Opening Pathways to Higher Education through Engineering Projects

David Cavallo, Arnan Sipitakiat, Anindita Basu, Shaundra Bryant
MIT Media Lab, 20 Ames St., E15-319, Cambridge, Ma. 02139
Tel: 617.253.8897, Fax: 617.253.6215
Email: [cavallo, arnans, anindita, bryant]@media.mit.edu

Abstract: A major obstacle to attracting minority candidates into engineering disciplines is the difficulty in ensuring a sufficient of interested and qualified candidates. We present our work in K-12 education in both school and informal settings on a constructionist approach to engineering projects based upon generative themes. Students design and construct artifacts embodying their ideas using a variety of computationally-rich materials. Through this construction process they not only learn important underlying concepts in math, physics, and engineering, but also gain significantly in their sense of themselves as capable learners. Children who had not previously achieved at necessary levels to enter engineering programs have shown tremendous progress and renewed interest in academic achievement. It is our hope that through a more widespread adoption of such an approach, we will have many more qualified minority applicants to university engineering programs.

Background

A major obstacle to attracting minority candidates into engineering disciplines is the difficulty in ensuring a sufficient of interested and qualified candidates. Unfortunately far too many potential candidates do not achieve the necessary levels of academic preparedness, interest, or opportunity in order to qualify for acceptance into university engineering programs. While minority candidates perform on equivalent levels to others through primary school, it is in the middle school years where differences emerge. If one is to accept that these differences are not due to any inherent lack of innate abilities, then one must attempt to create initiatives to overcome the barriers at these ages in order to create pathways and opportunities for all.

We have designed and implemented a number of initiatives in K-12 education, in both schools and informal settings, in which we used engineering projects as a basis for creating personally meaningful artifacts within generative themes. This has opened new pathways to achievement for a broad range of students not only among those who already had high achievement levels, but also including those who did not perform well in traditional school settings as well as those who were not technically inclined. Students were able to deepen and, strengthen their understanding of underlying mathematical and scientific as well as explore these concepts in areas of personal interest.

We have taken an interdisciplinary approach by providing generative themes such as "*Designing the City that You Want*" and "*RoBallet*" (a performing arts and technology environment), in addition to creating more straightforward engineering challenges such as ramp climbing, robotic contests, autonomous vehicle rallies, and so on. We also emphasize programming projects, whether in the creation of their own video games or for programming of robotic devices or designs. While each of these themes are extensive and a thorough review of each is beyond the scope of this paper, they share the underlying premise of the primacy of meaningful engineering as a gateway to important content and personal achievement. Through the course of design and construction, students encounter problems that require knowledge within the disciplines (i.e. math, physics, etc.). However, in large part because they need the knowledge to make their own project function properly, they learn what is required in a situated manner. Over the course of constructing a variety of projects, they encounter deep principles through recurrent need. This approach has proven far superior to using toy problems in brief time periods. Students use a variety of computational and engineering materials (e.g. programmable microcontrollers, sensors, simulation tools, motors, gears, pulleys, etc.), in order to design, construct, critique and modify their own projects.

We have found that by introducing engineering projects in a variety of contexts we have overcome many difficulties among students who found the math and science too abstract, not useful, or not meaningful. We also

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have avoided the problem of watering down the content in an attempt to achieve relevance as the functional engineering nature of the projects combined with the design critique process enforces robust and complete knowledge in the domains. Critically, we have found that by achieving success at sophisticated engineering projects that the learners know are difficult, they not only gain the satisfaction inherent in engineering projects but also gain in their belief in themselves as learners, problem-solvers, and creative thinkers.

In this paper we will present the underlying concepts, describe some sample, discuss some of the issues, and our ideas for continuation. For the purposes of this paper, we combine a number of different initiatives of ours from a variety of settings. The principles of learning through design and construction of engineering projects is consistent throughout. However, we have applied this in schools, in informal settings such as community centers in poor, urban neighborhoods, and in projects with children in our laboratory. What is important is not the setting, but rather the nature of the activity and what the children accomplish. Significantly, children, including minority children, who have not achieved academic success perform at high levels.

Theoretical Underpinnings

Like many others, we believe that knowledge is constructed by the learner and is not just a matter of transfer of information. We believe that this construction happens best when the learner is actively engaged in the process and is not treated merely as a passive receptacle. However, we add to this the idea that this construction of knowledge happens particularly felicitously when the learner is engaged in the construction of meaningful artifacts [Papert, 1991]. Construction uncovers underlying ideas and principles that can be glossed over and not fully understood through language. Learners externalize their ideas in the construction of the artifact of their choosing. Their design embodies their thinking. They then test this design against its challenge. The world provides feedback. Virtually every time, the creation will not work as hoped for on the first iteration. They have either expressed their ideas properly but their ideas are not accurate, or they have not expressed their ideas in the creation effectively. We ask them what were their limiting factors. We introduce the important underlying concepts in the context of the project and their expression. They then re-internalize the ideas after their experiments, re-design, re-build, and learn through this cycle. Since we create environments where students will design and construct artifacts of their own choosing in generative themes, issues of motivation typically fall by the wayside. This will become evident in the discussion below.

A Sampling Of Projects

Project work is the basic unit of endeavor. A student would typically work on a variety of projects simultaneously. Sometimes we presented challenges for everyone to do, at other times there were themes for work, and there were also projects of an individual nature. In order to gently introduce the way of working and some of the materials, we typically begin with a common project challenge, to make a non-powered vehicle that could go the furthest when let loose from the top of an inclined ramp. Before beginning, we would challenge students to construct a theory about what design will work best. Heavy or light? Many wheels or a few wheels? They expressed their ideas (it is common that virtually all students believe heavy will be better) and began building and testing. One nice feature of this type of methodology is that there can be a rapid design-develop-test cycle, and one has multiple opportunities to test one's theories by trying multiple approaches. Moreover, one can also use the material to reliably test the ideas. For example, most associated faster speed on the ramp with longer distance. However, how could one reliably determine speed? The path to this solution came through a variety of paths, but, typically, through a group-generated lacuna. Some adopted the challenge to make a soap-box derby, racing two at a time. When racing against each other, they quickly realized that if one let one's vehicle go early, they could get an advantage. They then designed and built a control system with a touch sensor at the top that would start a timer when released, and a light sensor at the finish line to get an accurate time. They next determined that if they only used one light sensor at the bottom, the first finisher potentially could obscure any subsequent ones (they expanded the number of lanes to accommodate more simultaneous racers and faster design testing), so they changed the design for independent timing of each lane. As this went on, once student decided to build a speedometer that could test any rotating device, soon realizing how the diameter of the wheel was a key factor for measurement. This challenge not only introduced concepts in mechanics but also conveyed powerful mathematical ideas. Rather than being repellant to students, mathematics became a way of understanding the world and achieving their desired goals.

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Our demand for verification of concepts helps enable this work to go beyond other project-based activities. Common complaints for project-based work include accepting that while the projects maybe enjoyable, we cannot necessarily ascertain what exactly the learners learned. Did they really understand the underlying scientific, mathematical, and engineering concepts? Were they just lucky? Did they

Ramp climbing

We then turned the challenge around by asking them to make a vehicle that could climb the steepest possible incline. This introduced motors and gearing into the devices. Again, we ask them to hypothesize about critical design factors. Fast or slow? Many wheels or a few? Wide or thin? Tall or short? They could apply the rapid design-build-test-debug cycles to think through the process. Many expressed their ideas as applying the model of riding a bike up a hill where you want to have as much speed as possible at the bottom as you will "lose momentum" as you climb. Students who chose this approach found a few flaws. If they placed their model on the floor speeding towards the ramp, it would just bounce off. Offered to begin on the ramp, the car would not move at all as the motor would stall.

Here we would intervene and ask, "What are your limiting factors?" In this case there are only a few. The motor may stall and we can discuss force, torque and mechanical advantage. The motor may work but the wheels merely spin. Here we can introduce friction and coefficient of friction. The vehicle may merely topple of the ramp, enabling the introduction of center of gravity. Working in this way we presented in context a model for thinking about the problem and moving towards a solution. In the above case, the student responded "The motor is not strong enough." We would ask, "What makes a motor stronger?" This gave a way to introduce powerful ideas such as mechanical advantage and force not in an abstract way but in a concrete, connected way. The ideas were powerful to them because they enabled them to achieve what they wanted. When we asked about the limiting factors, we modeled a productive process and introduced terminology in context. We do not expect everyone to invent important scientific content out of thin air. We do not fabricate toy situations to teach specific concepts. Rather, the concepts emerge due to need to make their own projects succeed. *Their* projects are *their* expression of *their* thinking about how to accomplish what *they* choose. This approach trivializes neither constructivism nor discovery. If their thinking does not achieve expected results, either their expression or their ideas need re-doing. We do not expect learning absent a culture of interesting challenges and supportive adults. However, we are not under the illusion that if we merely tell them an answer then that means they understand it fully. The project serves as the most important metric of understanding. It either works or it does not. The world provides the feedback. Our role is to introduce concepts and methodology to make sense of the events and to gain understanding and harmonious ways of thinking regarding acting in the world in a pragmatic sense. Multiple projects surface scientific principles as the same idea may apply in a variety of situations. The methodology, and the development of a culture built upon such exploration, investigation, and verification, potentially carries the learning past simply making something work as one uses the same approach and tools to verify whether the ideas are robust, complete, and have aesthetic value.

After several weeks of refining the ramp climbing devices, one of the students asked what were the success criteria. The teacher responded that the front wheels had to reach the top of the ramp. The student then designed a vehicle that climbed 110 degrees. He did so by making something about 20% longer than the ramp. The front wheels climbed and the rear wheels pushed the vehicle against the ramp. It was not what we had imagined but did fit our criteria. Indeed, it is an example of innovative, out of the box, thinking we try to inculcate. This work was consistent with the spirt of all scientific inquiry and historical exploration. It was also compatible with adolescence. Redefining terms and challenging convention became a regular practice after the ramp climbing experience. What makes this story more remarkable is that this student did not read or write, had left school at age 11, and had shown no achievement in school. He was one who tested at first and second grade levels even though at the time he was sixteen. We were advised not to admit him into our program because school administrators felt he was not sufficiently capable to benefit from it. Yet, he developed into our star student and truly showed brilliance in his work [Papert, 2000]. His means of working was to take an idea and try to apply it in every means he could conceive. He wanted to understand things deeply and thoroughly. He would work for weeks on ideas and projects. It is easy to see how such a student could fall through the cracks in a school environment where one can only work on tasks for short periods of time, where a curriculum is pre-determined, where subject matter is divided into the disciplines, and where the projects are not one's own.

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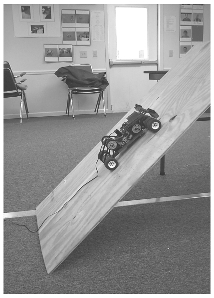 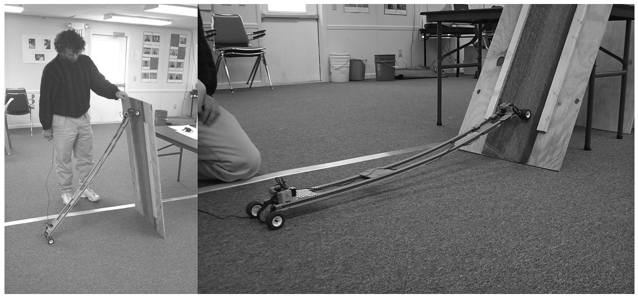

Ramp Climbing Extended

After achieving their remarkable feat, this boy and his partner decided to fortify their vehicle, as it was long and thin, and, by this time having gained structural expertise, knew that it was a rather brittle construction. So, they braced the structure, which required additional expertise. When they first attempted their reinforced climber, they were stunned to see that not only would it not climb at all, but also it vibrated severely and broke apart exactly where they had braced the structure. The vehicle needed flexibility so as to bend to climb at a greater than 90 degree angle. They discovered that rigidity did not always equal strength. This discovery led to a whole new range of extensions and ideas. We could study how bridges work, how flexible structures can be stronger for certain purposes, why how stress and load can be carried, why buildings do not fall under their own weight, and so on. A student created another interesting connection by using a digital microscope to examine whether she could match the surface of the ramp (as well as materials such as sandpaper that she would attach to the ramp) and the tread of the various tires available. She determined that there were better matches to get appropriate friction and could increase the incline. She built according to her theories in order to validate them.

It is easy to see why following the innovations and ideas of the students led to a rich and engaged learning experience. The content that they covered in their pursuit of succeeding with their projects is rich. It is organically inter-disciplinary, where the knowledge in the fields supports their quest, and thus is situated both in the context as well as in their construction of their thoughts. The math or physics is not abstract and isolated, but is put to use by the learners. Since their ideas were truly innovative, we could not plan beforehand what should follow what. However, we did not sit by idly either. When they began the ramp climbing, we introduced the methodology of looking for limiting factors, we brought in the language and concepts of force, torque, friction, etc., and when the innovative braced ramp climber fell apart, we suggested other connecting themes. As students needed concepts for use in their projects, or for extensions, or they expressed curiosity, we offered mini-lessons to demonstrate the necessary technique or idea. The ratio of teachers presenting to students doing is virtually the inverse of traditional classroom settings. We spoke little and in context and they led and accomplished more. We use an *emergent* approach to follow interests, introduce themes, and connect to important ideas [Cavallo, 2000]. We have carried out this project in urban community centers as well as in a project in a center for adjudicated youth, every time with excellent results.

The projects mentioned above illustrate the culture of the environment, although they are not fully representative as they were a sample of initial work and do not include computational elements. All students worked on a variety of projects using a variety of materials (computational, mechanical, and crafts), simultaneously. Many were purely computer-based, such as creating animations, making games, building simulations, managing stock portfolios, etc. Many projects were based upon Lego robotics. Some were challenges such as the above (e.g. getting weight across a divide, of throwing objects over barriers which proved especially compelling to adjudicated youth), while others involved more complex control structures using programming and sensing (e.g. locating objects and moving them to specified places, automatic Lego sorters, or even a soft drink dispenser that charged more or less depending upon the temperature (inspired by a news item and inspiring the creator to author a letter to a cola company offering his design). More complicated challenges were rallies where vehicles had to follow a path laid out in tape throughout the room, avoid obstacles, and hit certain markers at particular times. This required algebra in an authentic way to determine gear ratios and velocities. After they accomplished this, they laid out a path that would require changing gears and differentials by not having a constant relationship between distance and time. On the day of our first open house we challenged Michael, our star pupil from the ramp climbing, to add another demonstration project in the 3 hours before guests were due. We asked him to build a vehicle that could be placed anywhere on the

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blue carpet and have it find the metal strip that cut across the middle of the room, and once it found the strip, could traverse the strip from end to end. He stunned us by accomplishing this with more than an hour to spare.

RoBallet

We designed our RoBallet environment so that children could choreograph dances, use and or build sensors to place on their bodies and in the environments to control music they compose, robots they build, animation they program, lights they control via programming, and other devices they can choose to place in the environment. We do not expect them to learn by things happening and being presented to them in an immersive space. The space should not control the children. The children should control the space. They design and decide what should happen. We did not want to present the elements we used (i.e. music, robotics, programming) as fixed and determined. We wanted them to explore movement through space in time, what sounds pleasant and what not and which musical elements combine to create which types of feelings, how these could be different; how lighting can be mixed, can be expressive, can combine with the other elements, and so on. We wanted the children to have fine-grained design control over these elements so that they could explore the concepts in a non-trivial, personally meaningful ways. The immersive environment serves to create a rich experiential space for this exploration. We also chose to design our tools not just for direct manipulation, but in an environment for expression that can later be built piece by piece, taken apart, modified, reflected upon, modulated, and experimented with. However, with such ambitious design goals and not a lot of experience and domain expertise, we chose to run a workshop and use that as an "object to think with," to help us to see the possibilities and limitations [Papert, 1980].

Thus, for our initial foray into this space, we decided to build some prototype tools and use some existing software to experiment concretely early in the design process, knowing that we would in all likelihood not use those specific tools. We used both Stack boards from Joe Paradiso's group and GoGo boards designed by Sipitakiat [Benabast et.al., 2003, Sipitakiat et.al., 2002]. The Stacks are more sophisticated and advanced, with not just wireless communication but also accelerometers and gyroscopes on board. The GoGo board is simpler, designed to be accessible by being low-cost, using easily available components, and possible to assemble by hand. We have used different versions of the GoGo board in a variety of learning projects to integrate robotic control into other projects for learning. In this sense simpler and accessible have some advantages over sophisticated and advanced even if giving something up in terms of power, speed and capability.

We converted a traditional stage setting into a responsive environment that could dynamically interact with lighting and music systems, and added an animation system that could be projected into the dance space (Figure 1). After beginning their choreography, the group embedded sensors in the stage floor and the environment, allowing the students to program triggers for certain events. In addition, we provided a set of sensors that students could wear on their bodies. The body sensors plugged into small wireless wearable devices, both the Stacks (Figure 2), which students attached to belts and wore around their waists, and the GoGo boards. The Stacks transmit data from the body sensors to a server that we programmed, which in turn sends the sensor information to the computers that operated the lights, music and animation.

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Figure 1. The RoBallet environment.

For music and animation we decided to use what would be closest to what we would want, but easy to assemble rapidly for the workshop. We knew that for music nothing yet existed that would suit all of our design goals. However, to build what we desired would take too long and would delay our initial workshop. So, for music we programmed an environment in MaxMSP to enable the students to lay out what they wanted along various dimensions such as melody, rhythm, pitch, etc., and then program what effect change in sensor values should create. For animation we used both Microworlds Logo and an environment we built in Squeak. The environments would respond to sensor data and change the animation as programmed. We also built an interface in Squeak so that the lights could be programmed to respond to the sensor data as well.

Workshop

Another reason to do a workshop with children early in the process was that we had the opportunity to work with Jacques d'Amboise. d'Amboise is the former principal dancer of the New York City Ballet, and the founder of the National Dance Institute (NDI). d'Amboise was accompanied by Dufftin Garcia, who runs the NDI center in Trenton, New Jersey. Garcia is also a former student of d'Amboise's from the NDI work in New York City, and is currently studying computer science. The two agreed to work with us in a workshop with children in July, 2003 at MIT. We agreed that for the purposes of this workshop, we did not want children with lots of experience in either dance or programming. We wanted to see what "average" children would make of our space.

During our design of RoBallet, we had an initial generative theme in mind: for students to create dance pieces that expressed a particular emotion. We wanted children to think about how to express an emotion using all of the various elements available to them, from choreographing movements, to composing music, to designing lights and creating animations, and also to consider how these different media best augment each other.

While RoBallet was inspired by the girls who were making robots to dance with, our first instantiation of the project did not feature robots as there were many other elements that we wanted to work with. Since we had an extremely limited amount of time (8 days), and so many ambitions, we felt that if the children were to build robots and program them that would use up a significant portion of the time. Because we have had many years of experience working with children doing robotics, and wanted to maximize the talents of d'Amboise and Garcia as well as test out the other elements of the environment that were new, we decided to omit the robotics for the first workshop (an ironic decision given the name of the project). We began with a desire to provide students with multiple expressive tools that related to dance, so we first examined various elements of a traditional dance performance.

Once the environment was constructed, we held a workshop with a group of nine 9-12 year old children. The workshop was supposed to be a one-week event in which we could test the environment and have some preliminary feedback on the ideas, but at the request of the children, we extended the workshop for another week, and allowed them to invite friends to participate. During the first, "official" workshop, the NDI facilitators helped the children learn to choreograph, to think about what steps can be appealing, to express themselves through movement, to understand how to control movement through space in time, to match music and movement, and to keep in mind how a performance appears to an audience. Exposure to such expertise and experience was critical to us all to bring an understanding of dance.

Since the first workshop included professional dancers as part of the facilitating group, the students were introduced to the methods used by dancers to develop steps and combinations. This exposed an interesting similarity between dance and programming. d'Amboise taught by breaking dance steps into counts of eight and naming the steps with something the children could understand. For example, running in a circle to the left with knees high in the air was called the "pear." Running in the opposite direction was called "apple." Then he called out the names of steps in sequences to create combinations, which were then given names such as "fruit salad." This mapped directly to how the children were creating programs to run their music, lighting and animation. They mapped environmental events either to particular dance events or to particular dancers and named events accordingly. The programs were named like the step combinations, as a superset of the individual events. There was even an overlap between trying out steps one at a time in various combinations, and once one is satisfied, to name them and bundle them to be used in different combinations and variations. We were amazed by the similarities between how Jacques introduced choreographing dance and how we introduce programming.

In the second week, we encouraged the children to explore choreography on their own, to both invent and name steps and to take a step combination and perform it with different intentions, such as happiness, anger or frustration. We opened the workshop every day with a set of physical warm-ups and improvisation exercises to encourage children to both experiment with how to express emotions and formalize what they were doing.

The workshop in week two was completely open, so children chose their groups, emotions and how they wanted to approach their projects. In some groups, children wanted to work on different elements in parallel, so one would compose music for the emotion, while another worked on lights. In other groups, the students wanted to execute every part together. All of the groups had to revise and debug their programs however they approached them, however, since when they saw all of the elements combined, some aspects inevitably clashed or were not coordinated. This led to many different discussions, from which sensors to use and how to create effects most naturally to trying to more effectively convey an emotion through the combination of media.

The City that We Want

In this project we ask the students to analyze their community and design computational projects that exemplify their ideas about how they could improve life in their city, either by addressing a problem, augmenting an asset, or realizing a dream. We have run this project in schools over the previous two years and the results have been amazing. The level of work has been excellent, the level of participation incredible, and the improvement not only in math and science achievement excellent as reflected in test scores, but we also witnessed a change in attitude regarding such work in math, science, and engineering and their abilities to perform such work.

Projects have included many machines for automatic trash detection and recycling, an intelligent bus that knows when it is full and displays which seats are open, environmentally friendly cooling of classrooms, streetlights powered by friction of cars on the street, devices for handicap accessibility, energy-generating playgrounds, water

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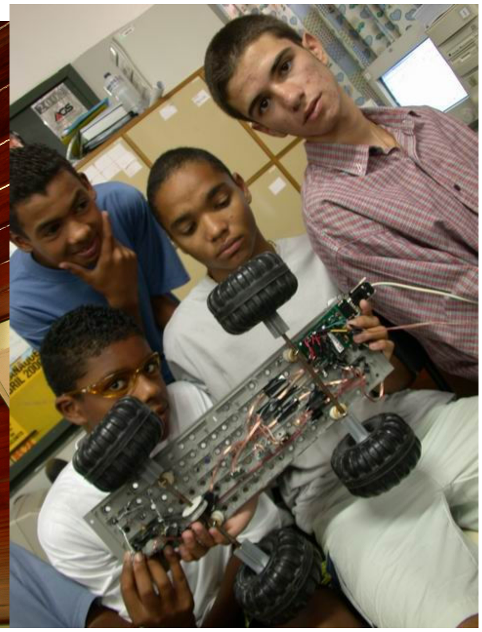
filtration, river pollution detection and cleaning, and many more. In one notable project, students in an economically distressed area determined that they could create a fish farm to generate revenue for their families by reclaiming and purifying water released from a swimming pool.



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The students worked on these projects over a variety of time periods, but the more complicated projects required months of work. Because of the complicated nature of the tasks, the students confronted many important concepts in the disciplines. In order to make their project function, they had to come to a certain level of understanding. We worked with a variety of materials so as to be as inclusive as possible.

Discussion

The projects we have described share certain characteristics. Students design and build their own projects according to their own ideas. In order to make these projects function they have to overcome technical difficulties and thereby learn important academic material. We have chosen a variety of themes in order to include as many youth as possible, not just those who were pre-disposed to engineering activities. Our theme of the city or work in the performing arts provides incentive to do engineering and work with technology to those who might never have thought it was in their interest.

An indicator of attitudinal change was how the youth did not want to leave the lab to return for their free time. Many preferred staying to work on projects to playing basketball and other activities. They worked hard in our programs. Their attitude was not different on their first day with us. Getting it to change was one of the key goals of our work. Finding a way to make working hard and succeeding acceptable within their own value system, that cooperating in our program did not mean they were weak, submissive to authority, or geeky. In every case the number who volunteered to enter the programs far exceed our capacity.

However, the interesting results were not limited to social and behavioral development. They were intricately tied to their accomplishments. As they observed their achievements in tasks they knew to be difficult, they changed their views of themselves as learners. As these views changed, they became more daring and more expert in their work creating a virtuous circle. Many of the students with whom we have worked were in special education classes. As opposed to presenting the same material slower, or utilizing the same epistemological framework, we focused on the *design* and *construction* of personally meaningful *projects* determined by the learners and not pre-set by others. We insisted that the projects go on over extended periods of *time* for depth and robustness of exploration, by not just focusing on articulation of knowledge primarily through text but rather by facilitating hands-on creation of concrete artifacts and thereby facilitating multiple learning styles. The better than 1:1 ratio of computational materials to students so that each student could create multiple projects simultaneously and express their ideas in forms more closely resembling their own conceptions, the students went far beyond their previous records of achievement. Upon a close review of the activities and the students' work, the Maine Commissioner of Education Duke Albanese proposed using the this approach as a diagnostic for students being assessed for special education to route suitable candidates to an alternative program based upon the same ideas.

While we focused on developing a more positive attitude towards learning and the development of computational, mathematical, and expressive fluencies, and thus did not focus on a particular curriculum or content, we therefore make no claims about the overall completeness of what children were learning. However, they learned the physics they needed for their constructions. They developed an understanding of coordinate geometry through their making of games [Kafai 1995, Harel, 1991]. They learned ideas in control theory, programming, and, depending upon the project, history, biology, chemistry, electronics, and so on. We are now using our learning from this project to guide us in thinking of how to develop materials to support such Constructionist, project-oriented, learner-centered environments that can be complete and function in a variety of settings.

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