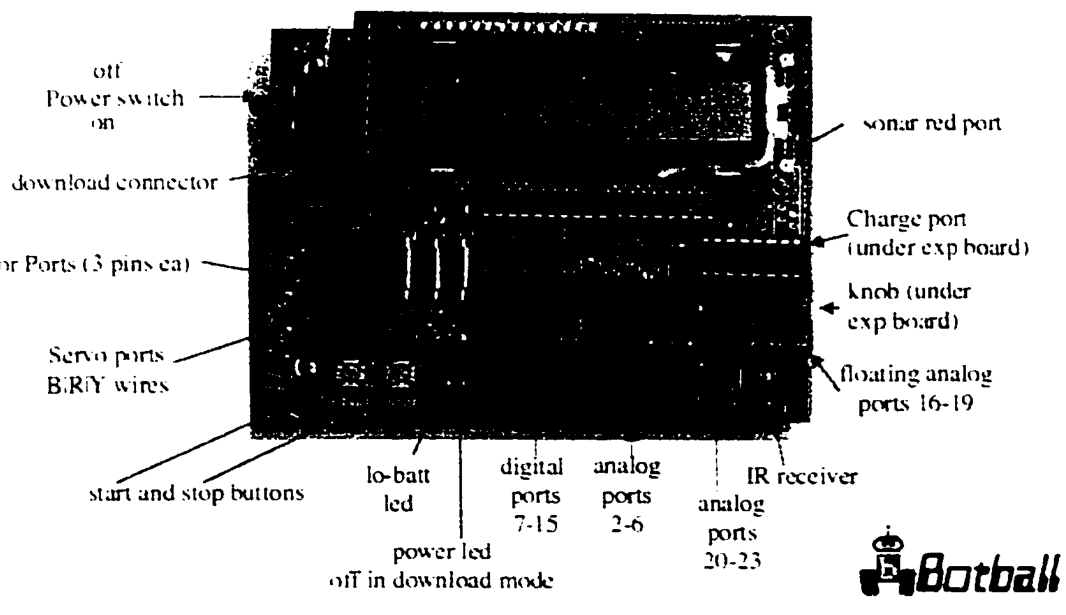
This chapter discusses the background, research design and methodology used in my study. As stated previously, the purpose of my study is to attempt to identify and describe the context of mathematical activities and the emergent conceptual constructions of students as they engage in open-ended problem solving involving building and programming autonomous robots. First, background on the robotics activities and preliminary studies conducted at the site is provided. This is followed by descriptions of the study design and methodology used.

Background

Botball

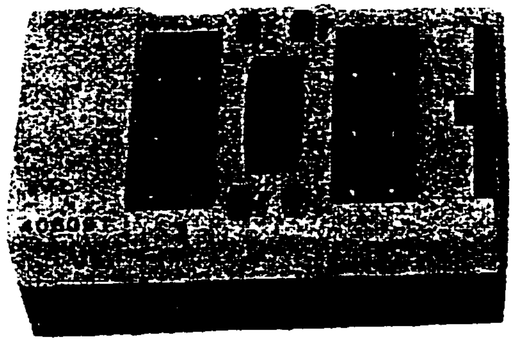
Botball is a six-week 6-12, inter-school robotics competition sponsored by the KISS Institute for Practical Robotics (KIPR). The entry fee is $2,000. This is a significant amount of money for many schools. However, most of the fee covers the cost of the Botball supplies such as the microprocessors, sensors, and Lego parts in addition to partially defraying the cost of the competition. Additionally, teams may apply for financial aid from KIPR to offset a portion of the fee. Teams that choose to enter the competition receive two small processors (a Handy Board and a Lego Mindstorms™ RCX microprocessor), *Interactive C* software for programming the microprocessors, various sensors for both microprocessors (see microprocessors in Figures 1 and 2 and list of sensors in Table 1), and Lego parts for constructing their robots. The sponsors and mentors attend a three-day workshop that introduces the basics of robotics, the *C* programming language, the Botball parts, and that year's competition rules. After the workshop, the teams have six weeks to design, build and program robots to compete against other teams' robots in a competition arena such as that shown in Figure 3 (see Appendix A for the contest rules and problem descriptions).

Figure 1 *Handy Board Microprocessor*



Note: From "Botball 2002 Teachers Workshop" presentation by D. Miller, KISS Institute for Practical Robotics, January 2002, Norman, OK. Copyright 2002 by KISS Institute for Practical Robotics (www.botball.org). Adapted with permission.

Figure 2 *Lego® Mindstorms™ RCX Microprocessor*



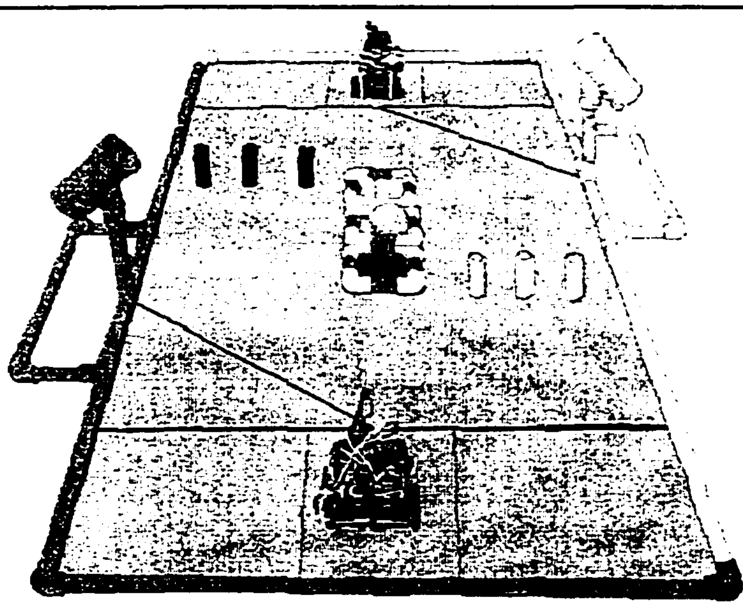
Note: Motor ports are lettered: A, B, and C. Digital sensor ports are numbered: 1, 2, and 3. From "Botball 2002 Teachers Workshop" presentation by D. Miller, KISS Institute for Practical Robotics, January 2002, Norman, OK. Copyright 2002 by KISS Institute for Practical Robotics (www.botball.org). Adapted with permission.

Table 1 *Robotics Sensors for 2002 Botball Competition*

Sensor	Analog	Digital
Light	4	
Reflectance:		
Handyboard	2	
Lego		1
Range Finder	2	
Sonar	1	
Slot Sensor/Encoder		2
Contact/Touch:		
Lever		2
Post		2
Button		2
Lego		2
Knob (Handy Board)	1	
Start & Stop Buttons (1 each, on Handy Board)		2

Each year, the competition problem and arena layout changes (see Appendix A for details). The competition has two major components: (1) To build and program a robot or robots for the arena competition, and (2) To research and build a website that addresses some speculative problem such as designing an autonomous robot capable of being sent to the Moon to conduct an archeological exploration of one of the Apollo lunar landing sites (Miller, 2001). As my interest was in the opportunities for embodiment and emergence of mathematical understanding in the context of the robotics activities, the focus of the data collection for this study was on the first component of the competition.

Figure 3 *2002 Botball Competition Arena*



Note: From "Botball 2002 Teachers Workshop" presentation by D. Miller, KISS Institute for Practical Robotics. January 2002, Norman, OK. Copyright 2002 by KISS Institute for Practical Robotics (www.botball.org). Adapted with permission.

Robotics Club

The Botball competition sparked an interest by students in extending robotics activities beyond the allotted six weeks. In the past year, the students formed a Robotics Club that met weekly after school. During club meetings, the students proposed and selected their own competition problems. Then they designed, built, and programmed robots to address their self-imposed challenges.

Robotics Cluster

In addition to the team and club, a Robotics Cluster (i.e., mini-course) was held each of the last two semesters. The Clusters were held once a semester for two consecutive weeks (i.e., 10 school days). The Clusters were made possible by borrowing five minutes from several class periods throughout the school day to expand the site's advisory period from 25 to 45 minutes, during which the Clusters were held. Teachers or students with sponsors could offer a Cluster on a topic of interest. If sufficient students sign up, the course "makes" and is held.

The Robotics Clusters were initiated with the intention of encouraging more students, especially female students, to become involved in robotics activities. Due to the time constraints involved, the Cluster sponsor and student facilitators jointly developed a simpler problem for the participants to address using one of the Botball arenas. A competition is held on the final day and trophies and ribbons are awarded (see rules in Appendix A). Again, the facilitators and sponsor jointly judge the competition. The Botball team, Robotics Club, and Robotics Cluster are open to students of all backgrounds and include students in the site's talented and gifted program, as well as those served by the special education program. Of note, three of the five student facilitators for the spring Robotics Cluster were special education students.

Preliminary Studies

Preliminary studies were conducted beginning while I was a faculty member at the site two years previous to this study. The preliminary study continued the following year, immediately preceding the study, once I had left the site's faculty to become full-time graduate student. Another graduate student and I collaborated to collect data throughout these preliminary studies, including observations, audiotapes and interviews. Some of this data from the year immediately preceding the study was used as a few of the participating students were involved in the robotics activities over the course of several years.

Study Design

This study was a phenomenological study in the naturalist paradigm (Guba & Lincoln, 1989) that drew upon enactivist research methodology as described by Reid (1996, 2002). According to Moschkovich and Brenner (2000), studies conducted from the naturalistic perspective have three essential features: (1) They consider events from multiple points of view, (2) Theory verification is connected with theory generation, and (3) Cognitive activity is studied in context. From an enactivist perspective, learning is seen as continual change that allows continued individual functioning and is structurally determined. Similarly, researcher learning through interaction with the data is determined by the researcher's structure (Reid, 2002). This structure simultaneously co-emerges with, and is constrained by, the environment, including the various forms of data and interactions with the study participants. To an enactivist, the environment is not seen as an "other" external to self. Instead, we are immersed in, inseparable from our environment and mutually co-emergent.

Co-emergence thus serves as an organizational theme of enactivist methodology and is engendered through the vehicle of multiple perspectives. Reid (2002) describes three ways in which perspectives can be multiple.

> Perspectives can be multiple over *time*, as in the interaction between a researcher and a videotape watched repeatedly, or over *form*, as in the interaction between a research (*sic*) and data represented on video and then as a transcript. In the first case the structure of the researcher is different because structures change continuously over time. In the second case the form of the data creates different constraints on the researcher's learning. Perspectives can also be multiplied *socially*. An enactivist researcher seeks to interact with others, not to arrive at a single, taken-as-true perspective, but instead to explore the complexity of perspectives offered by different structures. (p. 10)

Study Participants

The study took place entirely at the suburban middle school described earlier in Chapter 1. Sixteen male and female middle school students participated. The participants consisted of a purposeful sample of volunteer students in grades six through eight. Their academic backgrounds were diverse as academic standing was not a condition of participation, neither in the robotics activities nor in the study itself. Tables 2, 3, and 4 provide additional information about the study participants.

Table 2 *Age of Study Participants*

Age	Number of:	
	Males	Females
12	4	2
13	4	1
14	2	0
15	1	0

Table 3 *Grade Distribution by Subject*

Subject	A	B	C
Science	8/1	3/2	
Social Studies	9/3	1/0	1/0
Mathematics	7/1	2/2	2/0
Language Arts	8/2	3/1	

Note: Grades are listed as number of males/number of females.

Table 4 *Participation in other School-Sponsored Activities*

Activity	Participants: Male / Female
Sports	6/1
Band/Orchestra	6/2
Choir	4/0
Talented & Gifted program	8/1
Academic Competitions	4/0
OU Academy	7/1
Drama	3/1

Meeting times varied depending upon the type of robotics activity being studied. The Botball team met for multi-hour sessions two to three times per week for six weeks. The Robotics Club met once per week for two hours exclusive of the Botball competition phase. The Robotics Cluster was offered once per semester. It consisted of a two-week mini-course (10 consecutive school days concluding with a Cluster competition, see rules in Appendix A) that took place during an expanded 45-minute advisory period, each day during the ten-day Cluster. These activities together constituted the sources of the data needed to complete my study

Data Collection

Data to address these questions was collected from multiple sources. Video and audio recordings of participant activities, interactions, and interviews were the primary source of data. Field notes were taken during each robotics activity session to supplement the recordings and capture my perspective of the activities. Study participants were informally interviewed on an ongoing basis throughout the course of the study in order to explore their mathematical constructions. Additional information was drawn from participant artifacts such as the *C* programs students wrote, the Cluster and Robotics Club challenges they designed, the robots they created and the team's contest web site (see Appendix B for website documentation and student log). Data collection continued until there was an exhaustion of sources and a clear emergence of conceptual categories.

In addition, key informants were drawn from a cross-section of the students, with respect to gender and ethnicity, and representative of the small groups formed. They were interviewed (see Appendix C for guiding questions) and asked to reflect and explain why certain actions were taken. In addition, they provided member checks of my own observations, constructions of their thinking, and conclusions. These interviews were also audio and video recorded and supplemented by a survey (see Appendix D). The key informant interviews, observations of students working in their task groups problem solving, other participant interviews and external auditors/peer debriefings were used to provide multiple perspectives and interpretations of the events. As Reid (1996) points out, the aspects of multiple perspectives are, in practice, inseparable. In this study multiple perspectives were accommodated in the following ways consistent with enactivist methodology:

1. Over time:
    a. Repeated viewing of videotapes
    b. Repeated listening to audiotapes
    c. Repeated reading of transcripts
    d. Significant ongoing interaction with study participants
2. Over form:
    a. Videotapes
    b. Audiotapes
    c. Transcripts
    d. Interviews
    e. Surveys
    f. Field notes, observations, and reflections
3. Socially:
    a. Ongoing interactions with study participants
    b. Trusted agents
    c. Key informants

Procedures

Using enactivist methodology to inform the study, I acted as a researcher as teacher (Cobb & Steffe, 1983) while simultaneously fulfilling three basic roles as described by Resnick (1997, p. 50):

1. An *observer* of the participants' activities and interactions

2. A *catalyst* to propose experiments to participants, ask them questions, challenge their assumptions, and encourage the participants
3. A *collaborator* who works alongside the participants to help students in their sense-making while clarifying my own thinking

In particular, as a volunteer mentor, I met with the students during their after-school meeting times for the Botball team and Robotics Club and also during the school day for the two-week Robotics Cluster. The robotics sessions were periods of extremely intensive activity for the students and me. Often, I was required to act simultaneously as observer, mentor, participant, and data recorder as students engaged in their robotics problem solving. The roles were so interwoven that I could not realistically separate them. This complicated data collection necessitated extensive reliance upon the video and audio taping of the activities, often unmonitored, for later review. To date, a number of students have participated in preliminary studies involving the Robotics Cluster and Botball team/Robotics Club. Data collection included participants in each of the three robotics activities as they were offered.

As mentioned previously, the study addresses the following questions:

1. What mathematical understandings emerge as students engage in robotics activities?
2. How do students working cooperatively organize their efforts and negotiate meaning as they solve complex, open-ended robotics tasks?

Interpretive Framework and Data Analysis

As individuals' and groups' mathematical activity is believed to be interdependent, students' participation in the task groups and their discussions should give insights into their individual mathematical development. Theory and data are seen to co-emerge through the participation of the researcher (Reid, 1996). This interaction of theory and data transforms data analysis "into a continual process of change" and becomes the mechanism for the researcher's continued learning (p. 206). Particular attention was given to evidence of opportunities for the embodiment and the construction of mathematics.

Another purpose of this phenomenological study was to provide a thick description of the participants' problem solving activities. The goal was to construct a rich tapestry of the participants' efforts to organize their problem solving activities and negotiate meaning. As much detail and context as possible was captured so readers could conceptualize this type of open-ended learning environment and its potential for themselves.

A constant comparison method of analysis guided the investigation of socio-mathematical interchanges that might lead to individual mathematical constructions (Strauss & Corbin, 1990). After each session, I examined the data, which I first separated into specific event sections as frames in which to focus subsequent observations, interactions, and interviews. I coded and categorized each of these data sources within each event, looking for regularities and patterns in the ways students and teacher or students and students mathematically interacted within and then across sets. As new ideas, questions, and areas of interest emerged from the data, they were folded back into key informant interviews for checking.

Trustworthiness

In naturalistic studies, the quality that establishes the credibility of a study is its *trustworthiness* (Guba & Lincoln, 1989; Erlandson, Harris, Skipper, & Allen, 1993; Moschkovich & Brenner, 2000; Schwandt, 2000). Trustworthiness is the construct used to address issues of the rigor and objectivity of the data collected in naturalistic studies. Since multiple constructions of reality are assumed, any descriptions of those constructions must therefore have a subjective character. Also, as opposed to making claims of objectivity and denying the existence of bias, the researcher's perspective is presumed to be inherent in the study and acknowledged through description. Guba and Lincoln (1989) describe four aspects of quality that are common between naturalistic and traditional research practices: (a) truth value (b) applicability (c) consistency and (d) neutrality (Moschkovich & Brenner, 2000, p. 478). Table 5 shows the relationship between these aspects of quality and the strategies used in this study to address them.

Table 5 *Standards for Naturalistic Research*

Dimension of Quality	Traditional Term	Naturalistic Term	Sample Strategies
Truth value	Internal validity	Credibility	- **Prolonged engagement** - **Persistent observation** - **Triangulation** - **Member checking**
Applicability	External validity	Transferability	- **Thick description**
	Generalizability	Analytical generalizability	- **Purposeful sampling** - Multisite designs - Critical case selection
Consistency	Reliability	Dependability	- **Audit trail** - Multiple researchers - Participant research assistants - **Recording devices**
Neutrality	Objectivity	Confirmability	- **Audit trail** - **Defined researcher role**

Note: Strategies denoted by **bold** print were used in this study to address trustworthiness. From "Integrating a Naturalistic Paradigm into Research on Mathematics and Science Cognition and Learning," by J. Moschkovich and M. Brenner, p. 479. In A. Kelley & R. Lesh (Eds.), *Handbook of Research Design in Mathematics and Science Education*, 2000, Mahwah, NJ: Lawrence Erlbaum Associates. Copyright 2000 by Laurence Erlbaum Associates. Table adapted with permission.

Credibility addresses the fit between the constructed realities of the participants and the reconstructions of their constructs (Guba & Lincoln, 1989). The strategies used in this study to deal with credibility included:

- Prolonged engagement is a means of accounting for distortions in the data by spending sufficient time in context to make an account of the various influences. Prolonged engagement also helps in building trust between the researcher and participants and enabling the researcher to make the determination of when the data are no longer generating new insights.
- Persistent observation allows the identification of the characteristics of the situation that are most pertinent to the study and adds depth to prolonged engagement.
- Triangulation is used to cross-check specific data of a factual nature (Guba & Lincoln, 1989, p. 241) by drawing upon multiple sources to confirm the data.
- Member checking is used to check preliminary data and interpretations with study participants.

Transferability is the naturalistic counterpart to external validity or generalizability. Transferability is the process of checking between originating and receiving contexts for applicability. In naturalistic inquiry, the responsibility to determine transferability, or relevance, is left to the reader/receiver. Thick description and purposeful sampling were used in this study to assist the reader in determining transferability.

Dependability has to do with providing evidence that if the study were replicated with the same or similar participants and context, the findings would be similar. Providing an audit trail of documentation and a running account of the research process accomplishes this. In addition, audio and digital video recordings were used extensively for data collection.

Confirmability is the naturalistic term that addresses how the biases of the researcher are dealt with in the study. It addresses the question of how well the "data, interpretations, and outcomes of inquiries are rooted in the contexts and persons apart form the evaluator and are not simply figments of the evaluator's imagination" (Guba & Lincoln, 1989, p. 243). In this study, confirmability was addressed by explicitly describing the researcher's role in context to help identify biases and by means of establishing an audit trail so that the data can be tracked to their sources.

In my role as a researcher/participant, I tried to establish rapport, observe and listen carefully, be available to assist with participants' interactions and reasoning without being directive, ask questions that encouraged participants to reflect on their own thinking, and remain consonant with the trustworthiness criteria discussed above. All the while, I tried to remain alert to emerging patterns that would illuminate the questions that are posed by this study.

Chapter 4 presents the data that were collected during this study. The data is organized around two principal themes: (1) the typical types of problems that the team members encountered in building and programming their robots, and (2) the mathematics involved in the robotics activities. Remarks are included to help the reader make sense of the data as presented.

Chapter 4

RESULTS AND DISCUSSION

Just as an individual's structure changes in changing the context, so our expectations change as we observe, interview, and analyze according to our expectations. (Reid, 1996, p. 208)

This chapter presents, discusses, and analyzes the data collected in my study. The data described here were collected between December 2001 and May 2002, except as noted. First, I provide an overview of survey conducted with the team members. Next, I describe the organizing efforts of the Botball team and typical categories of problems the team members encountered. This leads to a discussion of the mathematics that emerged from the robotics activities and, finally, a summary of data is presented.

The problems the students confronted in their robotics activities were varied and exhibited multiple levels of complexity. For example, once the Botball team members were given the competition problem, they had to organize, strategize, build and program the team's robots. The problems that the students tackled as they built and programmed the robots led them to make further decisions which in turn affected the design and operation of the team. During this iterative process, strategies were modified on the basis of what the students learned from their problem solving and their reflections about the possible implications for the competition.

The themes that emerged from my persistent observations of and reflections on this process as derived from video and audio tapes of the team sessions, interviews of team members and key informants, survey responses, my notes and recollections, and peer debriefing are discussed in this and the subsequent chapter. The ensuing paragraphs attempt to present a montage of the participants' robotics efforts. It is a montage in the sense that a series of vignettes and other data are used to build a composite sense of the whole. As such, it does not so much present truth as represents my sense-making of the activities of the team. The study was approved in accordance with the University of Oklahoma Institutional Review Board procedures (see Appendix E) and parent consent and participant assent forms (see Appendix F) were secured for each of the participants. Pseudonyms were used to preserve the anonymity of the participants. I begin the discussion of the data with a survey the participants completed.

Participant Survey

After the regional Botball competition had been held, I conducted a survey of the team members. There were several reasons for conducting the survey. First, I wanted to gather some background demographic information about the students. Second, I wanted to add another perspective to my own observations regarding their attitudes regarding the robotics activities. Finally, I hoped to gain additional insight into what relationship, if any, that the team members saw between the robotics activities and their experiences in school, and mathematics in particular.

In addition to the demographic data reported in chapter three, the survey consisted of 14 statements for the team members to respond to according to a 5 point Likert scale (See form and results in Appendix D). A selection of 1 in response to a statement indicated strong agreement. A selection of 3 indicated neither disagreement nor agreement with the statement and a selection of 5 indicated strong disagreement with the statement. In addition, there was one free response question, "On the back, please suggest ways that robotics could be used to help understand math." Responses to the Likert scale are compiled in Table 6.

Table 6 *Survey Results*

Statement	Response: Question # / Stem	Response: Leaves
I enjoy building robots.	01	11111111111 222
I enjoy programming robots.	02	111111 222 333 4 5
I enjoy school.	03	1111 2222222 3 4 5
Working with robots is related to what I learn in school.	04	11 22 333333 444 5
Working with robots helped my understanding in Science.	05	1111 22 3333 4444 5
Working with robots helped my understanding in Math.	06	111 2 333 4444 555
Working with robots helped my understanding in other classes (please list here): Participant responses: Technology Education (1), Language Arts (1), Social Studies (1), Reading (1)	07	1111 2 33333 4 555
Building robots is related to mathematics.	08	1111 2222 333 4 55
Programming robots is related to mathematics.	09	1111111111 22 4 5

Table 6 *Survey Results, continued*

If I had a choice, I would prefer to work with other people on a project.	10	11 22 33333333 55
I enjoy working with others to build and program robots.	11	1111 2222 33333 4
Robotics could be used in school to help understand subjects	12	111 222 33333 4 55
I had some experience building things with Legos, K'nex, and erector sets, etc., prior to robotics.	13	1111111111111 5
I had some programming experience prior to robotics.	14	11111 22 3 4 55555

Notes: 14 respondents total. Female participant responses are denoted in bold print.

Almost all of the respondents reported that they enjoyed working with robots, which is not surprising since the activity was an after-school elective. More than half also reported enjoying programming robots and most also reported enjoying school. As the questions became more subject focused, there was less agreement. Most were either neutral or disagreed that robotics was related to what they learned in school or that it helped with their understanding in mathematics or science classes. Regarding other subject areas, there was a more mixed response with students reporting robotics helping with understanding in four areas: (1) technology education, (2) language arts, (3) social studies, and (4) reading. Responses were similarly mixed to the statement that robotics could be used to understand school subjects.

Regarding building and programming robots, most agreed that there was a relationship between building robots and mathematics and all but two agreed that programming robots was related to mathematics. In response to a general statement about preferring to work with others on a project, most were neutral. When the statement was made specific to robotics, most agreed or were neutral to working with others to build and program robots. Finally, almost all had previous experience with building blocks such as Legos of K'nex and seven of the 12 team members had previous experience with programming in some form. Most were returning members of the previous year's Botball team/robotics club. The other two students were 7^{th} graders and twin brothers whose father was a C++ programmer.

While constructing the survey I had intended questions 6 and 8/9 to address two different aspects of mathematics. By using the word "Math" in question 6, I assumed based upon my experience as a middle school teacher that the students would understand it to refer to their mathematics classes. Similarly, I used the word "mathematics" in questions 8 and 9 to intend a more personal and less mathematics classroom oriented construction of mathematics. One interpretation of the responses to these two different questions is that the participants don't see the mathematics that they encounter in robotics as related to the mathematics they encounter in the classroom. That is, the participants see that there is a qualitative difference between mathematics in the two milieus. This was my initial interpretation. However, I believe that it may have been in error.

In comparing their responses to the questions 1, 8 and 9; my observations of their robotics activities; and their responses to individual questions; I have come to believe that a more representative construction of their understanding is that they see the mathematics that they use in the classroom and the mathematics that they use in robotics as one in the same: the numbers, the operations, and the discrete, disconnected, and decontextualized procedures of traditional mathematics instruction. The reason that they don't see a relationship to the classroom may be that most of them have progressed beyond what they perceive as the easier basic operations and simple measurements of the mathematics that they are using in the robotics activities. One clue to this interpretation comes from participant responses to the survey's free response question. When asked to suggest ways that robotics could be used to help understand mathematics, the participant responses reflected this fragmented view of mathematics:

Stacy: *Programming formulas and calculating formulas*

Carol: *Timing, multiplying and dividing*

Gary: *Programming helps practice math skills but doesn't help with math class.* (As Gary handed me his survey form he explained that he had indicated on the survey that robotics didn't help with his understanding of the mathematics in his math class. He noted that he was taking high school level Geometry and did not see the mathematics that he used in robotics as related to the [higher level] mathematics he was required to perform in class, thus directly corroborating my surmise.)

Philip: *To see the length.*

Victor: *Math works with numbers so does programming. You have to adjust motor speeds, etc.*

These responses are consistent with student responses to interview questions regarding, "What is mathematics?"

Tom: *It helps you understand differences in amounts. Distance*

Donald: *It's addition and subtraction to algebra to geometry.*

Gary: *It's numbers, figuring out amounts, multiplication, division, addition, and subtraction.*

John: *Math is dealing with numbers and measurement.*

Participant responses to individual queries regarding mathematics in robotics, computer programming or increased understanding of mathematics due to robotics experiences reflect similar views of mathematics as a series of discrete, poorly related topics.

Tom: *There's math in the timing and turns.*

Gary: *Calculating how far and how long.*

Donald: *Degrees on a servo.*

John: *Timing in programming.*

Philip: It's r*otations on wheels, calibrations, integers.*

The view of the participants is that the mathematics they encounter in robotics is unrelated to mathematics as they have experienced it in the classroom. It is reasonable to conjecture that the mathematics that the participants' encounter in robotics emerges from the interplay of their choices in designing and building their robots, is affected by and modifies their structures, and thus influenced by their previous mathematical experiences. Making different choices can affect the mathematics that emerges from the robotics activities because different choices imply different changes in structure. If this is the case, then the two central questions of this study become pertinent:

1. How do students working cooperatively organize their efforts and negotiate meaning as they solve complex, open-ended robotics tasks?
2. What mathematical understandings emerge as students engage in robotics activities?

The data and discussion that follow are organized around these two central questions.

Organizing Efforts

The organizing efforts for the Botball team began with the Robotics club formation meetings in December. The meeting was held during an advisory period in early December. Approximately 90 students attended, of which, about 12 were female. During the meeting, the sponsoring teacher discussed the club and the Botball team and her expectations regarding the commitment to participate. The extensive time commitments for those interested in participating on the Botball team were emphasized (over 6 hours per week for the Botball team). I was introduced and I gave a brief overview of this study and requested their participation. A sign-up sheet was passed around for those interested in participating in Botball. Based upon the previous year's experience, we (the sponsor and I) expected that many of those present were using the opportunity to escape their advisory class and that less than half of those present would actually participate. This expectation was later confirmed as less than 40 students attended the first after-school robotics club meeting. This number dwindled to less than 30 students for subsequent meetings and eventually down to the 16 Botball team members used for this study and participating in the competition. Many of those who joined the robotics club, for one reason or another, chose not to participate in the Botball team.

The sponsoring teacher, Ms. N., influenced the club activities in that she determined what meeting schedule that she could sustain. In addition, she attended the teacher workshop for Botball, provided administrative support, wrote local public school foundation and parent-teacher association grants to obtain funds to support the program, communicated her personal and the school's concerns such as the proper behavior and supervision of the students, set the guidelines for care of the facilities (i.e., the robotics components, computers and her classroom), and administered operating funds involved (e.g., collecting money from the students for after-school work session pizza breaks, school grants, etc.). Finally, she determined the ultimate composition of the Botball team in consultation with the president and vice president of the robotics club, as well as, myself.

Brainstorming

The team's organizing efforts began in earnest during the first team meeting after the Botball teacher's workshop. The sponsoring teacher and I began the meeting by outlining the 2002 Botball competition arena design and rules found in Appendix A. Then the president and vice president of the robotics club, Tom and Gary, elected the previous year, took over the meeting to direct the team's organizing efforts. The entire team, comprised of students from each grade level (i.e., 6, 7 and 8), participated in the session.

Their first action was to conduct a brainstorming session with the entire team to generate ideas for robot designs and competition strategies. This was initiated without any input either from the sponsoring teacher or myself. She and I only participated to the extent necessary to answer occasional questions regarding our understanding of the competition rules and timeline. The students quickly generated five or six ideas that they then focused down to two as described in the conversation below.

Vignette 1: *Brainstorming*

> Tom: *Ok, from what I'm hearing is that we need to do a um...OK. We probably need to... everyone wants to build a bulldozer, front-end loader... something like that? And a forklift. Is that right?*
>
> Ken: *Yes, two bots. Are we going to try to use our scout?* (Referring to a third processor of limited capability. Ultimately the team decided not to use it because it could not be programmed in *Interactive C*.)

Tom: *So...that's our two robots. I'm not sure if we can use the scout yet. Ms. N., do you know if we can have three robots?* (Ms. N. nods affirmatively.)

Earl: *We don't have to use the scout. You could put a flag on it. Go around it...*

Tom: *So we might...we might use the scout for something like... start it out...and have it go straight at the tubes that we have and knock 'em over and take our bulldozer and go over and scoop everything up.*

Ken: *What are we going to do with scout after that?*

Gary: *The thing about the bulldozer is it's like a front loader. It pushes these things up and like a bow front and it slams down all the balls like a bow front-end loader.*

Tom: *Yeah, and Donny had a great idea for the forklift thing.*

Donny: *Uhh...it's kinda got these little rods it's not like a normal forklift that goes directly up. It's kinda like it rotates like little arms like this, it goes in and kinda wedges itself up under the back and lifts up and since there is another program here it lifts up to about here and this part falls back to about here then it pushes everything up and pours all the balls out so they are free from the nest. Then the bulldozer can come in this way and knock everything in.*

Tom: *Do you like that idea?*

All students: *Yeah, yeah*

The discussion shifts to a debate as to whether to use the scout processor or not. They students decide that it would not be worth the trouble of figuring out how to program the scout since its capabilities are limited and it is not programmable in *Interactive C*. The discussion then shifts to employment strategies for the two.

Tom: *I think we can. If we use the bulldozer, we can go around go straight at the tubes and keep going.*

Ken: *I really think we should scrap the scout idea. All it is going to do is take up room and it doesn't turn.*

Beth: *Yeah, I agree. Let's just scrap the scout idea.*

Lindsey: *Let's knock over the tubes ...*

Tom: *Well, we can come back to it later if we decide to use it. Are we all done? Alright...*

Frank: *What if we did use the roof idea and make one bot really flat and we were to go over there and knock over the tubes on the side? We could put a little fence around to keep the balls in.*

Tom: *We would still need two robots; definitely one for the nest and one to pick up the balls.*

Ken: *But Donald's idea was to take the nest. Does the nest itself count as points?*

Donny: *Yeah, it lifts it up, gets it on itself on our side and brings it back.*

Tom: *It is on your side.*

Ken: *That'll be five points.*

Gary: *The only problem with it being on our side is that somehow when we come back, to turn the bot and our side is only about that wide and you have to go up that way.*

Tom: *Go straight out, we will have to pick it up and bring it back.*

Gary: *You are going to have to turn...no you don't get half the board for your side.*

Ken: *We know that.*

Gary: *You only get the area on your side, only fifteen inches.*

Ken: *The robot will fit. Or we could just go around and hit theirs and drag it back.*

Tom: *That's right fifteen inches. Their nest?*

Ken: *Their nest, the other team's nest.*

Earl: *If we can just get another motor. We could make some links off of that and generator... power it to turn back.*

Tom: *Yeah.*

Oscar: *What you could do is we could just have the forklift because we are going to have a power-lift that is skinny to get under the tubes.*

Several observations can be made from the above discourse. First, no teacher was directing or managing the conversation; the student participants organized and negotiated the discussion without being directed. Second, even though the club president and vice president started the dialogue, their role was not impositional in that their ideas did not appear to be the intended implicit or explicit objects of the discussion. Third, at least ten students of the fifteen students present freely contributed to the conversation. There was no apparent pressure or discomfort exhibited by team members either contributing or not contributing to the discussion. Moreover, the discourse was respectful. Finally, it was apparent that all of the students were familiar with the brainstorming process. I was aware that brainstorming was taught as a problem solving strategy as part of the advisory curriculum at this site. Moreover, I knew that the president and vice president had had some experience with brainstorming while attending school leadership academies. Even so, I was impressed with how smoothly and effectively the process went; especially in comparison with my experience with/remembering traditional, teacher-centered patterns of classroom discourse that lacked cooperative, inclusive inquiry group process. During my discussion with Ms. N. at the end of that day's session, she confirmed that she agreed with my observations. Brainstorming was used periodically throughout the development phase for the competition whenever the team members felt that a reevaluation of robot design and/or strategy was required.

Builders, Programmers and Checkers

Once the general design and strategies for the two competition robots had been determined, the students broke up into two groups, each responsible for a separate robot. Again, the older students took the lead. The team settled on designs for the two robots and they split into groups to work on each robot. The following excerpt from their discussion indicates the team members' level of knowledge regarding the capabilities of each processor, the sensors, and the type of gearing that they anticipate that their robot will require.

> Tom: *Okay. So what we are doing is building a bulldozer/front-end loader and a forklift. Okay Donny, since you already have a design and everything okay I'll leave you and...How about you and half the other people to do the forklift...whatever.*
>
> Donny: *Yeah! Umhmm...*
>
> Gary: *With the...for the bulldozer, if we're going to build the bulldozer we're going to need the uh, uh probably the uh,...*
>
> Ken: *The RCX.*
>
> Donny: *We have to have... we'll need the servo and the Handyboard for the forklift part.*
>
> Gary: *You'll need the servo for the bulldozer too.*
>
> Ken: *No you wouldn't. If you have the big gear here and the little thing here you could push it up*
>
> Tom: *How about you talk. Yes what were you saying?*

Donny: *I did this at my house with my scout. What you do is you get a big gear and a little brace going down to here whenever it goes up... whenever this rotates it will flip and it puts it up and goes up it lifts it up just a fraction.* (Donny is attempting to convince the RCX team that they will not require a servomotor since they can accomplish the same task using a gearing he had used on a Lego scout processor at home.)

Oscar: *How do you plan on using the sonar?*

Tom: *I don't know... I don't need it.*

Veteran team members chose their favorite processors and the other team members sorted themselves after talking with their more experienced counterparts regarding the pros and cons of working with the processors. One group took on the responsibility for the design, programming and construction of the Handy Board processor robot (subsequently named X-Terminator) and the other group worked with the Lego® Mindstorms™ RCX processor robot (named Fluffy II). Once the processors were sorted out, the negotiation between groups centered on allocating motors, servomotors, pneumatics actuators, and sensors.

Each group had a similar composition in that it consisted of 5 to 6 students split into subgroups made up of *builders* and *programmers*. The builders were responsible for the mechanical structure of the robot including the motors, servos and the positioning of the sensors. The programmers were responsible for developing the programs to run the robots. The remaining team members worked with the sponsoring teacher to develop the team's website (see website documentation in Appendix B), a requirement of the competition.

I believe this organization made sense to the team members, because they were able to follow their interests. Some participants preferred to build but were not interested in programming and, vice versa. Some did both, while a third group broke off to build the team's web site. In addition, although both processors were programmed in C using the free *Interactive C* software, each processor had a few unique commands and its own unique communication system with the computer. Exchanging the communications cables on one computer required a system reboot. Therefore, it was easier to program the processors using separate computers. Usually, there were three computers available so each robot's programmers always had access to do their programming.

The team's organization made it possible for several forms of rivalry to crop up. First, there was a friendly rivalry that arose between the respective robot's groups. Each robot's group continually compared how their own group was doing with the progress of the other robot's group. This rivalry seemed to inject a certain amount of competitive tension into the groups as they strove to be the first to have their robot operational and to develop the "coolest" robot. This competitive rivalry did exhibit some negative aspects. Occasionally, "we stink" or a similar remark could be heard from a member of a group that appeared to, momentarily, be lagging behind in development. For the most part, however, the rivalry between groups supported creativity and provided positive energy to their work.

A second form of rivalry grew out of the division between builders and programmers, primarily in the Handy Board group. This rivalry had more of a negative character to it and appeared to be an outgrowth of the integration problems the Handy Board group experienced. These problems were due to the difficulty of constructing a sufficiently robust vehicle of Legos to carry the heavier Handy Board and the complexity of programming the more capable and flexible processor. The result was that the programmers would complain about the builders building a vehicle that would not hold together or with features that they did not know how to program. Similarly, the builders would accuse the programmers of breaking their "perfectly good" design whenever mechanical-structural difficulties occurred—especially when the vehicle didn't withstand the rigors of testing in the practice arena. The Mindstorms™ RCX processor group experienced less of this sort of rivalry since one of the builders was also a primary programmer.

In the following vignette, Frank and Victor are two programmers who, while working with the X-Terminator Handy Board robot, have an accident in which the robot falls to the floor. Donny, the principal builder of X-Terminator was called in to assist with the robot's damage assessment and repair. Donny, as he tended to do, assessed responsibility for the problem as due to human error in handling the robot rather than considering the possibility of a design flaw. This vignette provides insight into the team organization and illustrates the tension between the builders and programmers as described above.

Vignette 2: *Robot Repairs*

Sam: *Put the motor program back on it.*

Victor: *Okay, the motor program is downloading. It's downloading.*

Sam: *You know the one that we had the 10,000-second one.* (Referring to a program that they had previously used.) *Whenever we had the start test motor.*

Victor: *It's downloading. It's still downloading.*

Frank: *No, it's not.* (Switches the power switch on.) *Ahhhhhh...* (Robot lurches forward and falls off the table. This is due to the Handy Board's inherent tendency to initiate a transient power spike to the motors when switched on.)

Sam: *Turn it off!*

Victor: *You idiot! You, oh! You broke the robot! Donny! They broke your robot!*

Frank: *No, I didn't!*

Donny: *Shut up!* (As he approaches and surveys the damage to the robot.)

Frank: *Well, then we'll just put it together. I didn't know what it was going to do.* (Meaning he didn't realize that the robot might spontaneously move when switched on.)

Victor: *That's why it is called forward.* (Victor assumed, in error, that the problem was because the downloaded program executed.)

Frank: *I didn't read it, see, because you downloaded it too fast.*

Victor: *Forward, not IC.*

Sam: *For 10,000 seconds. Donny, you have a wheel falling off.* (Attempts to hand the robot to Donny for repair.)

Donny: *It's probably because you are holding it wrong.* (Donny asserts that the wheel falling off is due to mishandling by other people, not because his design needs work.)

Sam: *No, it's because he turned it on by accident and it fell off the table.* (Correctly identifying the spontaneous start as the problem.)

Donny: *Do you want to fix this or not? Here! Let me see this!* (Takes the robot and begins repairing it.)

Vignette 3 is similar to Vignette 2 in that, once again, Donny is called in to assist with the reconstruction of X-Terminator. The vignette begins with X-Terminator self-destructing by jamming its forklift arm into the arena wall and attempting to lift it. Whenever something like this occurred, emotions tended to run high in the immediate aftermath. Usually, as quickly as the emotional energy was discharged, the combatants would separate to different locations in the room, a calmer atmosphere would return and the erstwhile combatants would eventually resume their collaboration. Note that in this and the following vignettes, my role as a participant-observer is more visible. Whenever I participated, I tried to act as a collaborator in catalyzing their thinking while attempting to avoid being directive. In this regard, I met with varying levels of success.

Vignette 3: *Trial Run*

X-Terminator self-destructs on a trial run in the practice arena and there's some anguished screaming by those watching.

Gary: *It just went...KABOOM!*

Mr. A: *Well, it was calibrated nicely.* (Referring to X-Terminator activating properly with the light signal.) *You need to work on structure. Where's Donny?*

Donny: *How did the servo get un-glued? There is only one way to break this. It is by holding it by the servo.* (Blaming the problem on handling rather than considering the possibility of a structural weakness.)

Mr. A: *The front end has been falling apart while the program is running.* (Attempting to get Donny to consider what I perceived to be a structural weakness.)

Donny: *They must have been very careless while they are holding this.*

(Tape silence. A little bit later…)

Donny: *I wonder where this goes. Let's make this thing work. Here is the Handy Board. They're holding everywhere like here.* (Meaning that the programmers are holding the robot incorrectly thus causing the structural problems.)

Mr. A: *Hey, Donald! Why don't you think about working a little more closely with the programmers so you can show them how you expect it to be held?*

Donny: *I've explained it to them!*

Mr. A: *Who did you explain it to? Frank, come on out here. Donny wants to explain how you should hold it.*

Frank: *This little thing broke here. It started from here. It hit this over here. Then it hit that over there.* (Trying to explain to Donny why X-Terminator self-destructed.)

Donny: *What do you mean…HIT IT? HIT IT? HIT IT?*

Frank: *Well, it hit over here.* (Indicating the locations in the arena.) *Then it went to the gutter. Then it pulled up and began to fall apart here.*

Donny: *That shouldn't do it.* (Assessing Frank's account and finishing his repairs to the robot.)

As the competition date neared, a new function developed within the team organization that helped to address the problems generated by the Handy Board builder-programmer rivalry. The team selected members who acted as *checkers* to test out the robots once they had been built and programmed. The checkers would then report back to the programmers and builders regarding the results of the trial. At times this reporting had the appearance of a negotiation. The checkers appeared to act almost as a mediator between the builders and programmers to defuse tensions and help negotiate potential solutions and the video and audio tapes of their interactions bear out this assessment. The checkers seemed to alleviate some of the pressure due to the "blame game" that had been occurring between the builders and programmers. The team members developed this addition to the team structure on their own. This innovation is an example of the self-organizing capabilities of the team members to address emergent needs.

Problems Encountered

The problems that the team members encountered in the course of designing, building and programming their robots were of three general types: mechanical-structural, decomposition/recomposition and troubleshooting. Each of these problem areas is discussed below.

Mechanical-Structural Problems. The basic mechanical-structural problem encountered consisted of getting vehicles constructed of Legos to hold together under the stresses imposed by motors, movement, and incidental contact with immovable objects or other robots. No glue was allowed except to glue a non-Lego piece such as a sensor or servo to a Lego piece. So the only thing holding the robots together was the traditional Lego snap fit. The team quickly identified which members were "experts" at the design of durable Lego structures.

Donny was one such expert. One of the students on the team that was served through the special education program at the school, he was the acknowledged Lego structure specialist on the team. He was also the team curmudgeon and preferred to work by himself. As a result, he took very personal ownership in what he created and even more personal insult when one of his constructions broke down (See Vignettes 2 and 3). However, the other team members respected him and looked to him for guidance in building the robots. Vignette 4 shows Donny working with two other students to strengthen the mechanical structure for the Handy Board robot. It also reveals that functionality wasn't the only consideration when designing robots. Aesthetics was also important.

Vignette 4: *Building and Aesthetics*

Donny: *This is the side that's messed up. This is the side we will have to put braces on. I'll have to put two on it. Where did they go?*

Matthew: *I'll go find one.*

Donny: *Preferably the same color. Let's color coordinate our bots.*

Steve: *Are you sure if we just set that on there, that it's not just going to collapse?*

Donny: *Dude! It's not. Here we can put the braces. Here, this goes here. This goes here and then this goes here. This will work inverted. Cool, this looks cool! Mr. A., look at this!*

Mr. A: *This is like superman. He is so conservative.*

Gary: *How's the handy board going to fit on it?*

Donny: *Let's put it back here to balance it.*

Gary: *Why did you build it like this?*

Donny: *Because it looks cool!*

Decomposition/Recomposition

One of the greatest difficulties that students had was decomposing or breaking down familiar actions into discrete actions, corresponding to the various parts of the robot, and then recomposing them in the form of a C program that the processor could execute. For example, take a simple action like walking out the door of the room. We are all used to doing actions such as these without thinking about them and so are the students. We merely decide to leave the room and then do so; there is no thought given to even the specific path that we must take to exit the room. We will even walk around obstacles without thinking about them. However, if we thought about it, we might break the task down in this manner, "Go forward for about 10 feet, turn right, and go forward again until out the door." This level of specificity works for humans but not for robots. The actions must be broken down even further into specific commands for each robot component involved in the movement. Table 7 lists an example sequence of commands for such a movement.

Middle school students, as budding programmers, seem to have great difficulty conceptualizing movements at the level of detail listed in Table 7; perhaps because they have had few experiences asking them to think about sequencing at that depth of complexity or because they have not yet begun the transition into the formal operations necessary for abstract conceptualization of this nature. Often, they exhibit an inability to even recognize the individual actions below the "forward" or "turn right" level. This becomes a problem for them as they attempt to program their robots. One way that seems to help them over this hurdle is to have them act out the part of the robot with the help of some very specific instructions.

Table 7 *Simple Movement Command Sequence in C*

Command(s)	Effect
Motor (1, 75); Motor (2, 75);	Motors 1 (right motor) and 2 (left motor) on at speed 75.
Sleep (5.0);	Do the above (go straight) for 5 seconds.
Motor (1, -20); Motor (2, 75);	Motor 1 reverse at speed 20. Motor 2 forward at speed 75. (Creates a right turn.)
Sleep (1.1);	Turn right for 1.1 seconds
Motor (1, 75); Motor (2, 75);	Motors 1 (right motor) and 2 (left motor) on at speed 75.
Sleep (3.0);	Do the above for 3 seconds (until out the door).

Vignette 5, reconstructed from field notes and reflections, involves Brad and Alana, who participated in the robotics club, but not on the Botball team. They were trying to figure out how to program a basic "go forward, then turn right" sequence for their robot. In an effort to help them think through the problem I asked them to role-play a robot. In this vignette, their bodies appeared to literally become "objects-to-think-with" (Papert, 1980, p.11).

Vignette 5: *Human Robots*

Mr. A: *Now, Brad, I want you to pretend to be a robot and Alana will tell you what to do. If you are a robot, where are your motors?*

Brad: (Thinks a moment) Right here. (Points to each leg in turn.)

Mr. A: *Good. Where's your processor?*

Brad: *Points to his head?*

Mr. A: *Touch sensors? Light sensors?*

Brad: (Points to fingers and eyes in turn)

Mr. A: *All right! Now Alana will tell you what to do. You both must remember that a robot does exactly what it is told but each piece has to be told what to do and how long it should do it. For example, motors have to be told a speed, direction and time. Now Alana, think about what to say and have Brad move forward.*

Alana: *Move forward.*

(Brad starts forward and stops when motioned by Mr. A.)

Mr. A: *Brad, how did you know what to do?*

Brad: *She told me to go forward.*

Mr. A: *If you are a robot, how do you move forward?*

Brad: *My motors move my legs.*

Mr. A: *But did she tell any of your motors to turn on?*

Brad: *No.*

Mr. A: *Then how could you move?* (Brad shrugs)
Okay, let's try it again.

Alana: *Right motor, left motor, forward.*

(Brad moves forward and is stopped by me)

Mr. A: Brad, how long should you be moving forward?

Brad: I don't know.

Mr. A: *Well, the way she told you, you would be moving forward until you ran into something and your batteries wore down. To avoid that, you need to be told how long to move forward. Now go back to where you were. Alana, try it again.*

Alana: *Right motor, left motor, forward five seconds.*

(Brad moves forward for about 5 seconds)

Mr. A: *Good! Alana, can you move him back?*

Alana: *Right and left motors, move back for five seconds.*

(Brad moves back to his starting position.)

Mr. A: *Now Alana and Brad, think about this. How would you tell a robot to turn?*

Brad: *Right turn? Left turn?*

Mr. A: *What do you think Alana?* (She nods in agreement with Brad.)

How does a robot know what a left or right turn is?

(Alana and Brad both shrug.)

Mr. A: *Try this. Look at your feet and turn right.*

(Alana and Brad both turn right while looking at their feet.)

Did one of your feet travel farther in the turn?

(Brad and Alana think for a minute. Brad repeats a right turn several times with Alana watching, then Brad brightens.)

Brad: *My left foot went farther. My right one hardly moved at all!*

Mr. A: *Now think about you as a robot. How should Alana tell you how to turn right?*

Brad: *Oh! (Big light bulb comes on!) She should tell my left foot to move, but not my right foot.*

Mr. A: *Alana, what do you think?*

Alana: *That should work.*

Mr. A: *Good! Another way to do a turn is to have one motor go forward and the other to go backward. Now, go and try to write a program that tells a robot to go straight for five seconds and then do a right turn. Remember, the "sleep" command is what you use to tell the robot how long to do something.*

As they returned to their computer, I observed Brad and Alana moving their arms simulating the directions of motors as they discussed how to write their program. It appeared that, for Brad and Alana, being able to reference the individual components of the robot to their own body functions and experiences enabled them to think about decomposing the task to the level necessary to program the robot.

The role-playing that we did seemed to give Brad and Alana an entrée in to using their own embodied experience to help them think through the programming problem. In other words it gave them a means to take the perspective of the other, in this case a robot, and think as a robot thinks. As further evidence of this, I frequently noted in my programming discussions with students that they would often make conscious or subconscious body movements mirroring the robotic actions that they were describing. From my observations and viewing the videotapes, this sense-making behavior often occurred even with students that had not participated in any robotic role-playing.

Other efforts to get students to develop or draw upon embodied experience to help with programming were less successful. Miles was also one of the students who participated in the robotics club but not on the Botball team. I worked with him one day to help him with his program. After, doing a brief role-play similar to that of Vignette 5, the discussion in Vignette 6 ensued.

Vignette 6: *Another Human Robot?*

Mrs. A: *What are you doing?*

Miles: *I'm learning how to make it go forward and backwards. This is my friend Philip, the weird one.*

Mr. A: *So now you got it saved. Now, you need to do the same thing to have it turn. You got to have something to make it turn. Now what program…you were doing something to make it turn. How were you doing that when you were being the robot, how'd you turn the robot?*

Matthew: (Interjecting) *I know how you program it to make it turn. You just put "t, r" for turn around.*

Miles: *B. K. space 2*

Mr. A: (To Earl.) *"T" is not a command.* (Turning to Miles.) *If you are going to turn, think back to when you were a robot, what made you turn?*

Miles: *My front foot went forward and my back another and it made me turn.*

Mr. A: *If your right foot made you go forward, what did your left foot do?*

Miles: *Made me turn, because it stood still.*

Mr. A: *So that is one way to make it turn. That is one way to make it turn.*

Miles: *But you told me to put...*

Mr. A: *Remember, that is when you have two motors. Okay, so now it is turning. How does it know how long it should turn?*

Miles: *Is that what I do?*

It was clear to me from this interaction that Miles was not used to making sense from within his own experience. On the contrary, from Miles's body language and responses such as, "Is that what I do?" I came to understand that he somehow expected me to "deliver" the understanding to him. As we continued the exchange, I found myself becoming increasingly leading in my questions. The exchange broke off when I was called away to help with another problem. This attempt to get Miles to draw upon his experience in role-playing a robot was less successful, in my view, than the previous episode with Brad and Alana because Steve was not able to continue programming without having me present to lead him.

Troubleshooting/debugging

Being able to troubleshoot or repair their structures and debug their programs is an important aspect of robotics. In my view, the students tended to approach this important task in a somewhat unsophisticated manner in that they tended to focus on the first option that came to mind. Their natural inclinations in addressing problems appeared to fall into one of these three categories:

- *Blame someone else*. For example, if you are a builder, blame the programmers. Or, if you are a programmer, any faults must be due to the robot's structure. Donny exhibits this tendency in vignettes 2 and 3.
- *Blame inanimate objects*. For example, if a robot gets caught on the sides of the arena and self-destructs, it must be a problem with the

arena rather than a lack of robustness in the design of the robot or an error in its program.

- *Take a more measured approach*. Investigate all the possibilities, the design of their robot's program, its structure, and the motor and sensor connections. This was usually the last option tried by the team members.

The two vignettes that follow (7 and 8) are examples of troubleshooting interactions that illustrate the three troubleshooting approaches.

Vignette 7: *Troubleshooting*

Lindsey and Tom are trying to figure out why their robot is spinning when it should be going straight. I am called over to assist them with their troubleshooting. Carol who is collecting information for the team's competition web site joins us (See team web site information chronicled in Appendix B).

Mr. A: *So, you started up your program and it went backwards?*

Lindsey: *No, it went forward.*

Mr. A: *Let's see what happens when we touch the front bumper here.*

Lindsey: *Oh… It works!* (The robot responds by spinning in the opposite direction.)

Mr. A: *How about the back bumper?* (Touching the back touch sensor and no change occurs in the robot's activities.) *Something is not happening. Why isn't that bumper working?*

Lindsey: *I don't know but the back one works.* (Meaning the front touch sensor as indicated by her pointing.)

Mr. A: *Okay. Let's talk about this. What you thought was going to happen didn't. What did you think was going to happen with this program?*

Lindsey: *I thought... the front part was going to touch...the back. See! That's the thing... motors were supposed to...the motors... Oh!* (Looking at her program.) *That says 500! Is that it?* (Referring to a motor speed incorrectly set to 500 when the maximum speed setting is +/-100, speed inputs below/ beyond these values are processed as the –100/+100, respectively.)

Mr. A: *Well...it might affect it. You can change that because that is an error. Okay. What was the first thing that it was supposed to do?*

Lindsey: *It backed up. It was supposed to go forward.*

Mr. A: So *what you know is that this should make it go forward. So where could the error be if it didn't go forward like you expected.*

Lindsey: *Maybe the negatives...um I mean the positives mean go backwards.*

Mr. A: *You think that might change it? What can you do to find out?*

Carol: (Joining in to ask questions to chronicle the team's activities for the team's web site.) *Have you fixed your sensor problem?*

Lindsey: *I don't know yet, it just worked. What is this for?* (To Carol.)

Carol: *It is the journal for the web page.*

Mr. A: *Do you think that fixed everything?* (After Lindsey adjusts the robot's program to change the maximum motor speed to 100.)

Lindsey: *Hopefully. I still have to try to fix that problem.* (Referring to the touch sensor responses.) *The front bumper didn't work.*

Mr. A: *Let's look at it. Why do you think the front bumper didn't work?*

Lindsey: *I don't know. Maybe it's the...* (Tape silence/break in the recording.)

Mr. A: *Let's look at this. The problems could be software or the robot. Now if you think the software is good, what do you think could be wrong?*

Lindsey: *Three! It's on three not two! Cause it says three not two, cause it has to be connected right.* (Referring to a motor that's connected to a different port than specified in the program.)

Mr. A: *Do you have your changes made that you think you need to make?*

Lindsey: *The batteries are dead. It takes 7 AA batteries.*

Mr. A: *Okay, so the robots did everything except the bumpers didn't work the way you?*

Tom: *At the beginning.*

Mr. A: *And the way you fixed it was by changing the leads?*

Tom: *Yep.*

Lindsey: *And...*

Mr. A: *So, what does that tell you about your program?*

Lindsey: *That...*

Tom: *We messed it all up.* (Failing to recognize that there was nothing wrong with the program.)

Lindsey: *That we fixed it now.* (Excitedly.)

Mr. A: (To Tom.) *What do you mean messed it all up? It's going back and forth now.*

Lindsey: *I'm going to program it to do more now. Because it's fixed! It's fixed!* (Eager to move on to new programming experiences.)

Mr. A: *Well, make sure your program agrees with what you are doing on that.* (Meaning that the motors and sensors are connected to the processor as specified in the program as written.)

Lindsey: *Yeah, I will I'll look up on that and figure everything out.*

Mr. A: *Because just like before when you had the leads using 3 instead of 2.*

Lindsey: *Yeah, and I'll look at that and then I'll look at this.*

Mr. A: *So, you got the ping-pong sort of figured out. Now you can use the light sensor to make it follow along. You can find out how to do that in your book.*

Carol: *I want to know how to make it turn.*

Lindsey: *Oh! I know how to make it turn!*
(At this point Lindsey and Carol begin discussing how to program turns.)

This vignette demonstrates that troubleshooting involves a level of complexity not usually encountered in a mathematics classroom, having to determine what the problem is before solving the problem itself. In this case, the students' program for the robot had no errors that would prevent its execution as they had intended. Lindsey and Tom had simply connected one of the motor leads to the wrong (unpowered) port. However, Lindsey and Tom initially assumed the program as being suspect. As a result, they focused on trying to fix the program rather than checking the connections on the robot. It was only after my intervention that Lindsey discovered the motor lead problem and corrected it. Even so, Tom still thought that the program was in error in his assessment that "We messed it all up."

Tom and Laurens' reactions to their experience are a study in contrasts. Despite identifying and fixing the motor lead problem and having a successful trial with their robot thereafter, Tom still attributed the problem to the program. Lindsey, on the other hand, is delighted to have discovered and fixed the problem and is eager to move on and expand her programming repertoire. She reported excitedly, "That we fixed it now" and that she was "going to program it to do more now. Because it's fixed! It's fixed!" Lindsey accurately recognized that correcting the wiring problem resolved what they had initially thought was a software problem. This episode is one of many that I observed that suggests that the team members, perhaps due to a lack of confidence in their own or their teammates' programming skills, tended to assume that any error had to be in the program.

Vignette 8: *Robot Drift*

Vignette 8 starts with Frank and Victor having just performed a trial run of the X-Terminator. The robot drifted to one side although it was programmed to go straight. Frank and Victor are trying to determine what is causing the drift and what to do about it.

Mr. A: *Why do we have that little bit of drift? How can you adjust it?*

Victor: *I have no idea!* (Ever demonstrative, throws up his hands.)

Frank: *Take this tape off.* (Referring to tape that had been used to directionally shield a light sensor and had fallen onto the arena surface.)

Mr. A: *How can you tell what side is affected? If it is drifting to one side or the other, how would you adjust it?*

Victor: *One motor will go more than the other.* (Meaning that he would adjust motor speed to create a turn.)

Mr. A: *How do you tell it to go straight?* (Meaning, how would they eliminate the robot's drift?)

Frank: *Motor 1, 100. You got to make one motor move a different way. Will that turn it though?* (Meaning, "Is that enough of a correction?")

Mr. A: *Let's say it's going towards you Frank.* (That is drifting toward the side of the arena where Frank is sitting.) *Which motor would you adjust?*

Frank: *It is going towards me. This one, that one...make it 99. They are both at 100. Make it at 99 and see how it does.*

Victor: *I don't need the light. I don't have to have it. Don't put it that far. Move it up. See told you.*

Mr. A: *Why is it spinning like that?*

Victor: *All right Frank: it is your turn to program it now anyway.*

Mr. A: *So you don't have any idea, Victor?* (Joking with Victor.)

Frank: We are missing a ball. (Momentarily distracted as he attempts to reset the arena for another trial run.) *Victor has it.*

Mr. A: *Have you found some tank treads yet Carol?* (To Carol as she hunts for treads for a robot she is building.)

Carol: *Yeah.*

Mr. A: (To Victor as he is about to inadvertently step on two ping-pong balls.) *Be careful with those balls we have had to trash two today because someone has smashed them.*

Victor: *Two, wow!* (Sarcastically)

Frank: *Yeah. Victor, you put the left turn and the right turns on there all right. It did turn that way.*

Victor: *I know a glitch in the system.* (Bringing up a new topic about a software bug in the *Interactive* C program.) *Do you know how you are not supposed to be able to get a new "C" folder because it is not supposed to let you?*

Mr. A: *Yeah, it is supposed to be a shared folder.* (Referring to the school district's network system.) *What's wrong Carol?*

Carol: *Well, I want to find some things but they are not here.*

Frank: *Okay. I have slowed one of the motors down by one.*

Mr. A: *Which one did you slow down?*

Frank: *Motor 1 is on the right side. Well, it should be!*

Mr. A: *If that motor is slowed down, which side will be slower? It might be a good idea to write that in the comments...if motor 1 is right and motor 2 is left side.*

Victor: (Standing by Carol at the computer and introducing another new subject.) *What is it, KISSTER or KISS star?*

Mr. A: *What it is, is www.kipr.org. It's the KISS Institute of Practical Robotics.* (Turning to Carol who is at a computer looking up robotics web sites.) *Oh! You found a web site about KISS. Oh! That is in France! Look at this address. How is it going Carol? Finding what you need?*

Carol: *Uh huh.*

Frank: *Hey! It started! I fixed it!* (Having started another trial run and successfully correcting the robot's drift. However, a new problem crops up.)

Victor: *Those wheels are messing it up. They are scratching the board.* (Referring to the robot spinning in place in the arena.)

Mr. A: *It is the spinning around that is doing it.* (Thinking aloud.) *But if you are just doing an arc...check the timing. It takes a lot of time for the first turn because it has all that weight.* (Referring to X-Terminator dragging the weight of the first nest.)

In addition to troubleshooting, this vignette illustrates the complexity of interactions that occurred as Frank and Victor worked with X-Terminator. Note that Victor introduced several different topics of discussion, some unrelated to robotics. Moreover, other students (and myself) joined in and broke off from participation as was necessary. Despite all the interactions and seeming distractions, Frank and Victor continued to work through their problem with the robot. In my viewing and reviewing of audio and videotapes of student actions, these types of interactions where students continued working on a task although seemingly involved in unrelated activity or distracted by other teammates were typical in the continual swirl of activity in the robotics activities.

Mathematics and Robotics

There is a wealth of mathematics involved in the robotics activities of this study. Rather than attempting comprehensive documentation, I selected three areas: navigation, proportional reasoning, and geometric interpretation, that I felt were representative of not only the mathematics that the participants experienced but also to illustrate the richness of mathematics potentially accessible through the robotics activities, depending upon the participants' choices as they develop their robots. This raises the question of the implications these types of robotics activities with respect to mathematics instruction, especially with reference to affording students choice while being able to meet instructional or curricular goals.

Navigation

Navigation is one of the major problem hurdles the students face in programming their robots. The basic question is, "How does a robot know where it is in the arena so that it performs the correct action in the intended location in keeping with the team's competition strategy?" In this year's competition, one robot (X-Terminator) was targeted at the near nest (see Figure 3) to lift up one side, drag it back into our end zone and free its balls before putting it down to go back to get the center nest. Meanwhile, the second robot (Fluffy II) was to go down the left side of the board and knock over the cardboard tubes of our team's color for that round, freeing the balls inside. To do this, each robot had to exit the starting box without interfering with the other robot. There are multiple levels of complexity in terms of how the team could choose to address this navigation problem and, correspondingly, multiple levels of mathematical complexity that emerged from the participants' decisions. Now I will discuss various ways students could address the navigation problem.

Dead Reckoning. From my experience in working with middle school robotics teams, the students prefer to program their robots using dead reckoning. Dead reckoning means navigating only on the basis of time, velocity (in terms of motor speed), and direction traveled much as ancient mariners once determined the position of their vessels. This is the simplest means of programming the robots to navigate the arena. Table 6 is an example of a sequence of dead reckoning commands. However, while dead reckoning is easily accessible to middle school students, it has its drawbacks in terms of reliability because it fails to take into account and respond to changes in environmental and contextual factors.

Dead reckoning in robotics enabled participants to embody the relationship between distance, velocity, and time through the robot's actions in a dynamic way in the meso space of the competition arena in a manner unlike the typical mathematics classrooms where the relationship is limited to the two-dimensional micro space of the desktop. In practice, the participants navigated the robot by controlling motor speed and specifying the duration of time at that speed. The students could choose between two types of commands to affect motor speed. One type of command consisted of, either *fd (motor number)* or *bk (motor number)* depending on whether the motor was required to rotate forward or backward. Using the *fd* or *bk* command set the motor speed to its maximum rotation speed. The alternate command was a *motor (motor number, rotation speed)* command where the range of values for rotation speed was +/-100 with the sing of the integer determining direction of rotation. In a dead reckoning sequence, these commands would be accompanied by a *sleep (float)* where the *float* is a decimal value indicating the number of seconds to perform the commands in between the current *sleep* command and the preceding *sleep* command. Below are equivalent examples of the use of the two types of commands to command a forward movement and then a right turn where the number 1 indicates the left drive motor and the number 2 designates the right drive motor:

Forward:	fd (1);	motor (1, 100);
	fd (2);	motor (2, 100);
	sleep (2.5);	sleep (2.5);
Right Turn:	fd (1);	motor (1, 100);
	bk (2);	motor (2, -100);
	sleep (1.5);	sleep (1.5);

The use of these motor commands involves algebraic reasoning in that the students are essentially manipulating up to three variables: motor direction, time, and, in the case of the *motor* command, motor speed. Moreover, it also involves proportional reasoning. The distance traveled by a robot is directly proportional to the motor direction and time at that direction and inversely proportional to motor speed and time at that speed. While the students did not articulate these relationships, it was clear from their actions that they understood the relationship.

Each robot's team chose different approaches in their use of these commands (see Appendix I). The X-Terminator team coordinated all three variables in their efforts to navigate the robot. The programmers of Fluffy II took a simpler approach preferring to reduce the number of variables to two. They fixed the motor speed at the maximum value by using the *fd* and *bk* commands exclusively.

The students were aware of the tradeoffs in the two methods. The *motor* command allowed better accuracy, provided a means to compensate for drift through the use of differential motor speeds and was easier on the drive train of the robot. However, it was more difficult to coordinate the variable values to achieve the desired effect when using the *motor* command. In contrast, the *fd* and *bk* commands were simpler to coordinate, having two instead of three variables. However, because the motors were commanded to rotate at maximum speed, they tended to stress the robot's drive chain to a greater extent and cause gears to slip or pop out of place, especially in turns. When I asked Gary about his team's decision to use the *fd* and *bk* commands exclusively, he said that they didn't "want to mess with motor speed in case we have to reprogram during the competition. It takes too much time to get it right."

Like the dead reckoning those mariners practiced, dead reckoning in robotics is fraught with sources of error. Directional errors can be introduced by slipping gears, tires rubbing the robot's frame, or even by the taped markings on the arena surface. Similarly, as the robot's battery power supply is drained, motors rotate slower for a given commanded speed. This, in turn, affects the accuracy in distance traveled and degree of turn. As time goes on, the errors are compounded to the extent that the robot no longer executes its program effectively; occasionally with somewhat amusing or embarrassing results. Moreover, relying solely on dead reckoning without the use of sensors locks a robot into executing its program without any possibility of reacting to the environment and adjusting to changed conditions such as those created by the presence and actions of the competitor's robots in the arena.

Sensors. Sensors must be used to improve the accuracy of robot maneuvers and enable it to dynamically react to its environment. Touch sensors can be used to allow the robot to react to objects such as the arena walls or contact with other moveable objects such as robots. For example, a robot could be programmed to react to an input from a front-mounted touch sensor by backing for a few seconds and then turning. Absent the use of additional types of sensors, however, the robot is still navigating by dead reckoning. Table 8 is an example of Lindsey's program from Vignette 7 incorporating touch sensors. Her program has the robot moving forward at maximum speed unless one of the touch sensors is contacted. If the forward touch sensor is contacted, the robot backs up until the rear touch sensor is contacted at which point, the robot resumes going forward.

Table 8 *Lindsey's C Program Incorporating Touch Sensors*

```
void main ()
{
  motor (1,100);              /*motor 1 forward at max speed*/
  motor (2,100);              /*motor 2 forward at max speed*/
  while(start_button()==0) /*while the start button is not pushed*/
   {
    if(digital(15)==1)        /*if front touch sensor activated*/
     {
      motor (1,-100);         /*motor 1 on at max reverse*/
      motor (2,-100);         /*motor 2 on at max reverse*/
     }
    if(digital(7)==1)         /*if back touch sensor activated*/
     {
      motor (1,100);          /*motor 1 forward at max speed*/
      motor (2,100);          /*motor 2 forward at max speed*/
     }
   }
}
```

To enable a robot to react in a more sophisticated manner to its environment requires the use of reflectance, range finder, sonar, or encoder sensors. These sensors all depend on the transmission and reception of light or sound in order to function. Reflectance sensors operate by sending out an infrared (IR) light signal and reading the IR light reflected back. Their range is less than three inches and they can be used to differentiate between light and dark areas in the arena and objects of a desired color. Reflectance sensors can also be used to follow the black-striped markings on the surface or the black-colored PVC pipes surrounding and/or within the competition arena. Range finders also use IR light and operate in a manner similar to reflectance sensors. Their output can be used to determine ranges of objects between 4 and 30 inches from the robot. The sonar sensor operates much like the range finder except that it uses ultrasonic sound to determine range and its range is approximately 30-2000 mm with a 30° field of view.

According to the KISS Institute (2000, 2001, & 2002), the most precise means of determining position in the arena is afforded by the use of the slot sensor or encoder. This U-shaped sensor transmits IR light from a transmitter located in one prong of the U to a receiver located in the other prong. When used for navigation, a slotted wheel is set to rotate between the prongs and geared into the gear train of each of the robot's drive motors. The encoder reports each time the IR light value changes as the slotted wheel rotates. This can be compiled as a count or total ticks. Each rotation of the slotted wheel translates into a specific number of ticks.

From this start, the rotations of the slotted wheel can be related through the gear train to distance traveled with respect to the circumference of the robot's drive wheels. Thus the distance traveled becomes dependent on the programmed number of encoder ticks, not the power available in the robot's battery. In other words, waning battery power ceases to affect the distance the robot travels unless, of course, the battery is totally drained. However, speed is still affected. Similarly, robot turns can be controlled more precisely through the use of differential encoder counts on each drive motor. The relationship between rotations of the slotted wheel in the encoder to distance traveled provides a significant proportional reasoning and geometric interpretation problem for students involved in robotics activities. Table 9 illustrates a sample *C* program using encoders to control distance and turns.

Note the increase in complexity of the program in comparison with Table 6. This change is due to incorporation of additional sensors and the necessity to use conditional while, if, and else statements to enable the processor to determine a course of action contingent upon information received from sensors.

Table 9 *Example C Program Incorporating Encoders*

```
#define PI 3.14159                 /*This block defines constants*/
#define TICREV 12.0
#define WHEELSEP 152.4             /*mm*/
#define WHEELDIAM 81.6             /*mm*/
#define SPEED 50

#define R_MOTOR 2                  /*This block defines equipment names*/
#define L_MOTOR 0
#define R_ENCODER 1
#define L_ENCODER 0
#define BUMPER digital(15)

void main()
{
   int k_value, ticdist, float turns, distance, dist; /*declares integer variables for the program*/

   enable_encoder (R_ENCODER);
   enable_encoder (L_ENCODER);

 while (!start_button())
   /*This allows the Handy Board's knob value to be used to set the turns.*/
    {
     k_value = (knob()- 125)/10;
     printf("Val= %d Turns= %d\n", knob (), k_value);
     turns = ((float) k_value);
   }

   dist = circledist (turns);
   ticdist = distance_to_tics(dist);
   turntics (ticdist);
   motor (3, 90);
   sleep (0.4);
   printf("Goodbye!\n");
   ao();}
 float circledist (float turns)
 {
   float circumference, distance;

   circumference = 2.0 * PI * WHEELSEP;
```

Table 9 *Example C Program Incorporating Encoders, continued*

```
    distance = circumference * turns;
    return (distance);
}

int distance_to_tics (float distance)
/*Converts distance into encoder tics. PI and WHEELDIAM are pre-defined constants. The
(float distance) value must be in the same distance units as the wheel diameter (mm). */
{
    float revs, tics;
    revs = distance/(PI * WHEELDIAM);
    tics = revs * TICREV;
    return ((int) tics); }
void turntics (int ticdist)
{
    int current_tics = 0, r_dir, l_dir;
    if (ticdist < 0)
     {
      r_dir = 1;
      l_dir = -1;
    }
    else
     {
      r_dir = -1;
      l_dir = 1;
    }

  reset_encoder (R_ENCODER);
    reset_encoder (L_ENCODER);

    while ((current_tics <= ticdist) && !BUMPER)
     {
      motor(R_MOTOR, SPEED * r_dir);
      motor(L_MOTOR, SPEED * l_dir);
      current_tics = (read_encoder(R_ENCODER) + read_encoder(L_ENCODER));
    }
    ao();
}
```

Note: This program was written by myself to illustrate encoder use. Neither X-Terminator nor Fluffy II was equipped with encoders

Proportional Reasoning

Proportional reasoning is another area where the robotics activities exhibited significant potential. The participants themselves recognized several ways that proportional thinking was involved in the robotics. In Vignette 9, the participants discuss the mathematics that they see in their robotics activities.

Vignette 9: *Examples of Proportional Reasoning*

Mrs. A: *Do you guys like math? Is there any way you use math doing this?*

Frank: *Yeah a lot!*

Oscar: *Yeah, it is easy.*

Tom: *Sure!*

Tom: *Yeah gears have to be set a certain way.*

Afterward, Tom indicated that he was referring to the matching of a large gear to a smaller gear or vice versa depending upon whether power (torque) or speed was desired. This is a proportional reasoning problem involving gear ratios. The students were very conversant with which gear ratio to select, although they did not call it that, to achieve a desired outcome and regularly discussed the pros and cons of various gearings.

Frank : *Just like when I was setting the servo. It had to be set to 0, then I had to use180, and then compare the angle and stuff like when it is all straight lines it is like 1000, 2000 and so on, the degree to the amount.*

Here is a second and separate proportional reasoning problem involving programming a servomotor. Frank is attempting to describe the reasoning involved in coordinating the desired position of the system of angular measure that he knows (degrees) with the system required in *Interactive C*.

Oscar: *And like light sensors there are so many degrees wide that it sees. So you like got to decide and figure and make decisions on degrees.*

Frank : *And like especially the sonar, it shows in this book how many degrees the range of it should be. And you have to know how far it goes and reads.*

Oscar: *Look, see here are the standard gears. There is a 40, 32, 24, 16 and an 8.*

Frank : *I don't know what these ones are.*

Mr. A: *If you add a 40 one to an 8 gear one. How many times does the 8 have to go around to make it a 40?*

Frank : *5 times.*

Oscar: *5 times and then the 16 and 24 would have to be odd. For they would have to be different, not whole numbers they would have to be integers.*

Mr. A: *Are you talking about if they were geared with a 40?*

Frank : *Yeah.*

Oscar: *Yeah, but the 8 goes into everything on here.*

Frank : *It goes into 16 and 24 and 32 and 40.*

The students in this vignette mentioned two aspects of robotics where proportional reasoning is important. The first is in the gearing of the motors to the drive wheel of their robot. When asked about a 40 toothed gear paired with an 8 toothed gear, Oscar exhibits some playfulness in considering various gear combinations in extension of the question. "5 times and then the 16 and 24 would have to be odd. For they would have to be different, not whole numbers they would have to be integers." Moreover, both Frank and Oscar recognize 8 as the greatest common factor of the 16, -24, -32, and -40 toothed gears. The proportional reasoning involved in gearing becomes even more complex when encoders are used as sensors to help determine the robot's position, as Table 9 illustrates, in relating encoder output (tics) through the gear train to distance traveled in one rotation of the drive wheel.

Also in Vignette 9, Frank described another problem that required the use of proportional reasoning. The problem involved programming the servomotor controlling the forklift arm on X-Terminator. Servomotors are designed to rotate within a range of 0--180 degrees and hold any commanded position within that range. This makes a servomotor useful to position a device like the forklift arm on X-Terminator. The *Interactive C* language, on the other hand, allows servo commands in the range of 0—4000. To program the servomotor, Frank had to relate the degree range of the servomotor to the servo command range of the C language. This coordination became even more dynamic as the servomotor had not been set to either end of its range when it was glued to the forklift arm. Frank had to determine the initial starting position within the servomotor's range in order to coordinate his programming commands.

Vignette 10 illustrates proportional reasoning in action as Frank experiments with a sonar program that he adapted from a sample program provided by KIPR that sets the speed of the robot in proportion to its distance from an object. Frank's program is listed in Table 10. As I describe in the vignette, the speed of the robot's approach to an object is inversely proportional to the distance the robot is from the object. In other words, as the robot approaches an object it will go slower and slower until the targeted distance from the object is reached; in this case, 300 mm.

Vignette 10: *Sonar Ping-Pong*

Frank : *Okay. It's just... Start...hmmm...good. Okay, go.*

Mr. A: *Don't touch any of those touch sensors.* (Indicating the touch sensors so just the effect of the sonar is observed.)

Frank : *Oh! This is awesome!*
(Frank uses his hand as a wall. The robot approaches his hand until it reaches a distance of 300mm. It moves back and forth to maintain that distance as Frank moves his hand.)
Watch, now I'm touching the touch sensors.

Gary: *Oh that's cool.* (As the robot moves away from the touch sensor that was activated and then goes back to maintain its distance from Frank's hand.)

Mr. A: *It slows down. The farther away it goes the...*

Frank: *That is awesome!*

Mr. A: *...slower it goes. so approach it...*

Frank: *Let's see how fast it can go!*

Table 10 *Frank's Sonar Ping-Pong Program*

```
#use "calibrate.ic"

void main ()
{
  hb_calibrate(6):    /*calibrate using light sensor in port 6*/
  play_time(90,start_process(ping_pong())); /*sets program to run 90 sec.*/
  printf ("all done\n"):
}
void ping_pong() /*This is the actual program*/
{
  int speed; /*declares an integer variable called "speed"*/
  while(stop_button()==0) /*While the stop button is not pressed, do the
following.*/
   {
    speed=sonar()-300; /*adjusts speed of robot to maintain distance of 300
mm. */
    motor(1,speed); motor(2,speed);
  }

  while(start_button()==0) /*While the start button is not pressed, monitor
the touch sensors (digital 15 & 8).*/
   {
    if(digital(15)==1)  /*If front touch sensor contacted, back up*/
     {

      motor (1,-100);
      motor (2,-100);
    }

  if(digital(8)==1)    /*If back touch sensor contacted, go forward*/
     {
      motor (1,100);
      motor (2,100);
    }
  }
```

Note: Comments added.

In addition to proportional reasoning, this vignette and also Table 9 are examples of where robotics activities involve the notion of limits. For example, from Table 10, the command sequence:

```
speed=sonar()-300;
motor(1,speed); motor(2,speed);
```

takes the value returned from the sonar and subtracts 300 from it. This new value becomes the speed value used in the motor commands in the next program line. Note that the speed value could be either positive or negative, indicating direction of motor rotation, depending on the distance returned from the sonar function. As the distance from an object approaches 300mm, the speed value goes to zero. If the robot gets closer than 300 mm (or the object is moved closer) the speed value becomes negative and the robot will back away. This is an example of the concept of limits played out in action; something that I only realized upon reflection on our interchange. While I did not attempt to formalize the idea with Frank, he directly experienced through the actions of the robot how limits come into play. In a mathematics classroom, the actions of the sonar-equipped robot as guided by its program could provide an opportunity to discuss the concept of limits.

Geometric Interpretation

The robotics activities that the students participated in also enabled the students to enrich their geometric understandings. Some of these understandings have already been alluded to. For example, Brad and Alana conducted an embodied and qualitatively different geometric exploration of space from the typical pencil and paper of traditional mathematics instruction when they role-played as robots. As a result, they were able to experience the practical outcome of crafting a simple *C* program that successfully mimicked their actions in a robotic simulacrum. Similarly, Frank gained insight into angular measures and their descriptions as he struggled to coordinate the servomotor position range with the *C* programming language requirements. While he had trouble verbalizing his understanding of the relationship, Frank's hand movements of opening and closing angles indicated that he understood what he was trying to describe. He appeared to know more than he could say and his actions could be evidence of tacit knowledge supporting his construction of meaning (attending *from* what his hands were doing *to* what he was trying to say). While he seemed to be focusing on the telling, his hands looked as if they were indicating his understanding in the doing. This seems to be enacted knowledge, played out in the doing. Similar connections between experience and the development of understanding are not often achieved in mathematics classes. Like Brad and Alana in their earlier efforts, Frank was able to realize the fruition of his programming efforts in the successful positioning of X-Terminator's forklift to lift, carry, and place the arena nests during the competition.

The Fluffy II design team members also experienced their share of practical, geometric effects of their design decisions. For example, Gary and Tom chose to equip Fluffy II with four rubber-tired wheels. Fluffy II's two drive motors drove the rear two wheels. The front two wheels were not driven, nor could they be steered. As Gary described it, adjusting the rotation speed and direction of the drive motors controlled the robot's direction of travel. The Fluffy team planned to have the robot sit sideways in the start box and make a 180° turn out after X-Terminator had cleared the start box. Unfortunately, the friction caused by having rubber tires on the front wheels sapped power from the robot's battery and increased Fluffy II's turning radius to the point that it would hang up on the side of the arena before completing its exit turn.

Throughout the last day of preparation for competition, team Fluffy refused to consider removing the rubber tires from the wheels as chronicled in the extended transcription in Appendix G. When Gary and Tom were finally convinced by Lindsey to remove the tires, they expressed open amazement at the effect the reduced friction that the tireless plastic rims had on Fluffy II's turn radius. My analysis indicates that this experience seems to have afforded the participants a qualitatively different appreciation of radius in a meaningful context unlike that they typically experienced in a mathematics classroom. This assessment is buttressed by the discussion of responses that team members gave when asked to describe the mathematics they experienced during school.

Participant Views of the Mathematics Involved in Robotics

How do the study participants view the mathematics involved in the robotics activities? Not surprisingly, their conceptions of the mathematics involved mirrors the mathematics that they experience in school. When asked to describe the mathematics they use, their descriptions in conversation and on the survey (see Appendix D) are of lower level mathematics and primarily skill directed. They mentioned measurement, the basic operations, using numbers in activities such as timing, symbols, calculating and programming formulas, and notions of speed or distance. Interestingly, while they recognized that there was mathematics in the robotics activities, they didn't see it related to the mathematics that they experienced in the classroom as discussed earlier in this chapter.

Vignette 12 is a typical example of their descriptions of the mathematics in robotics. An elementary teacher from one of the site's feeder schools visited the team one afternoon with her class. Her students were very interested in what the "bigger" middle school students were doing with robotics. So much so that they were willing to come after school to visit the team. Tom and Gary acted as tour guides and explained the program to elementary students and described the mathematics involved.

Vignette 12:

Gary: *We are doing Botball. We are trying to get as many points as possible as we can. What we do is build the robot out of Legos and stuff, then go onto the computer, and then we have to write the programs. It has to know what to do on its own, and where to go, and how to react if things happen to it. We get scored on how many balls we have on a field, with extra points if they go into the gutter, those tubes on the side. And even more if they get onto the top thing, lift under them, and then get them up there. To enter she knows, $2,000 to enter, you can get a scholarship to enter, or a grant, and more if you enter early, and the school pays $100, and everyone here gets to go to the group on Saturday, so you just show up and do your part. You get kicked out if you don't do anything. Usually, we have teams, on what robot, to do different things and it all comes together in the end as a team thing. We have a Lego scout, and then me and Tom, work on the ball that goes through the gutter, and Donny, programs, and then Andre has been the main program of that one. We have not seen, it, you have to have mechanical skills, documentation, research, programming abilities.*

Teacher: *What is the math that is involved?*

Tom: *You need to know numbers, seconds for how many turns, the degrees, to turn right, for example. One way you can program it, measure how far and how long it takes, and then take that time and multiply it by a however much you want to get the distance you want to go, because it runs on 100.*

The robotics activities that the students participated in also have promise for enriching the understanding of higher-level mathematics. The choices that students make in the design and operation of their robots affect what mathematics emerges in the context of the robotics activities. Understandably, middle school students might make different choices than older students regarding their robots. The KISS Institute (2000, 2001, 2002) asserts that mathematics concepts such as those involved in geometry, trigonometry, and calculus are accessible through Botball robotics activities. Appendix H shows slides from the KIPR that illustrate some of the higher level mathematics potentially accessible to students through robotics activities.

Summary

The data in this chapter present a complex montage of the team members' activities as they organized their efforts to build robots for the Botball competition. As they negotiated and made decisions, those decisions altered their individual and collective structure (Reid, 1996, 2002) and how their structures constrained their understandings, actions, and future choices. For example, both robot groups chose not to utilize sensors that would help their robot navigate more accurately. This decision limited the complexity of their programs and affected the mathematics that was accessible in their activities. The process was complex, open-ended, recursive and on-going as the team members refined their robots for the competition. In the next chapter, I will take up the meaning and implications of this study.

Chapter 5

ANALYSIS AND IMPLICATIONS

Cold-hearted orb that rules the night,
Removes the colors from our sight.
Red is gray, and yellow...white.
But we decide which is right...
And which is an illusion.
(Hayward, 1967)

This descriptive study looked at the emergence of mathematical understanding in middle school students as they engaged in open-ended robotics activities. It chronicled the mathematics they used, the mathematics they perceived themselves to be using, and the opportunities for the embodiment of mathematics understandings as they engaged in meaningful problem solving activities using robots. In addition, it sought to understand how the students cooperatively organized their efforts and negotiated meaning as they solved complex, open-ended tasks. Guiding questions for this investigation were:

1. What mathematical understandings emerge as students engage in robotics activities?
    a. What mathematics are the students using?
    b. What mathematics do they perceive they are using? Do their perceptions change in the course of the activities?
    c. What are the opportunities for mathematical embodiment in robotics activities?
2. How do students working cooperatively organize their efforts and negotiate meaning as they solve complex, open-ended robotics tasks?

This chapter discusses the findings that emerged from the data presented in the previous chapter and speculates on the potential implications of those findings.

Findings

The robotics activities described in this study have potential implications for the teaching of mathematics through a fundamentally different approach than traditional mathematics instruction. The findings from this study emerged in four categories: self-organization of work groups, robotics as problem solving, the negotiation of meaning, and mathematical understandings. The findings related to each of these areas are discussed in turn. The findings are then recapitulated in the context of Doll's curriculum matrix.

Self-Organization

The participants of this study appeared to be able to effectively self-organize and negotiate meaning in the context of the robotics activities. Moreover, their organizing evolved over time to meet emerging needs in their interactions. The creation of a new team member function category, the checkers, is an example of the participants' ability to recognize a need and dynamically reorganize to construct an effective means of addressing that need. These changes were negotiated amongst the team members in a peripheral sort of way in that they emerged from the actions and interactions of the team members rather than being directed by the team's leadership in any formalized manner.

The participants organized in an informal, task-focused but flexible structure. Tom and Gary, the 8th graders who were president and vice-president of the robotics club, became the de facto organizers of the initial efforts of the team. Thereafter, their roles as leaders subsided somewhat and, for the most part, they interacted the other team members as co-equals. The composition of the various groups of builders, programmers, checkers and web site builders changed over time; forming and reforming to meet developing team requirements as well as shifting personal interests.

While the team's organization seemed to be somewhat informal, it was neither rudderless nor necessarily dominated by age or grade level. 6th graders worked alongside with 7th and 8th graders as peers of comparable status. Leadership roles emerged and receded more on the basis of various abilities such as building or programming or the needs of the moment rather than mere seniority. No one and everyone was an authority in some respect in supporting the efforts of the team. Participants were valued on the basis of their ability and contributions to the team effort—not by their in-school social or academic status.

There appeared to be differing tendencies regarding participation depending upon the gender of the team member. The male team members seemed to prefer working in one area of the room, with specific teammates, or on a specific part of the robot. For example they would choose only to build or program. Often, they would have loud disagreements over what to do and they would break apart with one remaining to continue working. Eventually, they would get back together, usually after making some type of jest. They appeared to need the space apart to calm down and reflect on the problem before resuming working with their teammates.

The female team members were more eclectic in their interests. They would build, program, or work on the web page as their interests altered. Yet they seemed able to keep tabs on what was going on with one or both of the robots. Often, the female members would be seemingly off doing something totally unrelated and then suddenly turn up to help with a programming suggestion or the perfect Lego piece to address some vexing structural problem. For example, a close read of Lindsey's actions on the last day of preparation for the Botball competition in Appendix G reveals that she was involved in and responded to many different activities using what Goldman Seagall (1991) describes as *peripheral vision*. She used her peripheral vision to remain aware of what Tom and Gary were doing with Fluffy II while simultaneously being involved in a variety of other activities. She would make a suggestion, then get involved in something else, and then return to monitor the boys' progress and make the suggestion again.

Yet her use of peripheral vision involved a spatial quality not present in Goldman Seagall's description. It was not a matter of being driven off by the older male students. Lindsey, a 6th grader, remained true to her conviction that her solution would work. Yet, instead of choosing a confrontational approach like that favored by many of the male team members, she continued to work her suggestion in tangentially; using space to avoid or moderate any potential conflict. She was persistent where her male teammates would have favored confrontation and patiently kept raising her idea until it was accepted. This cycle was repeated several times until Tom and Gary finally decided to listen to her. Ultimately, her suggestion was startlingly successful (to Tom's and Gary's surprise) and Lindsey was resoundingly validated in her persistence with her suggestion.

If there was an arbiter of status, it appeared to be prior experience with the team and experience with working with Legos or with programming rather than age or grade level. Although previous team experience was valued, current behavior, contributions and aptitude were valued more. Victor, a 7^{th} grader, was the most experienced *Interactive C* programmer on the team. Yet he was widely viewed as unreliable by the others on the team. As a result Frank, a 6^{th} grader, became the principal programmer for X-Terminator. Steve and Sam, twin brothers in 7^{th} grade, also new to Botball, became quite facile in their programming. Donny, a 7^{th} grade student served by the site's special education staff, was widely acknowledged as the team's structural expert.

In many ways, the richness of the tasks coupled with the potential for multiple solution strategies and levels of completion, and the give and take of robotics activities seemed to serve as a leveler of position, in some cases standing the usual in-school social structure on its head. Upper class members and A-students were no longer the de facto leaders, female students found ways to contribute and be respected on an equal footing with the male students, and special education students found themselves in unfamiliar positions that were atypical of their in-class experience, being seen and valued as experts and contributors. In many ways the open-ended nature of the robotics activities appeared to precipitate or catalyze the opening up of the in-school social structure, and new relationships emerged from the interactions of the team members. In this respect, the robotics activities reflect the advantages of mathematical play in "that students can take part at their own level and build on their individual knowledge and understanding. It [mathematical play] also enables students to make errors in a supportive environment" (Holton, Ahmed, Williams, & Hill, 2001, p. 413).

Robotics as Problem Solving

The National Council of Teachers of Mathematics (NCTM) defines problem solving as, "...engaging in a task for which the solution method is not known in advance" (2000, p.52) and serves as an integral, major means of learning mathematics. The robotics activities described in this study not only meet that description but also exhibit the many factors involved in problem solving mentioned by NCTM, such as (pp. 52-55):

- Problem solving draws on students' previous knowledge.
- Problem solving requires a significant amount of effort.
- Problem solving involves open-ended problems.
- Problem solving builds persistence, curiosity, and confidence in unfamiliar situations.
- Good problem solving integrates multiple topics and involves significant mathematics.

- Problem solving encourages collaboration, discussion, and alternative thinking.

Replace the words "problem solving" with "robotics activities" in each of the statements above and the result would aptly reflect the experiences of the participants in this study. NCTM goes on to state that "Good problem solvers become aware of what they are doing and frequently monitor, or self-assess, their progress or adjust their strategies as they encounter and solve problems" (p. 54). Thus the development of self-assessment seems related to the growth of the intellectual autonomy and personal sense making that is essential to the construction of logico-mathematical knowledge (Kamii, 2000). The team members were constantly evaluating their progress as they prepared their robots for competition. They determined how their robots were built and programmed and whether the robots were good enough (or viable) for the competition. The students were acting from a position of autonomy.

In terms of specific problems, the *C* programming language did not appear to pose a major obstacle for the students. The participants did not act as if the *C* language intimidated them and were quite willing to invest significant amounts of time to learn *C* in order to program the robots. That is not to say that they did not have problems with the language or, as a result, make choices that limited the complexity of their programs. The students appeared to have a different attitude towards *C* than many of the adult sponsors that I encountered in three years of attending Botball teacher workshops. In a context where both the students and the adult participants were on a more or less equal footing with respect to knowledge of *C*, the students seemed less inhibited about attempting programming and making mistakes, more willing to experiment. Where an adult sponsor might baulk, the students appeared eager to engage, perhaps because they saw this as unlike their typical in-school context where an acknowledged adult expert is present. An additional factor in the participants' willingness to attempt programming may be the intrinsic motivation of working with the robots and seeing the result of their efforts come to life. The students also did not hesitate to consult the *C* programming reference material when needed. The fact that these manuals appeared to be written at a higher level of reading than most middle school mathematics textbooks did not seem to deter students from consulting them in order to figure out *C* syntax or how to use particular commands; unlike in mathematics class where they are unaccustomed to reading the textbook for information.

In contrast to the students, *C* appears to be more problematic for the adult sponsors. Unfamiliarity with programming in general and the *C* language in particular are the concerns most often raised by participants at the Botball teacher workshops that I have attended. Unwillingness to forge into the unknown territory of *C* programming may constitute a perceived obstacle for educators when considering whether or not to sponsor or attempt these types of robotics activities.

Negotiation of Meaning

The meanings that emerged appeared to be related to a number factors of which I have identified three to discuss: (1) the open-ended nature of the robotics tasks (task structure), (2) the prior experiences of the participants (personal structure), and (3) the participants' understanding of the emerging team context with reference to their in-school experience (team structure. The study participants' negotiation of meaning co-emerged through the dynamic, indeterminate interactions of these structures in several ways:

- Argument
- Use of space
- Design choices
- Doing/action
- Collaboration/cooperation

Each of these aspects of the negotiation of meaning is discussed, in turn, below.

Argument. With a predominantly male team composition, the favored approach to negotiation of meaning was that differences in understanding were often worked out through somewhat conflictual arguments, with each party insisting that they were correct. These arguments were often loud and the participants often became quite emotionally involved. Resolution of these arguments tended to take one of three forms: (1) One party would convince the other of the soundness of their logic. Sometimes this form of resolution would be delayed until after a period of reflection and cooling off. (2) The parties would agree to test their differing theories in action using a robot. (3) The parties would agree to shelve their disagreement temporarily and work on something else.

In contrast to an in-school class structure, these arguments were always initiated by the students themselves and involved subject matter in which they were intensely interested and on which they were working together. Occasionally, an argument would expand as other team members joined in according to their interests and, infrequently, the sponsoring teacher or myself would join the fray. For the most part, argument served a constructive role in the team's efforts to build and program autonomous robots. As experienced in this study, argument seems consistent with Wood's (1999) definition in that they were discursive exchanges for the purpose of convincing others. However the use of argument by the team members also exhibited many of the features of synergistic argumentation as described by Cassel (2002) in that the learning of the whole, that is, those participating and attending to the argument, through argument was greater than what the participants would have been able to achieve individually. Arguments seemed to play a crucial role in developing both group and individual autonomy as new understandings emerged.

Space. Space emerged as significant in the negotiation of meaning. The importance of space became evident in several ways. In the context of argument, space was used to create physical and psychological separation between the parties to an argument. Of note, the use of physical space also appeared to be somewhat gendered. For the male participants, space was used to reflect and calm down as arguments neared resolution. In contrast, female participants appeared to use space during the argument to moderate its intensity prior to achieving resolution. Thus, while the males retreated to their individual spaces during conflict, the females used these times to interject ideas and offer resolutions. In either case, whether used to separate, reflect and calm down or to moderate intensity, space seemed to be essential to a constructive and productive argument.

Design Choices. Design choices also seemed to affect the mathematics used and also the meanings that emerged for the students. The mathematics involved in building and programming a robot are different depending upon the robot's composition and sensor configuration. In this study, neither Fluffy II nor X-Terminator used sensors except for a basic photocell used to detect the start signal. The students were aware that their choices in constructing the robots affected the mathematics involved. As Gary described the relationship between robotics and mathematics, "We could relate it to geometry by figuring out distances using the equations that we're learning. But with the programming we're doing we don't need to." Gary described the design choice in this way:

> *Well, we wanted to build the simplest robot we possibly could, so we wouldn't have any room to malfunction. So it's just really simple to just*

go straight and turn, instead of having to do circles or 180 degree turns. Alls we did was 90-degree turns.

From an enactivist perspective, the choices that the participants made in strategy and robot design affected the negotiation of meaning through changes in their personal structure as well as the team-as-a-system structure. The changes in structure in turn constrained both the further choices that might be made and mathematics involved, both from the perspective of mathematics that is used as well as the mathematics understanding that could potentially emerge.

Doing. The participants' negotiation of meaning was often played out through action or doing. For example, it appeared that for Brad and Alana, being able to reference the individual components of the robot to their own body functions and experiences enabled them to think about decomposing the task to the level necessary to program the robot. This enabled them to use their bodies as objects to think with (Papert, 1990) in coming to understand the level of complexity of instruction required to successfully program a robot. For Brad and Alana, programming their robot was not merely a process of translating their thoughts; they had to adopt the perspective of the robot. Using their body as an object to think with enabled them to come to know how to act and think like a robot. In other words, their embodied experience as a robot provided a vehicle for understanding how to program in a way that a robot could understand. The notion of learning/doing

(Fleener, Adolphson, & Reeder, 2002) captures the complexity of Brad and Alana coming to embody their understanding of knowledge, that is, thinking like and programming a robot, as a complex of relationships in the fabric of the active, social, and contextual processes involved in robotics activities. Learning/doing, as an emergent and synergistic process, is nonlinear and uses positive feedback into the learning dynamics.

Collaboration/Cooperation. Both collaboration and cooperation were evident in addressing the problems that the participants encountered in the robotics activities. Collaborative strategies involve two or more participants working intimately and interactively together, continuously negotiating as they address a problem. As such, collaboration is more focused on the process of working together, more internally driven or student-centered (Panitz, 1999). Cooperative strategies involve participants parceling out tasks in pursuit of a common goal, possibly with periodic comings-together to review progress toward the goal. Cooperative strategies are focused more on the end product and externally imposed or teacher centered. There is cooperation in the sense of working toward a common goal but the participants are responsible for only their piece of the project. In other words, in cooperative strategies, negotiation is episodic or periodical rather than continuous.

In this study, Donny worked from a cooperative perspective in that he worked primarily on his own to build robots. He would renegotiate his constructions only when forced to by their partial destruction. He considered the robot's structure in a proprietary way. It was *his* and also his contribution to the team effort. Victor and Frank, however, worked in a more collaborative fashion. There was a continuous stream of animated discussion between the two students as they worked on the competition program for X-Terminator. The program was neither Frank's work nor Victor's it was *their* work.

Both cooperative and collaborative efforts successfully contributed to the team's labors. More importantly, the participants found ways of contributing that best suited their strengths. Neither is necessarily superior, but often classrooms are organized favoring cooperative learning over collaborative learning. What this study points out is that in a classroom culture, having the space for both may be necessary, especially for students like Donny.

Mathematical Understandings

The mathematical understandings of the study participants appear to be enriched through the robotics activities. They seem enriched because the robotics activities contextualize the decontextualized mathematical abstractions that students encounter in the classroom. In this study, the relationship of time, distance, and velocity were contextualized in the *C* programs written by students for the team's robots and acted out in the ensuing maneuvers in the competition arena. Understandings appeared to be enriched, for example, Frank's experiences with proportional reasoning in his coordination of the familiar, degrees, with the unfamiliar, the servomotor command range of 0-4000, as he programmed X-Terminator's forklift arm and his experiments with the sonar. Additional mathematical understandings were accessible to the participants but their choices in building and programming the team's robots, especially in terms of sensors selected, precluded their emergence.

The participants reported that working with the robots helped their understanding of mathematics. However, they reported that they didn't see a relationship to the mathematics they encounter in school. From their explanations, it was clear that they viewed the mathematics they were using in Botball as easier than the mathematics they were studying in school. Even so, they were aware that their design choices affected the level of mathematics that they encountered. The mathematics concepts that the participants mentioned were referred to in ways that made it clear that the students thought of the concepts in a discrete manner such as: measurement, length, timing, the basic operations, or decimals. Other mathematical aspects of the robotics activities such as algebraic concepts went unacknowledged.

Each of the findings discussed above has potential implications for mathematics curriculum. How would robotics activities such as those in this study contribute to the construction of a curriculum infused with emergent mathematics? To answer that question, I will look at the robotics activities through the prism of Doll's curriculum matrix.

Doll's Curriculum Matrix

It might be useful at this point to view the robotics activities described in this study through the prism of Doll's curriculum matrix (1993). With his matrix, Doll proposed a post-modern perspective on curriculum as "generated not predefined, indeterminate yet bounded" (p. 176) and suggested the four R's of Richness, Recursion, Relations and Rigor as criteria. I will discuss each of these criteria and their relation to the robotics activities of this study in the paragraphs below.

Richness

Richness refers to a curriculum's depth, layers of meaning, and openness to multiple possibilities or meanings. For transformation that leads to new understandings to occur

> ...curriculum needs to have the 'right amount' of *indeterminacy, anomaly, inefficiency, chaos, disequilibrium, dissipation, lived experience*....Just what is the 'right amount' for the curriculum to be provocatively generative without losing form or shape cannot be laid out in advance. The issue is one to be continuously negotiated among students, teachers and texts... (p. 176).

Doll's description of richness is consistent with the robotics activities described herein and seems consistent with the concept of mathematical play wherein "there is no closed goal or no obvious closed path to a goal" (Holton et al, 2001, p. 413). There is indeterminacy in the potential choices the participants might make in team strategy and robot design. Those choices affect the meanings that might emerge from the inefficiency, chaos, disequilibrium, and lived experience of the team's efforts.

Recursion

Doll (1993) describes recursion as related to the mathematical concept of iteration. Iteration is a repetitive process wherein the end result of a procedure is used as an input to begin the procedure anew. Recursion is characterized by both stability and change. The recursive procedure is the same each time it is repeated. However the input and output variables change each iteration, often in orderly but unpredictable ways. In human terms, recursion refers to the human capacity for reflective thought, especially taking one's thoughts as objects of reflection. Recursion or thinking about thinking is how we make meaning and "lies at the heart of transformative curriculum" (p. 178). Recursion as an aspect of thinking/doing is especially valuable as results of actions are reflected upon and considered for future actions in recursive problem solving.

Doll describes transformative, recursive curriculum as having no fixed ending or beginning. In the robotics activities, recursion manifests in the continual refining and testing of the robots, programs, and strategies. The choices made by the participants in developing their robots are an expression of recursive activity. Similarly, the continuing process of incorporating changes and refinements is evidence of ongoing reflection on previous activities and choices.

Relations

The twin complementary aspects of relations, pedagogical and cultural, are reflected in the robotics activities portrayed in this study. Pedagogical relations are the relations within the curriculum that give it its richness. While not yet formalized as a curriculum, the robotics activities are rich in relations such as the relationship between student choice-making and ensuing choices, the development of autonomy, or the emergence of new understandings. Or the relations between doing, embodied experience, reflective thought and subsequent understandings revealed through action. The initial conditions of the Botball activities are constrained by the rules (See Appendix A) and are bounded by the competition yet the in-between is indeterminate, and the potential strategies and robot designs are innumerable. The relation between the competition and individual team outcomes is simultaneously determinate and indeterminate.

Cultural relations are those relations external to the curriculum within which the curriculum is embedded. There are both narrative and dialogical aspects to cultural relations. Narrative involves history, language and place situating the activity through story, its telling, and location. Dialogue interrelates history language and place to provide a local context for our interpretations and interconnections to external cultures and their interpretations. Dialogue and narrative merge in discourse "bound always by the localness of ourselves, our histories, our language, our place, but also expanding into an ever-broadening global and ecological network" (Doll, 1993, p. 180). In this framework, learning becomes a process of negotiating the passages between personal and others' (local) constructs and between our (local) constructs and theirs (extra-local).

Using Botball as a microcosm, the team members first negotiate strategy and form of the robots in the context of the team history and the anticipated context of the competition based upon the local interpretation of the rules. Once at the competition, the passages are negotiated between our team's local interpretation and other interpretations in the form of the actual competition arena, judges' interpretations of the rules, and other teams' interpretations in the form of robot designs and competition strategies. The process is interactive, interrelational and ongoing.

Rigor

Doll's description of rigor draws upon interpretation and indeterminacy to assert that "One must be continually exploring, looking for new combinations, interpretations, patterns." He continues to define rigor as "purposely looking for different alternatives, relations, connections" (p. 182). Rigor implies a conscious effort to reveal assumptions and valuations and negotiate the passages in between. The ensuing dialog is a result of rigor, a mix of both indeterminacy and interpretation from which meaning emerges.

In the robotics activities, rigor was revealed in the many exploratory activities of the team members as they developed their robots. Frank experimented with the sonar. Lindsey and Carol explored the use of touch sensors. Sam and Steve experimented with programming the Handy Board's text window. Each robot's structure underwent several transformations before workable versions were developed. Brainstorming was used to attempt to identify and account for potential strategies both for our team and opposing teams. Many of the programming and structural ideas were considered and rejected as dead ends in the process of developing the team's robots. Again, the notion of mathematical play seems related to rigor as exemplified in the team's meanderings on en route to their ultimate competition robot designs. Holton et al (2001) seem to be echoing the Doll's idea of rigor in their discussion of the importance of mathematical play in learning.

> It would seem that to achieve a high level of understanding, it is as valuable to know that certain things will not work and why they will not work, as it is to know positive results. This certainly appears to be the way we construct our own internal map of a new city. By taking wrong turns and seeing where we end up we achieve a better concept of the layout of the city. In this way, through play and exploration over a larger area than is actually required to solve a particular problem, we provide the foundation for further learning. (p. 413)

The robotics activities appear to exemplify the notions richness recursion, relations and rigor elaborated in Doll's curriculum matrix. If so, there may be potential implications for the application of robotics within the academic curriculum, especially within mathematics education in particular. Those implications of robotics are discussed in the ensuing paragraphs

Implications

Robotics activities such as those described in this study may have the potential to be employed in meaningful ways within the school environment to meet curriculum objectives in an emergent way. Curriculum dynamics supporting an emergent curriculum encourages self-organization through rich, recursive, relational, and rigorous problem solving activity.

> Perceived as a dynamic ...the curriculum, viewed as a self-organizing process, entails entirely different ways of understanding and organizing our interactions. (Fleener, 2002, p. 165) ... [B]orderland classrooms are the type of environments where curriculum dynamics will occur. ... It is in these borderland classrooms that new patterns will emerge, new problems will stimulate further growth, and new challenges to our very roles and identities will occur. (Fleener, 2002, p. 179)

Borderland classrooms will engage students in activities where they are able to make choices according to their interests without being coerced, as is the case with current curriculum structure. The richness of the context would enable new understandings that emerge from these choices to fulfill curriculum objectives without looking like curriculum to the students in the traditional sense of curriculum as "the race-course run" or set of pre-established learning events.

For the example, using the robotics activities of this study, the students' perspective is that the robotics activities are intrinsically interesting, accessible, and meaningful. They are not conscious of any curriculum concerns. From an educator's perspective, mine, the students appear to be using, enriching and constructing powerful conceptual understandings in the context of these rich tasks and I can see the connections for curriculum. Moreover, the educator's concern, the curriculum, has become invisible to the student. Meanwhile, curriculum objectives are met in the emergence of conceptual understandings from within the students' context of choice in the pursuit of the activities. In other words, these types of rich tasks within open environments may make it possible to meet the adult concerns, curriculum objectives, in a way that is less coercive and transparent to the students. The key question then becomes whether the robotics activities can be brought into the classroom without losing the features that make them intrinsically interesting for the students.

The accessibility of the robotics activities to a variety of students of varying backgrounds in 6^{th} through 12^{th} grades is just one indication of the richness of content, of which, mathematics is just one facet. Because of this richness, these activities have possible relevance beyond mathematics education. The case could be made that there are a host of potential applications for robotics or similar types of rich activities in science education or integrated studies as well.

Limitations

There were a number of limitations that affected this study. First, the study took place in the context of an after-school activity. This limited the students who were able to participate in several ways: (1) The main limitation to participation was the willingness of parents to provide transportation for their child. This limited the participation of students from those families unable to provide transportation due to socio-economic status. (2) Other conflicting after-school activities affected participation and the ability of students to meet the Botball meeting requirements. The availability of other after-school programs is the main reason that team members are lost going from 6^{th} grade to 7^{th} grade. Many students chose to participate only in the Robotics Club because its meeting times were more flexible. And, (3) many middle-school students are latchkey babysitters for their younger siblings, thus preventing participation. Despite the limitations of an after-school program and considering the exceptions noted below, the team members were fairly representative of the student population in terms of socio-economic status and academic standing.

A third limitation of this study is the level of female and minority student involvement. In previous years, no female students participated in the robotics activities despite the fact that two of the three adults working with the team were female. This study was encouraging in that, for the first time, three female students participated in the program and, hopefully, the proportion of female (and minority) students participating will continue to increase.

Fourth, the opportunities for students to program were limited by access to computers. During most sessions, there were three computers available for the participants to use. This effectively limited the number of team members that could become involved in programming to no more than six to eight of the participants. Ideally, it would be desirable to have at least one computer for every two students. Interestingly, this is the first year that computer access has been the major limitation for programming. In previous years, we did not have enough microprocessors and Legos to build more that two or three robots.

Finally, since the nature of this study was primarily descriptive, only a modest attempt has been made to assess what new mathematical knowledge the participants constructed. No pre/post assessments were used. A formal pre/post sort of assessment would imply pre-knowledge of the mathematics involved in the robotics activities and a specific, integral curricular agenda. I felt that it was premature at this stage in my research to be focusing on curriculum study before I had assured myself of the potential fruitfulness of robotics activities for learning mathematics. I wanted to answer the "What's there?" and "What could be there?" questions before addressing "How well does it work?" questions for a non-existent curriculum. In the end, these limitations coupled with the implications noted above point to the need for continued research.

Future Research

One intriguing aspect that emerged from this study was the accessibility of the robotics activities for students with special educational needs and identified learning disabilities. In many ways, their participation in the activities seemed to empower them in unexpected ways. They found themselves in unfamiliar roles as leaders and experts. Perhaps because everyone was on less familiar ground and there was no established school structure being imposed like that of an in-school classroom, they were freed to revisit their social and intellectual status. The mechanism of emancipation for these students would be worth investigating.

A related area in terms of accessibility that needs to be explored further is why the robotics activities did not attract a representative proportion of female and minority students. What are the factors? Is the problem due to the nature of the activities themselves, or having to contend with so many male students, or participating after school, or some other factor(s)? Are there other activities of similar richness, from a mathematical perspective, that female and minority students would find more attractive?

Regarding negotiation of meaning, are the male participants' favored modes of negotiation, that is, conflictual arguing an outgrowth of the authoritarian privileging of knowledge that they experience in the classroom? If, as is the case in traditional classrooms, the teacher is the knowledge arbiter, students are unlikely to experience the same quality of negotiation of meaning as they might in a problem centered classroom where synergistic argumentation occurs. Placed in a new context where there is not a central recognized knowledge arbiter, each participant might be individually trying to fill a perceived power, knowledge, or authority figure void marked by the absence of a teacher in a familiar role. This is consistent with Rogoff (1990) who contends that context influences the interactional processes that shape the development of either skills, understanding, or transformation of thought. If so, then it is possible that a traditional, teacher-centered classroom is implicated in inhibiting the development of the intellectual autonomy and critical thinking required for effective argumentation and, ultimately, transformative thought.

As alluded to earlier, the principal question that must be addressed in the future is: How can educators leverage the wealth of significant mathematics involved in rich activities such as robotics to fulfill curricular needs in an emergent way? One of problematic aspects of accomplishing this is that the team size of 16 participants is unrealistic in terms of translating or adapting the robotics activities into curriculum. Given the open, self-organizing structure of the team, 16 extremely active students was the maximum the two of us, the sponsoring teacher and I, could handle. Scaling these activities to the typical class size per teacher could be challenging. Another aspect that may affect the design of an emergent curriculum is that the findings indicate there may be a preference for having resources available to consult as needed rather than blanketing the students with decontextualized curriculum in the form of textbooks. Responding to challenges like these will be crucial to how can an activity like Botball be transitioned from the open-ended, self-organizing, collaborative, and informal experiences of an after-school context into the more confining structure and formalization of the in-school context. More importantly, can it be done without losing its intrinsic interest and richness for the students?

Concluding Remarks

The robotics activities portrayed in this study exemplify rich tasks that appear accessible to students of varied abilities. This accessibility may potentially provide an avenue to address equity issues in education such as those involving gender, minority, and students with learning disabilities. The accessibility of the robotics activities is also important since robotics has the potential to provide a meaningful context for the study of mathematics in a transformative mathematics curriculum. In this study, the students' choices influenced the complexity of the mathematics that emerged from and through the activities. Robotics seems to exemplify the appropriate use of technology to create meaningful, open-ended, problem solving activities. Further research is required in order to adapt these types of robotics activities into the in-school context as part of a transformative mathematics curriculum.

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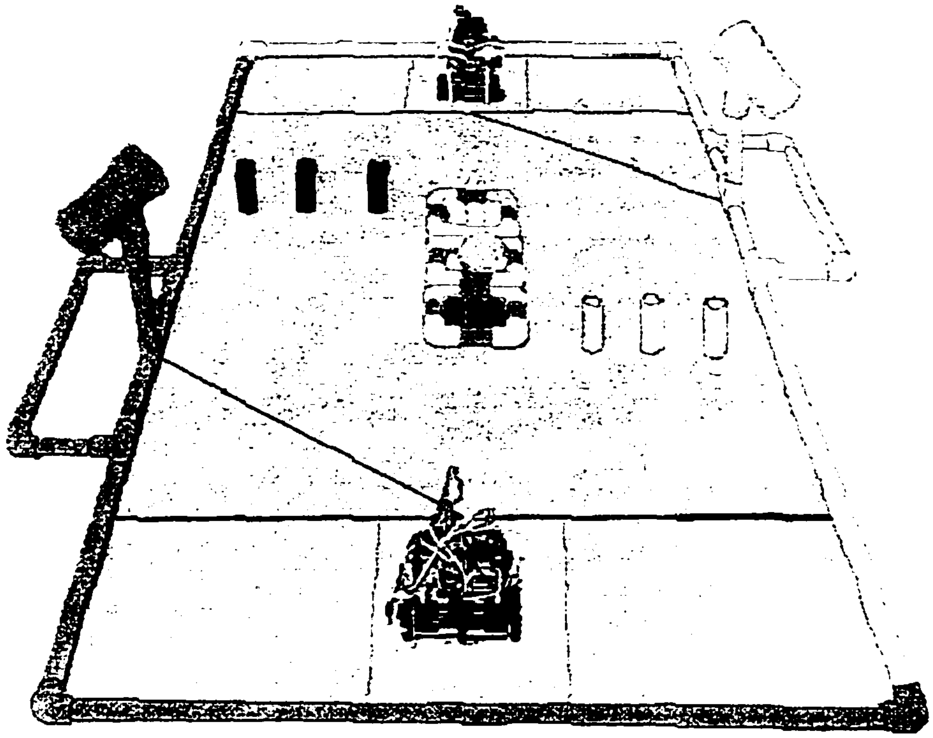
Appendix A: *Botball & Robotics Cluster Competition Rules*

Figure A1 *2002 Botball Competition Arena*



Note: From "Botball 2002 Teachers Workshop" presentation by D. Miller, KISS Institute for Practical Robotics, January 2002, Norman, OK. Copyright 2002 by KISS Institute for Practical Robotics (www.botball.org). Adapted with permission.

Robot Construction Rules (Miller, 2002):

- Robots may be made out of any or all of the kit parts except: the plastic box, bags and wrapping or packing material; the charger; download cables and interface electronics.
- Glue and tape may only be used for attaching non-Lego sensors, servos and motors to the robot. Never glue Lego to Lego. No glue or tape may be applied to paper!
- No more than one piece of LEGO may be glued to any of the sensors. The servos & modified gear motor can have up to 7 pieces attached: one to each side and one to the effector plate. Sensors that come from KIPR with one LEGO piece attached may have one additional piece glued on, if desired.

- You may add 36 square inches of paper (max 20lb) or foil. The paper/foil may only be held in place through the use of Lego and other kit parts (no glue or tape).
- You may add 36 inches of thread or line or cable (max diameter 1mm), for use ONLY as tensile elements in winches and pulleys.
- Additional paper or foil may be used as light guides for the sensors (light guides may be attached by glue or tape, but cannot be used structurally or for manipulation).
- All robots must start themselves when the game light goes on. Robots must stop themselves within 90 seconds after game start.
- Robots must fit in starting box 15"l x 12"w x 12"h.
- Each robot kit contains two computers/power sources.
- If two robots are made from a single kit, they represent a single tournament entry.
- Two robots from a single kit must together fit within the size constraints.
- Two processors may exist on a single robot.
- It is not necessary to use all the parts in a kit.
- No electrical modifications may be made to either processor, any sensors or any motors.
- No wire extensions may be used except those provided in the kits (foil may not be used as wire!).
- No external communications may be used during tournament play:
    - No external IR transmitters may be used.
    - The serial cable and interface boxes may not be used during tournament play.
    - Communications between a single team's robots is allowed.
- You may trim the connector potting material as needed to ease insertion or mounting of sensors.
- You may file or sand the mounting holes on the HB box to ease mounting of Lego parts to the box.
- You may use wire ties to neaten up the wiring on your robot (cannot have any structural role).
- Servo accessories, grommets, screws, etc may only be used to mount an effector plate (servo horn) to the servo, a piece of Lego to the horn, or lego to the servo (one piece per face). Only one servo horn may be used per servo.
- Servo horns may be trimmed to facilitate mounting to a Lego piece.
- Robot teams can have a maximum of 4 independent structures on the field.
    - All components together must fit in the starting box without any external restraint.
    - Each piece must be large enough so that it does not, in the judges opinion, constitute a jamming hazard.
    - Examples of structures include: robots, barricades, detachable baskets, etc.

- Lego parts cannot be physically modified except for:
  - Pneumatic tubing can be cut to desired lengths.
  - Lego straws and accordion tubes may be trimmed to desired lengths.
  - Lego pieces being glued to a non-lego part may be sanded or trimmed on the surface being glued to ease attachment.
- Each robot must have a name approved by an adult team leader (G rated) before the tournament.

Game Rules & Scoring

- Each team starts with one ball that may be placed anywhere in their end zone, including onto a robot.
- Each team scores points by:
  - Freeing their balls from tubes and nests.
  - Placing balls in the team's gutter
  - Getting the foam ball and nests in the endzone or gutter
  - Placing balls in team's basket
  - Placing foam ball in team's basket

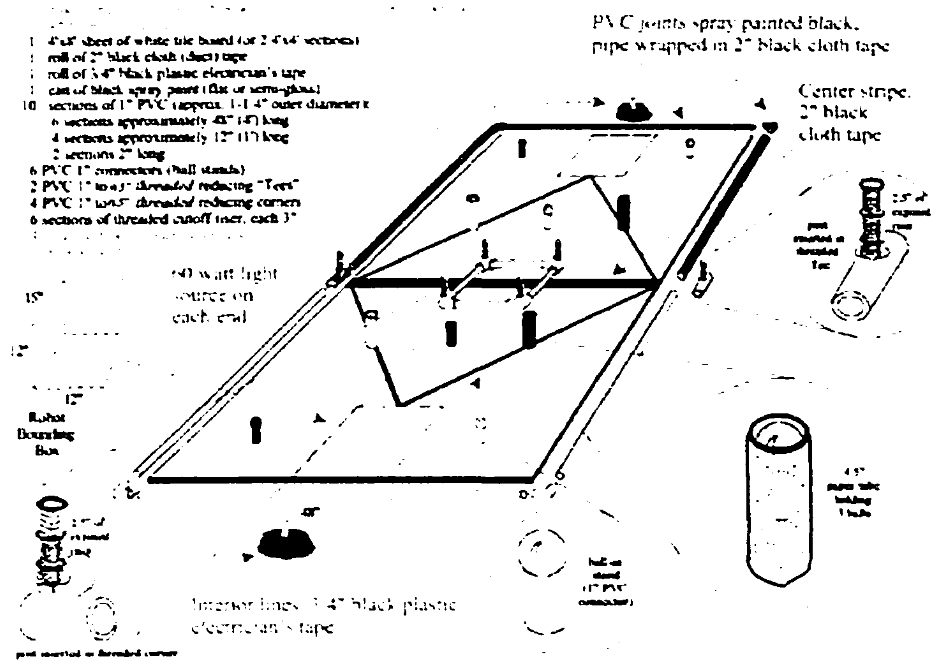
For the black team:

- Begin with 19 points.
- Subtract 1pt for each black ball that at the end of the game is:
  - Trapped inside a nest.
  - Trapped inside a tube that is within 45 degrees of vertical and touching the playing surface (the tube that is).
- +3 pts for each black ball whose center is within the vertical projection of the black goal gutter, and not in the basket.
- +7 pts for each black ball whose center is within the volume described by the black basket.
- +5 pts for each nest whose center is within the vertical projection of the black end zone or black gutter.
- +10 pts for foam ball whose center is within the vertical projection of the black end zone or black gutter.
- +30 pts for the foam ball in the black basket (ball is inside basket or breaking the surface of the opening of the basket -- the ball may be held in place by a robot).

Tie breaking is determined by (in order):

1. Team with fewest of opponents balls in their basket and gutter.
2. The team that has scored the foam ball.
3. The team that has the most of their points scored in the sum of their basket and gutter (not counting nests, freed balls).
4. The team who has a robot with a power switch closest to the foam ball (if the ball is on the playing field).
5. The team who has a robot with a power switch closest to the support post for the basket.

Figure A2 *2001 Botball Competition Arena*



Note: From "Botball 2001 Tutorial" presentation by D. Miller, KISS Institute for Practical Robotics, January 2001. Norman, OK. Copyright 2001 by KISS Institute for Practical Robotics (www botball.org). Adapted with permission.

Robot Construction Rules (Miller, 2001):

- Robots may be made out of any or all of the kit parts except: the plastic box, bags and wrapping or packing material.
- Glue and tape may only be used for attaching sensors and the servos to the robot. Never glue Lego to Lego. No glue may be applied to paper!
- No more than one piece of LEGO may be glued to any of the sensors. The servos can have up to 7 pieces attached: one to each side and one to effector plate.
- You may add 36 square inches of paper (max 20lb) or foil. The paper/foil may only be held in place through the use of Lego and other kit parts (no glue or tape).
- Additional paper or foil may be used as light guides for the sensors (light guides may be attached by glue or tape, but cannot be used structurally or for manipulation).
- All robots must start themselves when the game light goes on. Robots must stop themselves within 90 seconds after game start.
- Robots must fit in starting box 15"l x 12"w x 12"h.

- Each robot kit contains two computers/power sources:
  - If two robots are made from a single kit, they represent a single tournament entry.
  - Two robots from a single kit must together fit within the size constraints.
  - Two processors may exist on a single robot.
  - It is not necessary to use all the parts in a kit.
- No electrical modifications may be made to either processor, any sensors or any motors.
- No wire extensions may be used except those provided in the kits (foil may not be used as wire!).
- No external communications may be used during tournament play:
  - No external IR transmitters may be used.
  - The serial cable and interface boxes may not be used during tournament play.
  - Communications between a single team's robots is allowed using KIPR supplied software.
- You may trim the connector potting material as needed to ease insertion or mounting of sensors.
- You may file or sand the mounting holes on the HB box to ease mounting of Lego parts to the box.
- You may use wire ties to neaten up the wiring on your robot (cannot have any structural role).
- Servo accessories, grommets, screws, etc may only be used to mount a horn to the servo, a piece of Lego to the horn, or lego to the servo (one piece per face). Only one servo horn may be used per servo.
- Servo horns may be trimmed to facilitate mounting to a Lego piece Robot teams can have a maximum of 4 independent structures on the field.
- All components together must fit in the starting box without any external restraint.
- Each piece must be large enough so that it does not, in the judges opinion, constitute a jamming hazard.
- Examples of structures include: robots, barricades, detachable baskets, etc.
- Lego parts cannot be physically modified except for:
  - Pneumatic tubing can be cut to desired lengths.
  - Lego straws and accordion tubes may be trimmed to desired lengths.
  - Lego pieces being glued to a non-Lego part may be sanded or trimmed on the surface being glued to ease attachment.

Game Play & Scoring

- Game starts when lights go on.
- Black-ball team starts on black-pipe side
- Black-ball team attempts to score as many black objects as possible.

- Table Points:
    - 1 pt for every black ball touching the gameboard surface (start with 2 pts).
    - 1 pt for every black stand or black tube tilted at least 45 degrees off vertical and at least one point must touch the gameboard surface (horizontal is ok).

- Nest Points:
    - 2 pts for every black item (ball, tube, or stand) whose center is contained within the vertical projection of the **inside** of the nest.
    - Nest points cannot count as table points.
- Post Points:
    - 5, 15, 30, 50, or 75pts for having 1, 2, 3, 4, 5 or more black items suspended on/from a **single** post (may repeat for each post).
    - Post points cannot count as nest points or table points.
- 5 pts for having nest completely on their side (this also doubles nest points and points on nest posts).
- 5 pts for having one or more of their robots on or in the nest (this also doubles nest points and points on nest posts).
- White-ball team does the same with their balls.
- A team's nest points and nest post points are doubled if the nest is on their side of the court (the vertical projection of the center tape does not intersect the nest).
- A team's nest points and nest post points are doubled if a team's robot (defined as a CPU with an independent mobility system) is resting on or in the nest and not touching any other part of the outside court.
- If a team has two robots in the nest, they still only receive a single doubling.
- If one team meets both doubling criteria, their nest points and nest post points are quadrupled.
- An item counts as a post item only if:
    - It is supported by the post or surrounds the post or is resting on an object (*cage*) that does so.

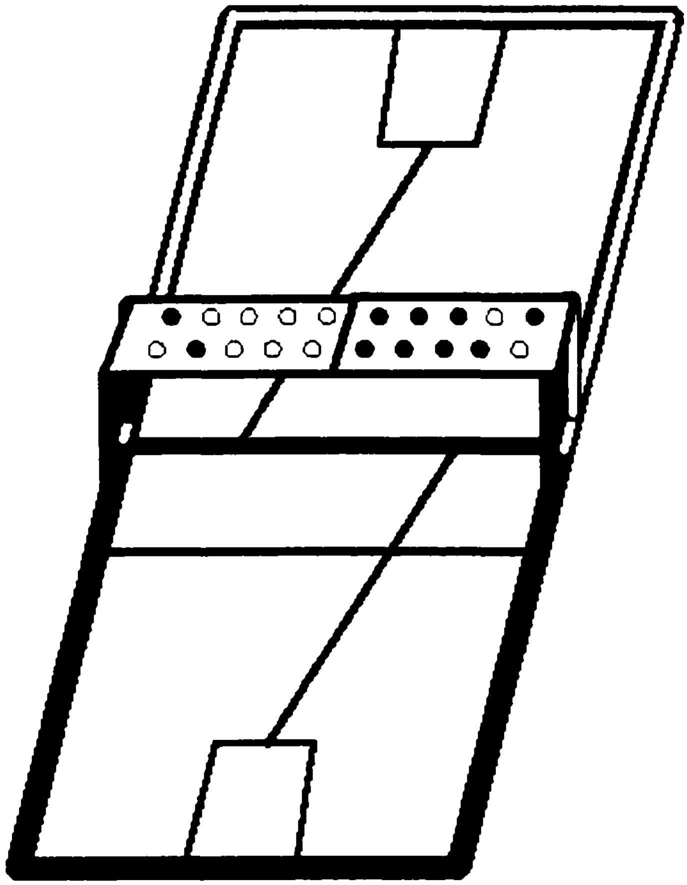
    AND
    - Neither the item or the *cage* is touching the game surface in or out of the nest.

    AND
    - Neither the item or the *cage* is touching any of your kit piece assemblies that touch the game surface (touching the nest frame is ok).
- White-ball team starts on white side
- Ties are broken by (in the following order):
    1. Team with the most items on posts.
    2. Team with the most items in any scoring position.
    3. Team with the nest most on their side.

4. Team whose closest CPU power switch is closest to the center of the nest.

- Scoring is determined by ball position at end of round (not how they got there).
- Items outside of arena are not replaced and do not score points.
- Robots may start their motors prior to game play, but must not leave the starting box until the lights come on.
- Robots MUST cut off all power to the motors by the end of the round (90 seconds after the lights come on).
- An unmolested robot must break the perimeter of the starting box within 10 seconds of the start of game play, or a false start will be called against that team.
- Two false-starts against a team will cause the forfeiture of that round by that team.
- Judges may decide against a molested robot's team if they believe that robot is incapable of movement.

Figure A3 *2000 Botball Competition Arena*



Note: Graphic by author based on Miller (2000).

Botball 2000 Robot Competition Rules (Miller, 2000):

- Robots may be made out of any or all of the kit parts except: the plastic box, bags and wrapping or packing material.
- Glue and tape may only be used for attaching sensors and the servos to the robot. Never glue Lego to Lego.
- No more than one piece of LEGO may be glued to any of the sensors. The servos can have up to 7 pieces attached: one to each side and one to effector plate.
- You may add 36 square inches of paper or foil. The paper/foil may not be used to hold Lego together, but may be used as netting, ball guides, etc.
- Additional paper or foil may be used as light guides for the sensors.
- All robots must start themselves when the game light goes on. Robots

must stop themselves within 90 seconds after game start.

- Robots must fit in the 15"l x 12"w x 12"h starting box.
- Each robot kit contains two computers/power sources.
- If two robots are made from a single kit, they represent a single tournament entry.
- Two robots from a single kit must together fit within the size constraints.
- Two processors may exist on a single robot.
- It is not necessary to use all the parts in a kit.
- No electrical modifications may be made to either processor, any sensors or any motors.
- No wire extensions may be used except those provided in the kits
- No external communications may be used during tournament play:
  - No external IR transmitters may be used.
  - The serial cable and interface boxes may not be used during tournament play.
  - Communications between a single team's robots, is allowed - but not explicitly supported by our software.
- You may trim the connector potting material as needed to ease insertion or mounting of sensors
- You may file or sand the mounting holes on the HB red box to ease mounting of Lego parts to the box.
- You may use wire ties to neaten up the wiring on your robot (cannot have any structural role)

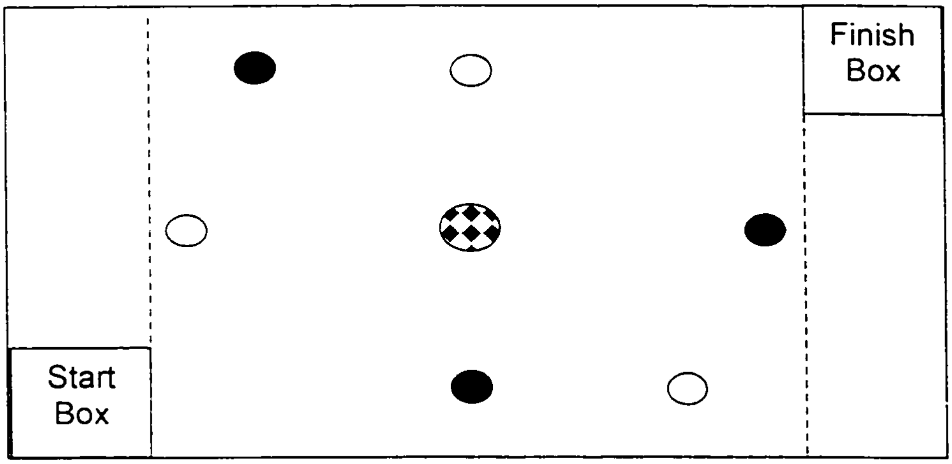
Game Play & Scoring

- Game starts when lights go on.
- Black-ball team starts on black-pipe side.
- Black-ball team attempts to score as many black balls as possible:
  - 1 Pt for every black ball on or above the gameboard, but off the mised platform (max 10).
  - 5 pt for every black ball on or above the tray, but off the raised platform (max 50).
- White-ball team does the same with their balls.
- A team's "tray points" are doubled if the tray is on their side of the court (defined as touching or over their thin cross-court line).
- A team's "tray-points" are doubled if a team s robot (defined as a CPU with an independent mobility system) is resting on the tray and not touching any other part of the court.
  - If a team has two bots on the tray, they still only receive a single doubling.
- If one team meets both doubling criteria, their "tray points" are quadrupled.
- White-ball team starts on white side.
- Ties are broken by:

- Team with the most balls on the tray.
- Team with the most balls in any scoring position.
- Team with the tray nest on their side.
- Team whose closest CPU power switch is closest to the center of the tray.

- Scoring is determined by ball position at end of round (not how they got there).
- Balls outside of arena are not replaced and do not score points.
- Robots may start their motors prior to game play, but must not leave the starting box until the lights come on.
- Robots MUST cut off all power to the motors by the end of the round (90 seconds after the lights come on).
- An unmolested robot must leave the starting box within 10 seconds of the start of game play, or a false start will be called against that team.
- Two false-starts against a team will cause the forfeiture of that round by that team.
- Judges may decide against a molested robot's team if they believe that robot is incapable of movement.

Figure A4 *2002 Spring Semester Robotics Cluster Problem*



You will earn points as follows.

1st to finish	5 points	1 point for each object knocked onto the surface
2nd to finish	4	1 point for parking in the box
3rd to finish	3	1 point for most interesting name
4th to finish	2	1 point for neatest design
5th to finish	1	1 point for simplest robot
		1 point for crossing the finish line
		5 points for knocking the Nerf ball on the surface
		5 points if Nerf ball is across Finish Line

Your team could earn up to 40 points!

Each round object is a paper tube standing on end containing three ping-pong balls of the respective color. The center tube also has a 4-inch diameter Nerf ball resting on top.

Appendix B: *2002 Botball Team Website Documentation & Student Log*

#1 Mechanical Design

Fluffy II uses the RCX brick. It lifts the balls over the pipe and places them in the gutter. It also knocks down the tubes, scoops up the balls, and drops them in the gutter. The 4WD helps traction for torque for going straight but not for turning. It uses pneumatics for lifting the arm. They used axles and fittings to make the scoop.

X-Terminator has good torque. The small gears go to big gears. It lifts the nest, rotates, releases the balls, places the nest on our side, and tries to go back for another nest. This is made with the Handyboard. A servo is connected to a fork (constructed out of a long 8 bar, skids, and L clamps).

#2 Software Design

Fluffy II makes a screeching noise when the calibration is wrong. This robots is designed to go straight, turn, lift, and go backwards. There are no If, Then statements. The robot turns, the servos raises and lowers the bulldozer. All code is timed and linear. For example, it sleeps for 3 seconds, goes backwards, sleeps, and brakes.

X-Terminator is supposed to go forward, back, stop for a few seconds, turns, goes forward fast and drops the nest and goes backwards fast. Some of the code is below.

> Servo0—2600, go back(1.0); servo0=1500 (lifts the nest); rightturn (1.0); servo0=2600 (drops the nest); goforward (2.0), stop (0.5); servo0=1500 (lifts and goes backwards).

#3 Software Code

Please see end of website for our codes as of this date.

#4 Team Strategy

The programmers have to find the right program for each bot. There are two robots, Fluffy II and X-Terminator. Fluffy II is meant to scoop up balls and place them in the gutter/ X-Terminator is meant to grab the nest with a fork-lift so the balls will be released. The programmers are also writing code specifically for gaining a lot of points at the seeding round.

#5 Testing Procedures

The builders came up with the idea for the two robots and built them while the programmers began writing code. Once they were built and code was written, they began testing them on a practice board we made. They keep testing until they finally get a program right. Timing is on problem. Our batteries aren't keeping their charge. They keep testing with new batteries to see the variation.

#6 Robot Names

Fluffy II and X-Terminator

#7 Team Assignments and Schedule

We have three groups: 1) Builders, 2) Programmers, and 3) Web Site Designers. We also have two archivists who document what occurs at our meetings.

We meet every Tuesday from 3:45 until 5:00, Thursdays from 3:45 until 7:00, and for two weeks on Saturdays for 3 to 4 hours.

#8 Weekly Status Report

Week 1. First, the teachers went to the tutorial and learned about the competition. O Tuesday, the teachers told the Botball team about the competition, its rules, and what's new in the kit. We knew we had to have people who would work on a website, people who would document, people who would program, and people who would build the robot. So, the teachers let us volunteer for our positions.

Then, we broke up into groups and figures out what we would build for the competition. We took out the pieces of the new kit and figures out what we would build. If we didn't volunteer to work on a specific thing, then our Robotics Club President would put you on a team. That is the team you would work with.

A team decided to build a forklift. This forklift is designed to pick up a nest and move it to our team's gutter. The team built the forklift and decided to use the Handyboard as the processor. Another team decided to build a bulldozer. The bulldozer is designed to knock over the tubes to release the balls. This also is designed also to scoop up the balls and place them in the gutter.

Students who volunteered to do the website started by learning the rules of the website, reading the material, and separating tasks. One student focused on research, another of web design, and another on importing graphics.

Week 2. The forklift team has started to make improvements on the forklift as well as making another robot.

The website team has accomplished more research, redid the initial page, and chosen more graphics. They have enlisted the help of another team member who is helping with design.

Week 3. The programmers are working to see how long it will take to get to the nest and back. Then, they made a program to flip the nest over so the balls will scatter everywhere. The bulldozer can scoop the balls up and put them in the gutter.

Week 4. The team members working on the Scout are adding a trailer to it. This is for the exhibition bot.

The programmers have been testing the servomotors and forklifts that is on the robot.

The website team has gotten rid of the stuff that was not important and put in some pictures.

Scout Bot—The gears took lots of work, then they tried different objects. Now it's ok, but there is non touching [*sic*] gears.

Programmers—Touch sensor didn't work, but now it does. It was the program.

Botball Bot—Add light sensor to the bot. They added a super pump.

Test Bot—The Handyboard was having difficulty, Its ok, [re]versed motors.

Exhibition Bot—It will be on an RCX computer with a super pump. The caterpillar is going to carry the robots over danger.

#9 Knowledge Base for Next Year's Team

1. Make sure two (2) main robots work before you build the exhibition [robot].
2. Make sure you get the robot working with programs and that they're equipped to do what the program wants it to do.
3. Always accept everyone's idea.
4. Work together—not on your own (at least 2 people on one bot).
5. Communicate—share ideas so we can try things out (speak your mind even if you think it's stupid.)
6. Don't write program and then write a whole new program. Stick with original program because you don't have time.
7. Download it [*Interactive* C] at home so you can practice.
8. Use the same program but add new details.
9. Don't spend too much time talking...spend more time with hands-on activities.
10. Take your time; don't rush.
11. Spend more time building robots than eating pizza.
12. STOP (Stop, Think, Observe, and Plan)—we haven't been observing as much as we should.

13. Builders need to tell programmers what exactly they want to do.

14. Don't lay materials where someone can knock it over.

Appendix C: *Participant Interview Guiding Questions*

1. Why did you choose to participate in robotics or Botball?
2. What experience do you have with: Computers? Legos? Robotics? Computer programming (If so, what kind?)?
3. How did you decide what to do as you built or programmed the robot?
4. Describe your working with other people to solve Botball problems.
5. Do you feel like you relied on the interaction of others in the building or programming task or is this something you could have done on your own? Please give some details in your answer.
6. Does Botball or robotics relate to any other subjects you have studied?
7. What is mathematics?
8. Describe your experiences with mathematics.
9. What was your worst experience with mathematics? What was your best?
10. Do you find mathematics useful? Why or why not?
11. Do you use mathematics in your non-school life? How?
12. How would you describe your mathematics abilities?
13. Does computer programming involve mathematics? How do you know?
14. Do computers or computer programming relate to other subjects you have studied?
15. When solving robotics or Botball problems, describe how you decided what to do?
16. Where there any strategies you used to solve robotics or Botball problems? Describe
17. Did you use mathematics to solve robotics or Botball problems? If so, how? How do you know?

18. Did your understanding of mathematics change because of your robotics or Botball involvement? Why or why not? How do you know? Please provide a few specific examples.

Appendix D: *Survey Form & Results*

Name:________________________________ Gender:________ Grade:______ Age:______
Age____ Ethnicity:__________________ Computer at home?_____ Internet at Home?____

Please check all activities/programs that you participate in:

Sports____ Band____ Choir____ Talented & Gifted program____ Special Ed program___

Student Government____ Academic competitions___ OU Academy____ Drama____

What grade do you typically get in: Science___ Social Studies___ Math___ Lang. Arts___

Please respond to the following statements using the scale:

Strongly Agree		Neither or Neutral		Strongly Disagree
1	2	3	4	5

Statement	Response
1. I enjoy building robots.	1 2 3 4 5
2. I enjoy programming robots.	1 2 3 4 5
3. I enjoy school.	1 2 3 4 5
4. Working with robots is related to what I learn in school.	1 2 3 4 5
5. Working with robots helped my understanding in Science.	1 2 3 4 5
6. Working with robots helped my understanding in Math.	1 2 3 4 5
7. Working with robots helped my understanding in other classes (please list here).	1 2 3 4 5
8. Building robots is related to mathematics.	1 2 3 4 5
9. Programming robots is related to mathematics.	1 2 3 4 5
10. If I had a choice, I would prefer to work with other people on a project.	1 2 3 4 5
11. I enjoy working with others to build and program robots.	1 2 3 4 5
12. Robotics could be used in school to help understand subjects	1 2 3 4 5
13. I had some experience building things with Legos, K'nex, and erector sets, etc., prior to robotics.	1 2 3 4 5
14. I had some programming experience prior to robotics.	1 2 3 4 5

On the back, please suggest ways that robotics could be used to help understand math.

Table D1 *Survey Results*

Statement	Response	
	Question # / Stem	Leaves
I enjoy building robots.	01	1111111111 222 55
I enjoy programming robots.	02	111111 222 333 4 5
I enjoy school.	03	1111 22222 3 444 5
Working with robots is related to what I learn in school.	04	1 22 333333 444 55
Working with robots helped my understanding in Science.	05	1111 3333 444444 5
Working with robots helped my understanding in Math.	06	1 2 333 4444 55555
Working with robots helped my understanding in other classes (please list here): Participant responses: Technology Education (1), Language Arts (1), Social Studies (1), **Reading (1)**	07	111 2 33333 4 5555
Building robots is related to mathematics.	08	1111 222 333 44 55
Programming robots is related to mathematics.	09	111111111 22 4 55
If I had a choice, I would prefer to work with other people on a project.	10	1 2 33333333 4 555
I enjoy working with others to build and program robots.	11	111 222 33333 44 5

Table D1 *Survey Results, continued*

Robotics could be used in school to help understand subjects	12	11 222 33333 **4** **555**
I had some experience building things with Legos, K'nex, and erector sets, etc., prior to robotics.	13	11111111**111** 555
I had some programming experience prior to robotics.	14	1111 222 3 555555

Notes: 14 respondents total. Female participant responses are denoted in bold print.

Table D2 *Age of Study Participants*

Age	Number of:	
	Males	Females
12	4	2
13	4	1
14	2	0
15	1	0

Table D3 *Grade Distribution by Subject*

Subject	A	B	C
Science	8/1	3/2	
Social Studies	9/3	1/0	1/0
Mathematics	7/1	2/2	2/0
Language Arts	8/2	3/1	

Note: Grades are listed as number of males/number of females.

Table D4 *Participation in other School-Sponsored Activities*

Activity	Participants: Male / Female
Sports	6/1
Band/Orchestra	6/2
Choir	4/0
Talented & Gifted program	8/1
Academic Competitions	4/0
OU Academy	7/1
Drama	3/1

Participant responses regarding how robotics could be used to help understand mathematics:

- Stacy: *Programming formulas and calculating formulas*
- Carol: *Timing, multiplying and dividing*
- Gary: *Programming helps practice math skills but doesn't help with math class.* (Note: As Gary handed me his survey from he explained that he had indicated on the survey that robotics didn't help with his understanding of the mathematics in his math class. He noted that he was taking high school level Geometry and did not see the mathematics that he used in robotics as related to the mathematics he was required to perform in class.)
- Donald: *It can't be used for math.*

- Philip: *To see the length.*
- Victor: *Math works with numbers so does programming. You have to adjust motor speeds, etc.*

Appendix E: *Parent Consent & Participant Assent Forms*

Parent Consent Form

The University of Oklahoma, Norman Campus
Consent to Participate in a Research Project

Robotics and Mathematical Development

Keith V. Adolphson, Principal Investigator

I would like to investigate the mathematical development of middle school students as part of a graduate degree completion requirement at the University of Oklahoma. I will be working with the Longfellow Middle School Robotics Cluster, the Botball team, and the Robotics Club and would like to investigate how these activities affect the development of mathematical reasoning and understanding. This project is designed to help educators understand and meet the needs of students studying mathematics.

If you consent for your child to participate in this project, they will be asked to participate in two interview sessions that will last approximately one-half hour each. These interviews will take place during team meetings and will be audio taped to ensure the information is gathered as accurately as possible. No personal information will be sought from your child beyond the basic demographic information that is part of your child's school registration. I will also be observing your child as he/she participates in the robotics activities. I would also like to conduct videotaping when possible to ensure accurate data is being obtained. The data collected will be used to fulfill doctoral degree requirements and may be presented at education conferences or possibly included in future publications about mathematic education.

I see no foreseeable risks of participation in this project for your child. Her/his participation will greatly help educators improve the mathematics instruction for middle school students. You and your child may gain insight from participating in the study through discussing the day's activities and developing mathematical insights.

Your child's participation in this project is strictly voluntary. Refusal to participate in this study will involve no penalty at school; nor is participation a prerequisite for participation in either the Robotics Cluster, the Botball team, or in the Robotics Club. Your child may withdraw from the study at any time without penalty as well. All information from this project, including interviews, audio tapes, video tapes, and observations will be kept in a locked file cabinet by the principal investigator, and will be destroyed at the conclusion of the investigation. A pseudonym will be give for your child and locale so real names and locations will not become known.

If you have any questions about this project, please contact me at (405) 325-2599, or my University faculty supervisor, Dr. M. Jayne Fleener, at (405) 325-1081. If you have any questions about you and your child's rights as a research participant, please contact the University of Oklahoma's Office of Research Administration at (405) 325-4757.

Keith V. Adolphson, Doctoral Student, Instructional Leadership

CONSENT STATEMENT
I consent to the participation of my child, ______________________________, in this research project. I know what my child will be asked to do and that he/she can stop at any time. I give my permission to: observe ____interview ____ audiotape ____ videotape ____ (please initial all that apply) my child for the purposes of this research project.

______________________ ___________________________ ______________

Name (printed) Signature Date

Participant Assent Form

The University of Oklahoma, Norman Campus
Assent to Participate in a Research Project

Robotics and Mathematical Development

Keith V. Adolphson, Principal Investigator

I would like to investigate the mathematical development of middle school students as part of a graduate degree requirement at the University of Oklahoma. To do this, I will be working with the Longfellow Robotics Cluster, the Botball team, and the Robotics Club. I would like to find out how robotics activities could help students improve their mathematics understanding. This project could help teachers better meet your needs as a student.

If you decide to participate in this project, you will be asked to participate in two interview sessions that will last approximately one-half hour each. These interviews will occur during team meetings after school and be audio taped to ensure the information gathered is as accurate as possible. We will also be observing you as you participate in the robotics activities. I would also like to videotape the interview and team activities, when possible, to ensure accurate information is being obtained. The data collected will be used to fulfill our graduate degree requirements and may be presented at educational conferences or possibly included in future publications about mathematics education.

I do not believe there are any risks of participation in this project for you. Your participation could greatly help teachers improve mathematics instruction for middle school students. You may also gain deeper mathematics understanding from participating in the study through discussing the day's activities and developing mathematical insights with other students and your parents.

Your participation in this project is strictly voluntary. Refusal to participate in this study will involve no penalty at school; nor do you have to participate in this study to be in either the Robotics Cluster, the Botball team or in the Robotics Club. Also, you may choose not to participate in the study at any later time without penalty as well. No personal information will be sought from you beyond the basic information your parents provide during school registration. All information from this project, including interviews, audiotapes, videotapes, and observations will be kept in a locked file cabinet and will be destroyed at the conclusion of the study. A false name will be given to you so that your privacy will be protected.

If you have any questions about this project, please contact me at (405) 325-2599, or my university faculty supervisor, Dr. M. Jayne Fleener, at (405) 325-1081. If you have any questions about your rights as a research participant, please contact the University of Oklahoma's Office of Research Administration at (405) 325-4757.

Keith V. Adolphson, Doctoral Student, Instructional Leadership

ASSENT STATEMENT
I agree to my participation in this research project. I know what I will be asked to do and that I can choose to stop at any time. I give my permission to: observe ____ interview ____ audiotape ____ videotape ____ (please initial all that apply) me for the purposes of this research project.

______________________	______________________	____________
Name (printed)	Signature	Date

Appendix F: *University of Oklahoma Institutional Review Board Approval*

The University of Oklahoma

OFFICE OF RESEARCH ADMINISTRATION

January 10, 2001

Mr Keith Adolphson
1306 Lindale
Norman OK 73069

Dear Mr Adolphson:

The Institutional Review Board-Norman Campus has reviewed your proposal, "Robotics and Meaningful Mathematics: Making the Connection with Middle School Students Through Authentic Activities," under the University's expedited review procedures. The Board found that this research would not constitute a risk to participants beyond those of normal, everyday life, except in the area of privacy, which is adequately protected by the confidentiality procedures. Therefore, the Board has approved the use of human subjects in this research.

This approval is for a period of twelve months from this date, provided that the research procedures are not changed significantly from those described in your "Application for Approval of the Use of Humans Subjects" and attachments. Should you wish to deviate significantly from the described subject procedures, you must notify me and obtain prior approval from the Board for the changes.

At the end of the research, you must submit a short report describing your use of human subjects in the research and the results obtained. Should the research extend beyond 12 months, a progress report must be submitted with the request for re-approval, and a final report must be submitted at the end of the research.

Sincerely yours,

Susan Wyatt Sedwick

Susan Wyatt Sedwick, Ph.D
Administrative Officer
Institutional Review Board-Norman Campus

SWS:pw
FY01-164

Cc: Dr. E. Laurette Taylor, Chair, Institutional Review Board
Ms. Stacy Reeder, Education
Dr. M. Jayne Fleener, Education

1000 Asp Avenue, Suite 314, Norman, Oklahoma 73019-0430 PHONE (405) 325-4757 FAX (405) 325-6029

University of Oklahoma Institutional Review Board Approval Continuation

The University of Oklahoma

OFFICE OF RESEARCH ADMINISTRATION

January 23, 2002

Mr Keith Adolphson
1306 Lindale
Norman OK 73069

SUBJECT: "Robotics and Meaningful Mathematics: Making the Connection with Middle School Students Through Authentic Activities"

Dear Mr Adolphson:

Thank you for returning your completed progress report for research conducted with human subjects under the above-referenced protocol. The Board has reviewed and approved your report. Since you indicate the study is continuing, they have extended your approval to continue this research for an additional twelve-month period ending 1/10/2003.

Please note that this approval is for the protocol and informed consent form reviewed by the Board. If you wish to make any changes, you will need to submit a request for change to this office for review.

Thirty days before the expiration of this approval you will receive notice from the IRB secretary that your approval anniversary is approaching along with information you can use to complete your progress report and request an extension of the approval date.

If you have any questions about the approval given your protocol, please contact me at 325-4757.

Sincerely yours,

Susan Wyatt Sedwick, PhD
Administrative Officer
Institutional Review Board-Norman Campus

SWS:lk
FY2001-164

cc Dr. E. Laurette Taylor, Chair, IRB
Ms. Stacy Reeder, Education
Dr M. Jayne Fleener, Education

1000 Asp Avenue, Suite 314, Norman, Oklahoma 73019-4077 PHONE: (405) 325-4757 FAX: (405) 325-6029

Appendix G: *Final Team Session before the Competition*

Gary: *Why isn't turning as much?*

Tom: *Gary, that was fine right there.*

Gary: *It needs to be right on there.*

Tom: *We have only 20 minutes.*

Gary: *Dude! We have only 20 minutes!*

Gary: *The time is not right. Wait! I need to measure it. Okay, light on.*

Tom: *It is on.*

Gary: *Okay, light off. Yes! Power. Oh, you guys get out of the way. Oh! Darn! It fell apart.*

Mr. A: *Okay.* (Referring to a part that has a tendency to come loose.) *Remember you are going to have to check that every time.*

Tom: *Actually it worked. It just got stuck there.*

Mr. A: *Remember, you are going to put in a fresh set of batteries.*

Gary: *Oh, good! I got a good calibration.*

Tom: *Demolition bot, yeah!*

Gary: *All I have to do is work it. It is perfect. I just need to work it, like, three times.*

Tom: (Referring to both robots.) *I hope they both work together just like they do by themselves.*

Frank: *I have worked so hard to program this* (the Handy Board robot). *See, the thing is just getting the wheels to stay on.*

Carol: *Okay. Here comes Earl. Slow down a little.*

Gary: *Okay. Download it. Tom, here we go. It should work all right.*

Tom: *Oh, we are missing a piece…a small piece like this.*

Mr. A: *It's really important that you guys know how to put the bots together.*

Gary: *Oh gosh! It didn't even go forward!*

Tom: *This really sucks.*

Gary: *Really, my bot does. Just check everything.*

Tom: *See! It is not going to work now. It is too close. Stop it now!*
Gary, why is it turned this way? It should turn the other way!

Gary: *Because since the first time it wasn't on this. It is going to go straight forward, where all the other bots are going to be.*

Tom: *How do you know that the other bots are going to be in the middle?*

Gary: *I just know that is where our bot is going to be. It will be trying to grab the nest. I think the others will too.*

Tom: *Have you seen the other teams?*

Gary: *It will work like 1 out of 10 times.*

Tom: *Don't change much because I can guarantee you that the batteries are going down. That is why you don't need to change things. Do you have your bot fixed, because I want to try it in the next 10 minutes? We need to try both of them.*

Mr. A: *Are you sure you went through the calibration technique?*
If you don't press run, it works.

Frank: *Well, that is we have been pressing run.*

Mr. A: *Well, that is it then.*

Frank: *Oh, my God! We have checked everything!*

Mr. A: *It is not the wiring. It is not the software. It is the calibration.*

Steve: *Is Geometry easy, Victor?*

Victor: *Yeah! It is the easiest thing in the world.*

Steve: *Is it easier than Algebra?*

Victor: *What it is, is just different.*

Mr. A: *Did you press run that time?*

Gary: *Is their robot too long?*

Frank: *It is about as short as it can get.*

Mr. A: *It looks like it is right on the edge. It is 15 inches from the pipe to the edge. That is right.*

Gary: *Is it okay to hang over like this?* (Referring to part of Fluffy II hanging over the starting box line. Mr. A. shakes his head, no.)

Tom: *Then you will have to back yours up a little then.*

Gary: *Well, it will back up a little and it takes about a minute to turn.*

Mr. A: *Well, you will have to do a right turn.* (Turning to Frank.) *Have you figured out the problem yet?*

Frank: *Yeah, I got it. It has something to do with the calibration. I was hitting run.*

Mr. A: *Okay. So it does start...with the light on?*

Frank: Yeah. It comes back on. It waits 3 seconds, then comes on.

Gary: *Victor, you guys are going to do a right turn...a 90-degree turn.*

Frank: *We are going to make it wait then....* (inaudible)

Victor: *Okay, what is doing wrong?*

Frank: *Watch it.*

Gary: *It is set up perfect on our side.*

Frank: *Victor wants to see what is going on now. See, right in front, not with the fork sticking out. Victor wants to see how it is set up.*

Victor: *See, I can see from here.*

Frank: *Whenever he turns on the light, it will start up.*

Victor: *Just one second should do it.*

Gary: *Oh my gosh! It is going to go a lot faster with new batteries, Mr. A.*

Victor: *How fast does it need to turn on?*

Frank: *Where does it turn, after go forward. Oh, okay.*

Victor: *We need to download.*

Mr. A: *Okay, now we are cooking. It has got to face the left.*

Frank: *All right! Yeah! I know. Light on. Light off.*

Mr. A: *Okay, how long did you set it for?*

Steve: *One-half second...180 degrees at the very beginning.*

Mr. A: *Make sure you do the comments. Get in the habit of doing that. So when it comes to game day, you can find your place easier.*

Victor: (Referring to a light sensor) *Okay, we can use tape on the shield but not on the bot.*

Gary: *Okay, then I will turn this then. It should work still. I can do it. We might need some different pieces here so we can move the light sensor.*

Mr. A: *Why don't you leave it where it is? You can just try it and see.*

Tom: *Yeah, why don't you just try it and see?*

Mr. A: *You should get some light by reflection.*

Gary: *I know! It will need to be fixed still.*

Mr. A: *Okay, let's try downloading it.*

Gary: *Does that work now? Mr. A, now?*

Mr. A: *So, now you know what you want to do?*

Gary: *I know what the plan is.*

Ms. A: *Okay, so what will the scout do?*

Oscar: *It is just for looks. We are just testing it to see if it has enough power. See, earlier we had a trailer and we need to see if it has enough weight to push it. See the trailer kept on turning it. The scout was not supposed to turn.*

Then we totally destroyed the idea. Then we put it back on to see if we could get it go straight again.

Ms. A: *Thanks.*

Mr. A: *Let's make sure that the Handy Boards are all charged up.*

Oscar: *Hey. it is going! It is going! Stop it!*

Frank: *Bye Victor. Your dad is here.*

Oscar: *Let's try that last one. He just left. Bye Victor. I have to go pretty soon too.*

Mr. A: *When we get to where we think it should be it. Let's name it game day.* (Referring to the competition program for the Handy Board.)

Frank: *Okay. that is a good idea. Hold on! Let me see what time it is.*

Steve: *It has been a minute.*

Frank: *Not yet!*

Tom: *I think it has been a minute now.*

Frank: *Oh. too bad! I know how to fix it.* (As a piece falls of Fluffy II.)

Steve: *I do too.*

Frank: *Okay. first he needs to put his on.* (Referring to Fluffy II) *You guys get it on.*

Steve: *You need to move it forward.*

Oscar: *Mr. A. do we have to activate after three seconds?*

Mr. A: *Well. the other way we could do it is to have Gary start out first. Then pause and move out.*

Gary: *Let mine drive out. then do the turn.*

Mr. A: *That would be another way.*

Oscar: *Is this going to be the actual size?* (Referring to the size of the practice arena.)

Mr. A: *Yes.*

Gary: *We have a problem. The tire is blocked now.* (Referring to Fluffy II and X-Terminator being interlocked in the start box.) *It is in the shadow of the tire.*

Tom: *The tire? Do it again. Can you mount that up on top?* (Referring to a sensor housing on X-Terminator that is blocking one of Fluffy II's wheels.)

Mr. A: *That is the only thing I can think of.*

Victor: *Hurry up! I have to go!*

Gary: *Can we do a calibration over?*

Mr. A: *Yeah, you can. But if you keep getting a bad calibration, they will start anyway.*

Frank: *Okay, turn it about...to a three.*

Tom: *It is going to be past there.*

Frank: *Okay. On. Off. On. Off.*

Gary: *Okay, you have to try it now. Victor has to go in about three seconds.*

Tom: *Why are you doing that? Are you pressing the wrong button? You have got to be.*

Gary: *Oh, no way can it see the light. It is way down there.* (Makes an adjustment) *Okay. Off. On. On. ON!*

Victor: *Here, Bob! Come over here and do this. I have to go. See you tomorrow at 7:15.*

Ms. N: *Okay, Devin. I don't have a permission slip so you are not going with me, right?*

Devin: *Yeah!*

Tom: *Let's try to calibrate it. Ooh, that is too fast!*

Mr. A: *Do you have your shield on?*

Frank: *Yeah, but she turned the light on really fast. I...*

Tom: *It doesn't turn so fast.*

Mr. A: *Do you have full speed on both motors?*

Frank: *No, I have it on 80 and 85. It will turn a second to qualify.*

Tom: *Turn! Keep turning! The batteries are going down!*

Ms. N: *I don't think it is a battery issue because it went really fast at the beginning.*

Mr. A: *It may be using a lot of energy to be turning. Can you do like one back and one forward.* (Referring to the motors on Fluffy II.) *Okay, I am just saying if that is what the trade off is. Then you just have to live with it. The other thing you can do is take off the rubber tires.*

Gary: *Yeah, we thought about that but if we take off the rubber it won't be at the right height so when it goes down, it is at an angle.* (Referring to the bucket on Fluffy II) *It won't work.*

Mr. A: *What about a different diameter wheel?*

Gary: *Oh, do we have a bigger diameter wheel that would be this big?*

Steve: *Oh, we have one, the gray ones. Like the gray single loops?*

Gary: *Okay, bring it here. It might work. Let's try the white ones. Because it turns so slow. See! If we use these, it will increase the time because it will cause less friction.*

Frank: *Okay, on.*

Ms. N: *Oh, that is better.*

Gary: *Yeah, 1.4 seconds.*

Tom: *How many people are here? There are only 7. We are down to the people who are working on everything.*

Steve: *The pizza is here and it smells good.*

(Lunch break)

Earl: *Konichi-wa.*

Mr. A: *Okay, you guys you need to focus on programming.*

Tom: *Turn. It is turning. It is coming like right this way.*

Gary: *No, but the gears are slipping.*

Tom: *Just push down on the thing. YES!*

Gary: *Yes, I am going to put 70 points in for one.*

Tom: *Do NOT touch that turn.*

Mr. A: *Okay, guys. Are you ready to test it?*

Tom: *I don't know how to start it.*

Earl: *Start it?*

Mr. A.: *We're leaving at 11, if it is ready or it isn't.*

Tom: *Too far!*

Gary: *Ah, dang!*

Tom: *That is too far! Come on, get that right! Since we don't have a board* (Meaning an arena to practice on at the competition.), *we need to get it perfect before we leave today. Just program it. It needs to be as perfect as possible.*

Gary: *Semi.*

Tom: *Oh, semi-radioactive perfect?*

Gary: *Yeah!*

Tom: *It needs to be as close to perfect as it can.*

Gary: *Turn it off. Turn it on. I need to change the first turn.*

Tom: *You can't!* (Joking) *I will hurt you...hurt you with my knife.*

Gary: *What the...? I didn't change it! Mr. A., I didn't change the first turn and it went more that time!*

Mr. A: *Maybe the gears aren't working together.*

Tom: *Maybe it was the way it was set up?*

Gary: *No, it is set up the same way.*

Tom: *Maybe the gears were loose?*

Mr. A: *So that works, why don't you work on getting the bucket? Straightening out the bucket?*

Gary: *No, we have to get it to turn at a right angle though. We are trying to figure out what the right angle is.*

Mr. A: *Well, you are almost there.*

Gary: *We were...we almost had it the last time.*

Tom: *You have to remember to pump that thing up and check everything every time.*

Ms. A: *Do you want to knock over the black tubes?*

Gary: *No, we want to avoid the black things.*

Tom: *You will be on the spotlight. It is working, don't change that turn.*

Gary: Okay, now I have to make it go further.

Tom: *Just a tad.*

Earl: *Like .25 seconds.*

Tom: *Not even that.*

Earl: *Oh, like .05 seconds then?*

Tom: *Yeah, like just add less than a quarter of a second.*

Ms. A: *Where does the other robot turn?*

Tom: *We aren't sure. We are figuring it out.*

Ms. A: *Frank what did you do different to fix yours?*

Frank: *Just changed the down by 1 second.* (Meaning the forklift arm positioned down.) *Light off. Light on. Light off.*

Victor: *Didn't work!*

Earl: *We don't have to have it go too fast.*

Tom: *Oh, you turned it off so it couldn't do it.*

Gary: *Oooooh. Oh my gosh!*

Tom: *Oh, that is too close cut. Because we don't know where those tubes are going to be in the competition. We won't know if those tubes are going to be a centimeter forward or backwards. We have to make that adjustment to cover it. Now it is turning too far, man.*

Gary: *It changes every time!*

Tom: *Every time?*

Mr. A: *Well, you are just going to have to go with what you got.*

Ms. A: *Have you tried those rims with to replace the rubber rims on the front side?*

Gary: *We can't find any that are the same size.*

Lindsey: *Let's go look.*

Ms. N: *Can you change all four?*

Gary: *No, this would be off because if we took any on or off, it would be off.*

Ms. N: *It used to faster, right?*

Tom: *No.*

Carol: *Can you take the rubber off?*

Gary: *We tried the gears even.*

Tom: *That collapsed even.*

Earl: *Can you just take all the rubber off?*

Frank: *Can you get the bulldozer bot off? Is the bulldozer bot ready?*

Earl: *Okay, try this again.*

Frank: *Okay, light on. Light off. You can see through it. Light on. Hold on. I am trying to see if I can see through it. Okay, light on. Light off.*

Tom: *Not far enough.*

Frank: *Not fast enough.*

Carol: *Just make it go a little further.*

Gary: *What is up with the spinning?*

Frank: *It is because it doesn't have the nest.*

Ms. N: *I am not feeling as confident as I was last year.*

Tom: *Neither am I.*

Earl: *So what do we need to do?*

Mr. A: *What adjusting were you doing?*

Ms. N: *Especially at this time. It seems like it went faster last time.*

Steve: *Maybe you are just stressed and that is why it seems like it was going fast.*

(Discussion digressed into blame for not programming while the robots were being built)

Tom: *Yeah. I am calibrating it.*

Gary: *Tom! That will blow it out. Wait. Wait!*

Tom: *Now, now it needs a little more. Maybe that will turn a little more.*

Gary: *Oooh...ooh the timing on that is right.*

Tom: *It needs to be turned a little more this way.*

Gary: *No, Tom you want it in an angle like that*

Tom: *No, remember we have to have a little more so it will straight on so it will flip it or else the balls will go under like that?*

Gary: *Yeah! Okay. Wait. Let's ask.*

Tom: *We are just adding more time and taking time off where it is needed. So it will turn more or turn less.*

Earl: *They are programming.*

Frank: *Okay, let's just check it out.*

Tom: *Work you devil thing, work.*

Frank: *Light on, light off.*

Steve: *Hey, look it went straight on at the light.*

Mr. A: *It is not like it knows that the line is there.*

Frank: *It ran away, it was afraid.*

Tom: *It would have been perfect, Gary, but the robot...*

Mr. A: *I think it was perfect.*

Gary: *It would not be the right height so it would be...*

Tom: *Turn it off, please.*

Mr. A: *Okay, so Frank what happened?*

Frank: *It didn't go, let's re-do it again.*

Gary: *Guys let's try ours so it doesn't hit ours.*

Frank: *Yeah, let's do it again.*

Gary: *No, we are going to do ours by ourselves because it is on the same program.*

Mr. A: *Frank, which motor is on the left side and which one is on the right side?*

Frank: *I am not sure.*

Mr. A: *Frank, you need to comment that in the program so you will know.*

Tom: *Okay, on. Off.*

Frank: Okay, *this is motor one and this is motor two.*

Mr. A: *So do you think…it is possible that when you changed you might have changed the wrong one? I am just thinking, I don't know. What do you think?*

Frank: *Well, I guess I could check.*

Gary: *Oh my gosh! It is changing its turning every time!*

Steve: *And that time it didn't even go far. It lifted itself off the ground.*

Mr. A: *The tension builds.*

Tom: *Gary, those might be just like some of the other bots.*

Gary: *Let's make it try to get everything.*

Frank: *Light on. Light off.*

Gary: *It is going to hit that thing.*

Frank: *Okay, that needs to be a little bit faster.*

Lindsey: *Why don't you try to make it just a little bit longer?*

Gary: *Oh, the gear is coming out. So that is why it is coming out! Tom, that is why.*

Tom: *The gear is popping out?*

Gary: *That is why that last one was like that.*

Tom: *Yeah, that is why every time we have to check everything. Before every thing we have to check it.*

Mr. A: *Yep, they are Legos. They fall apart.*

Gary: *Okay, on. Off. On. Off. On.*

Earl: *Does it really need that last on?*

Tom: *Yeah, to start it.*

Frank: *If you didn't have that last on, it would be a false start. If it starts! Yeah, if it starts without the light being on, then it is a false start.*

Mr. A: *Go ahead and check it guys.*

Gary: *Okay, light off. Light on.*

Lindsey: *A little more... Almost!*

Mr. A: *Okay, guys. Can you start a little more to this side of the box? Can you start it all the way on this side and put the robot on this edge?*

Earl: Okay, light off. Light on.

Lindsey: *I was going to be the light man, light woman, I mean person. But then I decided I had to leave. But now I have found out that I still have another hour. I'm leaving at 6:45 and it is only 5:51.*

Tom: *Now...*

Gary: *It is turning way too...not the same!*

Mr. A: *Are you powering both wheels on the turn?*

Gary: *No, not the first one. The second one, yes!*

Mr. A: *It doesn't seem like it.*

Gary: *It is getting less and less now every time in the turn.*

Tom: *Batteries? Check everything and make sure it is all-together.*

Gary: *I did!*

Tom: *Okay, what do I need to do?*

Gary: *Wait, I am going to try this again and if it goes slower...I don't know.*

Mr. A: *You do realize the power on the batteries will run down real quickly?*

Ms. A: *Do you have enough batteries to put in new batteries every time you test it?*

Gary: *No, not every time. On. Off.*

Philip: *How are you supposed to get that ball in here?*

Tom: *We're not!*

Gary: *We're not!*

Philip: *Well. they said you could.*

Steve: *We're not going to try it. It will be too hard.*

Gary: *Look. it is going less every time now it is slower. We need Duracell batteries. I can't believe it. that batteries would go down in less than five runs.*

Lindsey: *Let's lift up the nest.* (Speaking to Frank as they program X-Terminator)

Frank: *It is not strong enough to lift up the nest.*

Mr. A: *It just takes a lot of power.*

Lindsey: *Plus. that nest is going to be gone by the time that one gets to it.*

Gary: *How can batteries go down so fast?*

Mr. A: *I think it is because you have so much resistance from those tires in the turn.* (Meaning the front tires.) *What do you think?*

Frank: *Yeah. this also takes a lot of energy.*

Ms. N: *Why don't you put new batteries in it and see how it works?*

Gary: *But we put these in today! We have only tested it about 10 times!*

Lindsey: *Why don't you program it to the new batteries? That way during the competition you can put new batteries in. It will be more reliable.*

Gary: *It takes how many batteries? Eight?*

Frank: *A perfect run!*

Lindsey: *I know why their batteries don't run down like ours.* (Referring to the X-Terminator)

Ms. N: *Why?*

Lindsey: *Because they don't have the resistance that we have. They don't have those rubber tires pulling at the board.*

Gary: *This is a more complex robot than that one.* (Referring to Fluffy II) *We would have been a lot better off with the handy board.*

Ms. N: *Then why didn't you guys look at that one?*

Tom: *Because Donny... because we did.*

Gary: Because he said his would work without the Handy Board.

Mr. A: *No. you guys...you guys...no you guys picked...you guys picked the handy...you guys picked the RCX.*

Gary: *That is because Donny said it wouldn't work without the Handy Board.*

Mr. A: *You guys chose the RCX though.*

Tom: *Hey. do you want me to add more time?*

Ms. N: *Hey. you guys always want to blame it on Donny. He wants to blame it one someone else.*

Gary: *Well. actually he said his wouldn't have worked without a Handy Board when it would have worked with half an RCX.*

Ms. N: *I am going to buy some more batteries.*

Mr. A: *It is just like the nest capture last year. It is very similar.* (Referring to the X-Terminator)

Gary: *He said it wouldn't work without a handy board.*

Tom: *Okay. on. off. on. Leave it one.*

Frank: *It needs to go a bit slower.*

Tom: *There you go. Is it straight?*

Gary: *Don't turn it on until I say so. On. Off. Okay on.*

Tom: *Now hit run.*

Gary: *Okay. on. Off. Like leave it on. Okay, see we put new batteries in and it is turning even more.*

Lindsey: *Well. that is because you messed up the program.*

Tom: *Ok. let's put it back to 0.4.*

Lindsey: *Put it back to where it was.*

Tom: *I am talking about the second turn.*

Gary: *You are going to have to buy so many more batteries then.*

Ms. N: *I will.*

Frank: *OK. my turn.*

Lindsey: *I think I have found those other tires but they are the same size as the other ones.*

Mr. A: *Someone is going to have to keep track of all those batteries because we can use them in the club activities.*

Frank: *Okay, light on. Light off. Light on. Ahhhhh...that is the same as it was before.*

Mr. A: *Have you thought about not just adjusting the speed but the timing of the program?*

Frank: *Well if it goes too slow the motor will lock up.*

Mr. A: *No, I am just saying adjust the timing of the turn. You see, instead of having less power on the thing, planning for it to turn for a longer time.*

Tom: *On. Off. On. I am going to give her the job.*

Gary: *Yeah, let her have the job.*

Steve: *Okay, I'll just sit here.*

Tom: *Whoa! Turn it back to 2.5 or 2.*

Mr. A: *You need to mark those too, so you know what specs you have to decide upon those turns.*

Gary: *That is the only hard part. It is hard to get timing down.*

Ms. N: *How was your party?*

Laura: *I had a birthday party. I turned 14. It was nice*

Gary: *On. Those are what we have tried.*

Tom: *We have programmed it for brand new batteries.*

Mr. A: *Yeah, you will have to have brand new batteries nearby.*

Gary: *Look how far it turned that time Tom! It turned even more and I've lessened it.*

Lindsey: *That is scary.* (Continuing to look for rims without tires to help the bot turn easier.)

Gary: *That is why we should have used the handy board.*

Mr. A: *The lessons learned, could be before nationals, is to put the handy board in this and the RCX in the other.*

Steve: *Make it one second longer.*

Ms. N: *Gary have you tried anything like those that she has in her hand.*

Gary: *Yeah, but if I take the rubber off of this it won't work.* (Estimating that the rims without tires won't be tall enough to suit the lifting geometry of Fluffy II's bucket.)

Ms. A: *But when it is bigger. I think it still might work. Yeah, yeah! It would just drop down and gather as many or more.*

Mr. A: *Try it and see.*

Gary: *Light on. Light off. On. No…close, not quite.*

Mr. A: *It doesn't look like it will interfere with the bucket.*

Tom: *No, that line has to be equal in the middle, it needs to be equal with the nest. It has to be in the center.*

Frank: *Yeah, I know.*

(New rims without tires are put on Fluffy II)

Mr. A: *I think that will work. It puts it all the way down doesn't it?*

Gary: *I guess? Yes...it should. I will take out this tire…seems high. Now, we are only using the back wheels. (To power the robot) Let's see how the timing is now.*

Mr. A: *See what happens. Get those NASCAR wheels out of the way.* (Referring to wheels blocking the robot's path)

Gary: *What the...the gears are all there!*

Frank: *It sounds like something is wrong with the motors. Change it around. Change it around!*

Mr. A: That is a grind there. (

Lindsey: *Is something skipping? It sounds like a skipping noise.*

Tom: *Hey, Gary is the Handy Board hanging down in the back?*

Gary: *It is not dragging. Okay, on. Off. On. Whoa! That is great!*

Mr. A: See, you won't be losing as much power.

Tom: Oh, that was sweet!

Lindsey: See! Oh, boy! (Excitedly dancing in place having been vindicated in her insistence on having tireless wheel put on Fluffy II.)

Mr. A: *See how quick that was?*

Ms. N: *Good suggestion!*

Philip: *I think we might actually be able to do* that! (Referring to having a operational robot in the competition.)

Tom: *Gary, what do you want me to do for the second turn, 3.2?*

Gary: *0.5 seconds.*

Frank: *Hold on! That is great! Put that thing back down. I have got it so far.*

Mr. A: *So...after it dumps the nest?*

Lindsey: At least we figured out the problem on the other bot. (Referring to Fluffy II)

Tom: *Okay, we have reduced the time to the very lowest that we had before. I think that will work.*

Mr. A: *So, you won't need as many batteries as you thought you would.*

Tom: *Okay, 1.5 needs to be reduced a little bit. Oh gosh, we reduced it from 8.5 to one second. Wow!*

Gary: *We are going to have to wait longer at the beginning.*

Mr. A: *What you might want to do is add some pauses here and here.*

Carol: *I have an error. What does that mean?*

Mr. A: (Turning to help Carol.) *Okay, do you have a semi-colon before? How about after?*

(Chatter about logistics of the competition day)

Frank: Okay, on. Off. On.

Tom: *You are going to have to make sure you sit that bot in the exact spot every time.* (Referring to X-Terminator) *We can't readjust the location.*

Frank: *We need Victor here. Okay, let me have it set there so we can test it.*

Tom: Oh yes! That is it!

Frank: Don't change it!

Tom: Pick up the nest! Yes! It is on the other side!

(Lots of laughter and happiness at a successful trial for Fluffy II.)

Frank: *It has to stay at a certain spot. Light on. Off. I need more of turn.*

(Chatter about supplies needed for game day)

Gary: *It is turning faster now.*

Lindsey: *Are you sure it is because you don't have as much friction?*

Gary: *No. I did it the first time. I thought I had it.*

Tom: Me too! Ready...ready, off. On. Okay, here it goes. Good. Gary, you need to do your dance. That will get in there. It is going in there. Pick it up!

Frank: *Okay. I found the problem. I changed the wrong turn.*

Mr. A: *Was it because you didn't read your comments or because there weren't any comments there?*

Tom: *Set the robot a bit forward. It turned at exactly a 90-degree angle. You know it turned it was just a little bit back. It will be a perfect 90-degree angle.*

Gary: *Okay. on. Off. On. What is the problem?*

Mr. A: *Are you powering the front wheels again?*

Gary: *No...off. On. There you go... Dang it!* (Fluffy II gets hung up on the sides of the arena)

Frank: *Our turn.*

Ms. N: *Why do you guys have such long black things anyway?* (Referring to the part of Fluffy II's bucket that got wedged under the side of the arena.)

Tom: *To hold the balls in. If you don't do that they will roll all over. These contain them.*

Gary: *This is the bar that holds it all in.*

Tom: *You are going to figure out where you are putting in. You are putting it a little bit forward and a little bit back each time.*

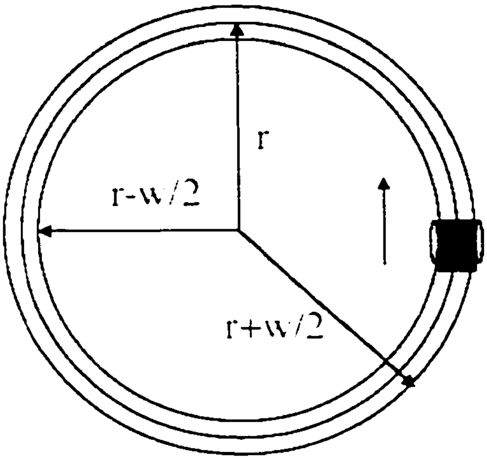
Lindsey: *How about a pattern?*

(Tape ends.)

Figure H1 *Higher Level Mathematics & Robotics*

H1a Geometry in Robotics:

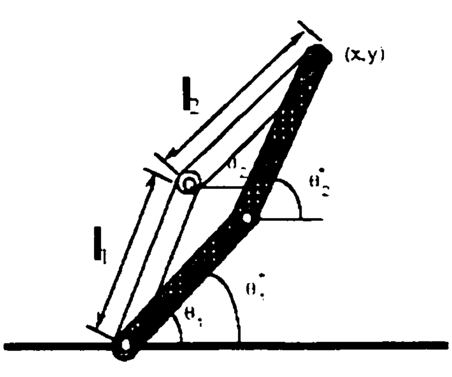
Calculating Turns



- For a robot with a wheel separation of w...
- When traveling a complete circle the robot will travel $2\pi r$
- The left wheel will travel: $2\pi r - \pi w$
- The right wheel will travel $2\pi r + \pi w$
- If the right travels $2\pi w$ further than the left, the robot's made a complete CCW circle
- If the left goes πw more than the right, the robot has turned CW 180 degrees.

H1b Trigonometry in Robotics:

Inverse Kinematics



$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right) + \cos^{-1}\frac{l_1^2 + x^2 + y^2 - l_2^2}{2l_1\sqrt{x^2 + y^2}}$$

$$\theta_1' = \tan^{-1}\left(\frac{y}{x}\right) - \cos^{-1}\frac{l_1^2 + x^2 + y^2 - l_2^2}{2l_1\sqrt{x^2 + y^2}}$$

$$\theta_2 = \tan^{-1}\left(\frac{y}{x}\right) + \cos^{-1}\frac{l_1^2 + x^2 + y^2 - l_2^2}{2l_1\sqrt{x^2 + y^2}}$$

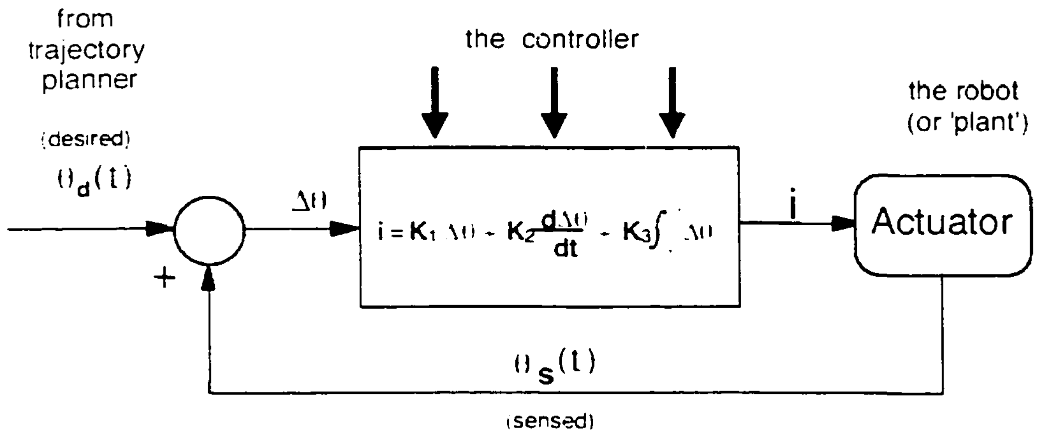
$$\theta_2' = \tan^{-1}\left(\frac{y}{x}\right) - \cos^{-1}\frac{l_1^2 + x^2 + y^2 - l_2^2}{2l_1\sqrt{x^2 + y^2}}$$

Mathematics to calculate the joint angles to move the end effector to a given position

Figure H1 *Higher level Mathematics & Robotics, continued*

H1c Calculus in Botball:

PID Control of a Joint



Note The first slide is from "Botball 2002 Teachers Workshop" presentation by D. Miller, KISS Institute for Practical Robotics, January 2002, Norman, OK. The remaining slides are from "Botball 2001 Tutorial" presentation by D. Miller, KISS Institute of Practical Robotics, January 2001, Norman, OK. Copyrights 2001, 2002 by David Miller. Adapted with permission

Appendix I: *2002 Botball Competition Programs*

X-Terminator:

```
/*load the calibration library*/
#use "calibrate ic"

void main()
{
   hb_calibrate (6); /*calibrate using light sensor in port 6*/
   play_time (90. start_process (botball())); /*start competition program*/
   printf("All Done!\n"); /*game over*/
}

void botball()
{
   init_expbd_servos(1);
   rightturn2 (0 5); /*turn out of box*/
   goforward (0 4).
   servo0=2600; /*position lift arm down*/
   /*while (1) { set the min to 3549 and max to 4000 on fork lift bot DO NOT CHANGE!!!!! put
this program in the other programs for the fork lift robot and I repeat don't change anything
plea or (servo0= min; servo0< max; servo0 += step) update();*/
   sleep (2 0).
   servo0=1500. /*lift nest*/
   stop (0 5);
   sleep (1 0). /*wait*/
   goback (2 0).
   stop (0 5).
   leftturn (4 0).
   stop (0 5);
   goforward (0 2).
   servo0=2600; /*puts nest down*/
   goback (1 0)
   servo0=1500.
   rightturn (1 4); //turns inline with Nerf nest
   servo0=2600.
   goforward (1 0);
   stop (0 5).
   leftturn (0 4);
   stop (0 5).
   goforward (1 0);
   servo0=1500; /*lift nerf nest*/
   //leftturn (1 0);
   goback (2 0);
   stop (0 5);
   servo0=2600;
}

/*void update()
{
   printf("%d %d\n". servo0);
   sleep(.1);
}*/
/* right wheel is motor 2. left wheel is motor 1*/
```

```
void goforward (float t)
{
   motor (1. 95):
   motor (2. 100):
   sleep (t).
}
void goback (float t)
{
   motor (1.-100):
   motor (2.-100):
   sleep (t).
}
void stop (float t)
{
   motor (1. 0):
   motor (2. 0).
   sleep (t):
}
void leftturn (float t)
{
   motor (1. -80).
   motor (2. 80):
   sleep (t):
}
void rightturn (float t)
{
   motor (1. 80):
   motor (2. -80).
   sleep (t):
}
void rightturn2 (float t)
{
   motor (1. 100). //left motor
   motor (2. -80). //right motor
   sleep (t).
}
```

Fluffy II:

```
#use "calibrate.ic"

void main ()
{
  rcx_calibrate(1);
  play_time(75,start_process(my_rcx_botball_program()));
  printf("All Done\n");
}

void my_rcx_botball_program ()
{
  sleep(3.0);
  bk(3);
  sleep(.20);
  brake(3);
  fd(1); fd(2);
  sleep(1.5);
  allbrake();
  fd(2);
  sleep(1.5); /*first turn*/
  fd(1);
  sleep(1.5);
  allbrake();
  fd(2);
  sleep(1.5); /*second turn*/
  fd(1);
  sleep(3.7);
  brake(1); brake(2);
  fd (3); /*start dumping*/
  sleep (.25);
  brake (3);
  sleep (1.0);
  bk (3);
  sleep (.25);
  brake(3);
  fd (3);
  sleep (.25);
  brake (3);
  sleep (1.0);
  bk (3);
  sleep (.25);
  brake (3);
  bk(1); bk(2);
  sleep(.35);
  allbrake();
  bk(2);
  sleep(1.5); /*third turn*/
  fd(1); fd(2);
  sleep(5.0);
  allbrake();
  fd(2);
  sleep(3.0); /*fourth turn*/
  fd(1);
```

```
sleep(5.0);
allbrake();
fd(1);
sleep(1.5); /*fifth turn*/
fd(2);
sleep(.7);
allbrake();
fd (3); /*start dumping*/
sleep (.25);
brake (3);
sleep (1.0);
bk (3);
sleep (.25);
brake (3);
fd (3);
sleep (.25);
brake (3);
sleep (1.0);
bk (3);
sleep (.25);
brake (3);
bk(1); bk(2);
sleep(.6);
allbrake();
bk(2);
sleep(1.5); /*sixth turn*/
fd(1); fd(2);
sleep(5.0);
allbrake();
fd(2);
sleep(3.0); /*seventh turn*/
fd(1);
sleep(5.0);
allbrake();
fd(1);
sleep(1.5); /*eigth turn*/
fd(2);
sleep(.7);
allbrake();
fd (3); /*start dumping*/
sleep (.25);
brake (3);
sleep (1.0);
bk (3);
sleep (.25);
brake (3);
fd (3);
sleep (.25);
brake (3);
sleep (1.0);
bk (3);
sleep (.25);
brake (3);
bk(1); bk(2);
sleep(3.0);
allbrake();
```

```
    bk(2);
    sleep(1.5); /*ninth turn*/
    fd(2); fd(1);
    sleep(5.0);
    allbrake();
    fd(2);
    sleep(1.5); /*tenth turn*/
    fd(1);
    sleep(2.5);
    allbrake();
    fd(2);
    sleep(1.5); /*eleventh turn*/
    fd(1);
    sleep(5.0);
    allbrake();
    fd(1);
    sleep(1.5); /*twelth turn*/
    fd(2);
    sleep(.5);
    allbrake();
    fd (3); /*start dumping*/
    sleep (.25);
    brake (3);
    sleep (1.0);
    bk (3);
    sleep (.25);
    brake(3);
    fd (3);
    sleep (.25);
    brake (3);
    sleep (1.0);
    bk (3);
    sleep (.25);
    brake (3);
}
```

Appendix J: Copyright Use Permissions

Subject: RE: Permission to use table
From: Thea Zanfabro <Thea.Zanfabro@erlbaum.com>
Date: Tue, 11 Jun 2002 16:59:12 -0400
To: Keith Adolphson <kadolphson@ou.edu>

PERMISSION GRANTED provided that material has appeared in our work without credit to another source, you credit the original publication and reproduction is confined to the purpose for which permission is hereby given.

This is an original email document, no other document will be forthcoming. Should you have any questions, please don't hesitate to contact me.

Regards,

Thea Jelcich Zanfabro
Permissions/Translations Manager
Lawrence Erlbaum Associates
10 Industrial Avenue
Mahwah, NJ 07430
email address: tzanfabr@erlbaum.com <mailto.tzanfabr@erlbaum.com>

Dear Keith,
I apologize; I thought I sent this out to you the day it came in. Please let me know if you have further assistance
Regards, Thea

-----Original Message-----
From: Keith Adolphson [mailto:kadolphson@ou.edu]
Sent: Wednesday, May 15, 2002 5:33 PM
To: Thea Zanfabro
Subject: Permission to use table

Dear sir or madam,

I have adapted the attached table from this source:

Moschkovich, J. & Brenner, M. (2000). Integrating a naturalistic paradigm into research on mathematics and science cognition and learning, In A. Kelley & R. Lesh (Eds.), *Handbook of research design in mathematics and science education*, Mahwah, NJ: Lawrence Erlbaum Associates, p.479.

I am a doctoral candidate at the University of Oklahoma in the College of Education. May I please have permission to use the table as adapted, per the attachment, in my doctoral dissertation entitled *Mathematical Embodiment through Robotics Activities*? I expect to defend my dissertation this summer. If you need any additional information to reach a decision, please let me know and I'll happily provide it. Thanks for your consideration and assistance.

Sincerely,
Keith V. Adolphson

Subject: Re: Permission to Use
From: Cathryne Stein <cstein@kipr.org>
Date: Mon, 08 Jul 2002 14:52:25 -0600
To: Keith Adolphson <kadolphson@ou.edu>

Keith,
Thanks for the reminder. I'm so glad your team participated and enjoyed themselves, and hope they continue to get even more involved in the conference activities as they get older.

Congratulations on your new position at Eastern Washington University! Will you continue to do research with middle schools? Please do stay in touch and send us your new addresses so that we can continue to keep you posted on Botball and our other educational robotics activities.

Below, the legal stuff.

Keith Adolphson,
You have my permission to use the information and graphics drawn from KIPR Botball Teachers' workshops for the competition years 2000, 2001, and 2002. This permission is limited, as this information is to be used only as part of your dissertation. This assumes the citation of presenter and KIPR as the source and copyright holder along with the website information, www.botball.org, as you indicated in your email.
Cathryne Stein
President and CEO.
KISS Institute for Practical Robotics

-----Original Message-----
Subject: Permission to Use
From: Keith Adolphson kadolphson@ou.edu
Date: Mon, 08 Jul 2002 10:51:35 -0500
To: cstein@kipr.org
CC dmiller@kipr.org

Cathryne,

Could you please email me a permission to use for information and graphics drawn from KIPR Botball Teacher's workshops for the competition years 2000, 2001, and 2002? All materials used are cited with presenter and KIPR as the source and copyright holder. I've also included the KIPR website information. I am trying to finalize my dissertation and would like to include a hard copy of the permission that you have already verbally given. Thanks so much!

I also wanted to thank you, David, and the KIPR staff for doing such a wonderful job with the national tournament and conference. The [deleted school name] team members were thrilled to be able to attend and experience what other teams were doing nationally. Keep up the good work! I hope to continue doing research about mathematics and robotics from my new position at Eastern Washington University near Spokane. Thanks for all that you've done and I look forward to our continued association in the future.

Sincerely,
Keith Adolphson