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SENSE IT: Teaching STEM principles to middle and high school students through the design, construction and deployment of water quality sensors

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ABSTRACT

This paper describes the structure and impact of an NSF-funded ITEST project designed to enrich science, technology, engineering, and mathematics (STEM) education using educational modules that teach students to construct, program, and test a series of sensors used to monitor water quality. During the two years of the SENSE IT project, over 30 teachers across New York State were provided with equipment and professional development, and then implemented the modules in their classrooms with over 1,700 middle and high school students. Project evaluation results indicate that the curriculum was well received by teachers and students, could be integrated into several different subject areas and types of courses, and was effective for a wide range of students.



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Key Words: STEM education, SENSE IT, water quality

INTRODUCTION

This paper describes the development and implementation of SENSE IT (Student Enabled Network of Sensors for the Environment using Innovative Technology, <http://senseit.org>), a carefully scaffolded set of curriculum modules tied to the New York State and national standards in science, math, and technology, which integrate fundamental STEM principles while at the same time introducing students to the field of sensors and sensor networks in the context of assessing water quality. Over the course of two years, SENSE IT was implemented by over 30 teachers and 1,700 students in schools in three regions in New York State (Potsdam, Troy, and Beacon) chosen to represent three school environments—rural, urban, and suburban—along New York State’s two major rivers, the Hudson and St. Lawrence.

Developing a sensor network for environmental monitoring creates a broad technology project which can readily provide a motivating context for a variety of science, math and pre-engineering classroom curricula. Sensors and sensor networks involve an information flow of the sensed quantities from the natural environment through the physics of the transducer and the electric circuit in which it is embedded, to a computer, to programs for data gathering and analysis and IT tools for data sharing, storage and display. Using SENSE IT materials, students build, calibrate and test a set of sensors and circuits in order to measure a variety of water quality parameters (temperature, conductivity, turbidity and depth). To build and understand their sensors, students must use a wide range of core knowledge of mathematics and physical science, as well as learn practical hands-on technology skills such as soldering and debugging circuits. Students then interface their sensors with computers, write programs to gather raw signals, implement calibration curves, and perform data manipulation and data logging. In later modules, students program their own communications protocols for wireless transmission of the sensor data and connect their computerized sensor stations together to form a distributed wireless sensor network (Hotaling et al, 2011). Additional modules explore the use and implications of this technology for biosciences and environmental research. All of these stages require mathematical reasoning consistent with those typically addressed at the high school level.

The set of SENSE IT modules gives students an opportunity to acquire and then use STEM skills while at the same time providing a real world application of science (particularly environmental science), technology (pre-engineering and computing) and mathematics, all tied in a holistic way within the overarching theme of water quality. The project’s overarching goals were:

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- To develop a sensor technologies curriculum for the high school classroom.
- To use environmental sensors to teach technology, engineering, mathematics, science, and critical workforce skills.
- To encourage learners to look at a local problem and local data with a global perspective.
- To promote awareness of sensor network-related careers and opportunities among high school teachers, students and guidance counselors.

In what follows, we will first address the question of why sensors are an excellent vehicle for such a curriculum, describe the curriculum and its participants in some detail, and then examine its impact on the students in terms of some of the specific skills and concepts that were embedded in the curriculum modules. Changes in student career awareness are not discussed here but are the subject of a separate paper.

WHY SENSORS?

Sensors are everywhere. From motion-sensing light switches to environmental observatories, we are connected to our physical world in real time. The sensor revolution is, in effect, giving the world its first electronic nervous system (National Science Foundation, 2005). Sensors now play a particularly important role in environmental research. The education of the 21st century environmental technology workforce therefore demands an understanding of sensor technology, as well as the ability to resolve complex environmental issues and to communicate findings to a broad audience. Developing and maintaining such a workforce calls for innovative educational programs that prepare future sensor technology professionals at a variety of levels and in a variety of environmental fields (Ocean Commission Report, 2004). This type of multidisciplinary, technology-based approach is not sufficiently reflected in our current educational programs.

The classroom integration of sensor development is therefore not only topical but offers highly interdisciplinary subject matter, providing motivating scenarios for teaching a multitude of science, technology, engineering and mathematics (STEM) subjects and skill sets. SENSE IT provides students with the opportunity to learn about sensor technology through a hands-on, collaborative process of designing, constructing, programming and testing a student-implemented water monitoring network in the Hudson and St. Lawrence Rivers, which together span the state of New York. Design-based activities such as SENSE IT provide a rich context for learning and lend themselves to sustained inquiry and revision. Application of learning is a worthy learning objective and an effective route to greater retention of knowledge and depth of mastery. As Caine (1991) notes, "Children learn best if they are immersed in complex experiences and are given the opportunity to



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actively process what they have learned.” This emphasis on application through design has been informed by research on the use of design for learning complex and interrelated ideas (Brown, 1992; Blumenfeld et al., 1991; Harel & Papert, 1990, 1991; Perkins, 1986; Mishra & Koehler, 2006). Design-based activities also bridge to many of the models of project-based learning (Blumenfeld, Marx, Soloway & Krajcik, 1996; Blumenfeld et al., 1991; Dewey, 1934; Papert, 1991; Khardon & Roth, 1995; Roup, Gal, Drayton, & Pfister, 1992). In addition, SENSE IT reflects the best practices for professional development—extensive, iterative, ongoing, and in context (Fishman, 2003; Wenglinsky & Silverstein, 2006; Mishra & Koehler, 2006)—as well as best practices for developing technical talent as outlined in the BEST (Building Engineering and Science Talent) report, “What It Takes: Pre-K-12 Design Principles to Broaden Participation in Science, Technology, Engineering and Mathematics”: (1) Defined outcomes; (2) Sustained commitment; (3) Personalization; (4) Challenging content; and (5) Engaged adults.

THE PROJECT

The Curriculum

The SENSE IT curriculum is comprised of four educational modules (<http://senseit.org/curriculum.html>). In Module 1, *Sensor development*, students learn about the principles of transducers and then design, analyze and calibrate electronic circuits around their transducers in order to make numerical measurements of environmental quantities in appropriate units. Initially students work with thermistors and multimeters to begin to understand the relationship between temperature and resistance (see Figure 1). A second resistor is then added to the circuit containing the thermistor and multimeter, and through the data-gathering process students build a temperature sensor with a linear calibration curve.

This module requires the use of mathematics skills (e.g., systems of equations, data plotting and curve fitting, rearranging formulae), science skills (understanding physical quantities, measurement and error estimation, electrical components and circuits), pre-engineering skills (engineering design, tool use, testing and debugging) and 21st century skills (teamwork, communication).

In Module 2, *Sensor deployment and data gathering*, students learn how to interface their calibrated temperature sensor with a microprocessor, the LEGO NXT microprocessor. Students use mathematical skills to calibrate the outputs of the sensors and write computer programs to implement these calibration curves and display sensed quantities on a screen in appropriate units. Students then learn how to write data-logging programs to log time-stamped data over a sustained period of deployment.

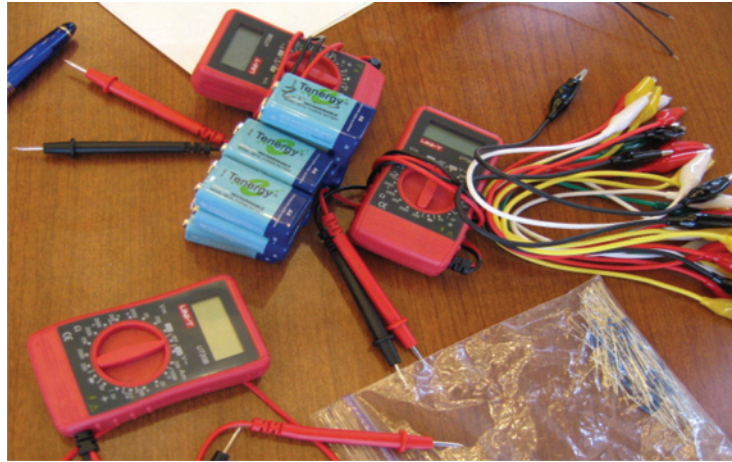


Figure 1. Equipment needed for Module 1, Lesson 4, Potential Dividers. The Lesson demonstrates how potential divider circuits can be used to change the output characteristics of a sensor.

The balance of Module 2 leads students through the development of additional sensors, including salinity, turbidity and depth sensors. The salinity sensor involves students passing a current between two lengths of copper wire and measuring the voltage between the electrodes to calculate the resistance, and then converting that measurement to a conductivity value. Students finish by writing a NXT program to collect conductivity measurements and calibrate their sensors.

The turbidity sensor consists of two main components, a light source (light emitting diode or LED lamp) and a light sensitive device (photo-resistor). The LED and the photo-resistor are fixed a short distance apart in such a way that water can flow between them. The more turbid the water, the less light from the LED lamp will reach the photo-resistor. The photo-resistor is a device which changes its resistance depending on how much light falls on it. Therefore, by measuring the resistance of the photo-resistor, students can measure how much or how little light reached it from the LED lamp, and therefore turbidity. Students construct and calibrate their turbidity sensor and write a NXT program to display and collect turbidity measurements.

The final sensor that students build is a pressure sensor to measure depth. Students figure out the mathematical relationship between pressure and depth, calibrate the sensor, and then write a NXT program to convert the signals from the pressure sensor into a depth measurement. The program actually takes two measurements—it measures absolute ambient atmospheric pressure at the surface and simultaneously measures the absolute underwater pressure at depth. An electronic circuit then subtracts the atmospheric pressure from the underwater pressure reading to give a gauge pressure,



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such that pressure at the surface is defined as zero. Because the sensor takes two measurements and calculates the difference, it is known as a differential pressure sensor. Students calibrate the depth sensor and write a program to record and display the depth measurements.

The deployment and data-gathering module requires students to use mathematics skills (systems of equations, simple statistics, manipulation of formulae), science skills (hydrology, electrical circuits), pre-engineering skills (design, testing and problem solving, tool use), technology skills (programming and interfacing a microprocessor) and 21st century skills (teamwork, communication).

Module 3, *Environmental science*, puts the engineering activities in context by exploring environmental science issues that provide a meaningful motivation for the development and deployment of sensors. In this module, students work through a series of lessons which reveal water as a precious resource and demonstrate the importance of everyone doing their part to protect and manage water quality. Students investigate careers in environmental engineering that focus on the management of water and explore the sensors and sensor network engineers are developing and deploying to monitor, manage and protect our water resources.

The environmental science module requires the use of science skills (hydrology, chemistry associated with water quality tests, water science—specifically how parameters interact such as temperature and dissolved oxygen), technology (using computers for data analysis and display and information gathering) and 21st century skills (teamwork, communication).

In Module 4, *Wireless sensor network*, students learn about wireless communications and work in teams to build and program their own wireless distributed sensor network. Each sensor network consists of several remote sensor nodes, each node comprising temperature, salinity, turbidity and depth sensors that have all been built by the students. The students then program their own wireless communications protocols, so that each remote node transmits its sensed data back to a central hub, where it can be time stamped and logged and uploaded to a PC for analysis.

The wireless sensor network module requires the use of mathematics skills (data analysis), science skills (understanding of the physical quantities measured, hydrology, environmental science), technology skills (internet research, programming) and 21st century skills (cyber-collaboration, communication).

Materials

Students construct their sensors from scratch using standard off-the-shelf electronics components. They are led step by step through the physics principles, electric circuitry and mathematical analysis required to build each sensor, with the aim of demystifying the “black box” effect associated with using commercially available probes in classrooms. The hope is that by building their own sensors, students will gain a better understanding not only of how sensors work, but also of the meaning of the quantities that the sensors are used to measure.



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Once students have assembled a sensor, they connect it to a LEGO NXT microprocessor (see Figure 2). Students write programs on a PC and then download them to the NXT, where the programs are executed. SENSE IT uses the NXT-G programming language, a very simple icon-based programming system that is easily assimilated by beginners with no previous programming experience but is sophisticated enough that students can use it to take readings from D-to-A converters, encode the equations of calibration curves using math blocks, write wireless communications programs using Bluetooth, and write data-logging programs to store sequences of time-stamped sensor readings in files (see Figure 3).

When deciding what kind of sensors the students would build, care was taken to create sensor designs that were accurate enough for students to make meaningful measurements, but also simple enough that high school students could understand what they were building and how it worked.

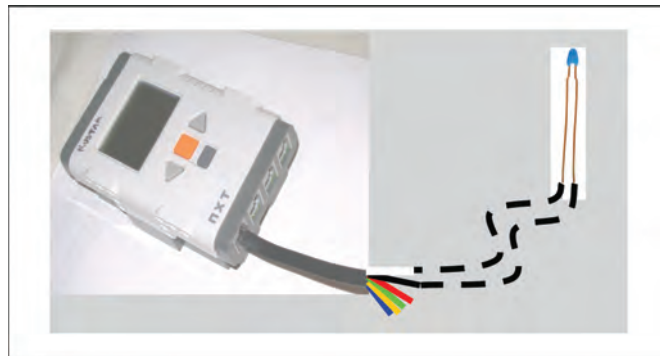


Figure 2. Connecting a thermistor to an NXT computer to measure water temperature.

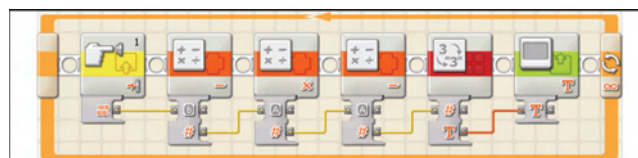


Figure 3. A simple program in the NXT-G Mindstorms language. These programming blocks read a voltage from a thermistor circuit via a D-to-A converter, use math blocks to convert this into temperature °C by encoding the equation of a calibration curve, convert this reading to a text string and display it on the screen, then repeat this process within a continuous loop.



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The Professional Development Model

The professional development model for the teachers planning to teach the SENSE IT curriculum adopts the Technological Pedagogical Content Knowledge (TPACK) framework, which sees content knowledge, technology, and pedagogy not in isolation but believes that good teaching requires an understanding of how technology relates to both the pedagogy and the content, and how all three are bound together (Mishra & Koehler, 2006). To be effective, professional development must therefore be in-depth, take place continuously over time, and be in context (Fishman, 2003; Wenglin-sky & Silverstein, 2006). SENSE IT teachers completed 120 hours of professional development by participating in two summer institutes (two week institutes during two consecutive summers, the second week with students), four professional development days (one each semester for two years), and on-site classroom support visits during implementation.

During the first week of the summer institute, the teachers learned the module content, with enough time to work through all of the lessons and begin to devise implementation plans for their own classrooms. During the second week, each teacher was invited to bring two students to participate in a teaching laboratory, with the teachers teaching the modules in a highly supported environment, surrounded by SENSE IT staff (see Figure 4). This opportunity to implement the materials with students gave the teachers an opportunity to review the materials again and to see how they worked with students. They found this a very effective approach, both in terms of the amount of additional time they were able to spend with the curriculum and in terms of how seeing their own students work through the modules increased their own confidence in their ability to teach the SENSE IT modules to entire classes.

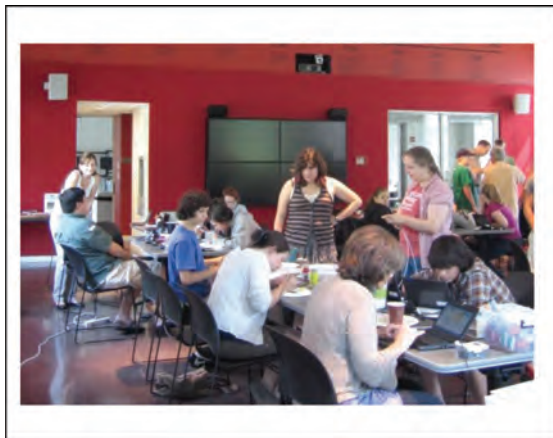


Figure 4. Teachers and students during second week of summer workshop, Beacon.



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The professional development days, led by SENSE IT staff, were used to share successes and challenges, as well as to develop additional sensors and discuss STEM career information and opportunities. During the classroom visits, SENSE IT staff offered support during implementation and also experienced first-hand any implementation issues.

In addition to the in-person professional development offered to SENSE IT teachers, a webinar focused on Science, Technology, Engineering and Mathematics (STEM) career awareness was offered to guidance counselors associated with the SENSE IT participating schools and to the parents and students who attend the schools. The webinar participants discussed future employment opportunities, career preparation pathways, and advice on what teachers and students should look for in STEM programs when applying to schools.

And finally, all of the SENSE IT modules and developed support materials were made available on the SENSE IT project web site (<http://senseit.org>).

The Participants

In Year 1, SENSE IT was implemented by 36 teachers in 41 courses, with over 900 students, most of whom were in high school. In Year 2, it was implemented by 31 teachers in 32 courses, with about 800 students, this time about 75 percent high school and 25 percent middle school—the result of teachers moving levels and wanting to continue with the project.

These were all experienced and stable teachers, with 87 percent having taught for more than five years and 80 percent having done so in the same school. All had undergraduate majors in a STEM subject and all but one was also certified in a STEM subject. However, a background survey administered before the project began its Year 1 activities showed that they had much less experience teaching the actual material covered in the SENSE IT curriculum: less than half had taught electricity or water quality (with different teachers having taught each), and less than half had used sensors (or probes) in the classroom. Only a few were familiar with LEGO programmable bricks and even fewer had taught simultaneous equations (necessary for calibrating the sensors); 20 percent had taught none of these. Even integrating a problem-based learning project into the classroom was not a common practice, with most saying they only did group projects occasionally, and having students design open-ended investigations was even less common.

The subjects covered, and materials used in the SENSE IT curriculum were also not familiar to most of the students. A student background survey, administered each year before the students began the project, showed that although these were almost all college-bound students (almost 90 percent in both years expected to get at least a college degree), only half reported that they had studied electrical circuits (mostly middle school students), only about one-quarter had ever used probes or sensors, and about the same percentage reported past experience (in or out of school)



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with the LEGO programmable bricks. Eighty percent of the teachers in Year 1 and 66 percent in Year 2 reported that most or all of their students were not prepared for the math (in this case, algebra) involved. This lack of experience was confirmed by the students' pre-test scores, which were poor for both electricity and algebra, particularly at the middle school level.

In addition, only about one-third of the students in both years reported that they had designed an investigation that collected and analyzed data (mostly science fair projects), while less than half reported that they had studied water quality in school, although more had studied environmental issues, primarily global warming and pollution. Not surprisingly, the two main environmental problems they saw in their own communities were pollution and littering. Only a few of the high school students were able to describe what a sensor does. On the other hand, students at both levels were reasonably disposed toward science, with about three-quarters in both years reporting that they enjoyed science, although only about two-thirds said the same for math. However, when asked to specify a future career or job, only one-third in Year 1 and one-half in Year 2 listed a STEM-related career, with females twice as likely as males to list a science career and males five times as likely as females to list an engineering career.

Classroom Implementation

During the first year, teachers were required to implement Modules 1 and 2, using the temperature sensor. It came as a surprise to both the teachers and the SENSE IT team how many of the teachers found that they needed to augment or simplify some of the lessons to meet their students' needs (for instance, by adding more detail, deconstructing the lessons for note-taking purposes, assigning certain lessons as homework, restructuring worksheets make them easier to use). Others reported having to repeatedly reinforce the students' math skills. As a result, major modifications were made for the second year, including a "fast-forward" version of Modules 1 and 2—with no algebra—that was added as an option.

By the start of Year 2, the teachers had four sensors to choose from—temperature, conductivity, turbidity and depth (see Figures 5 and 6). They were asked to build at least two sensors, but could design their SENSE IT units using any of the lessons contained within all four modules. All reported that their students built the temperature sensor, while 63 percent reported that they built the conductivity sensor, 47 percent reported that they built the turbidity sensor, and 31 percent reported that they built the depth sensor. The "fast-forward" version of Modules 1 and 2 was used by about 25 percent of the teachers.

Although it had not been an initial goal to test SENSE IT for flexibility, in the end this proved to be one of its strengths. Teachers were able to integrate the curriculum into a wide variety of courses and subjects with a wide range of students. The teachers took advantage of the opportunity to mould



Figure 5. Students working on assembling the circuit board required for the depth sensor.



Figure 6. Students deploying their water quality sensors in the Hudson River.

the curriculum to fit their classrooms. The courses in which the curriculum was taught covered a wide range, in terms of broad academic area (mostly science but some math), in terms of specific subject (from regular curriculum subjects to special SENSE IT courses), and by level (from general science to AP and Honors). In both years, about one-quarter of the classes were Regents (the New York State requirement for graduation).

In addition, the timing and structure of classroom implementation varied greatly from teacher to teacher and course to course. Teachers used SENSE IT to introduce a key topic, generally electricity; fit it in as a unit on its own; or used it as an add-on, extension, or reinforcement.

Many teachers reported that it had been a challenge to find the time to integrate such an extended project into their curriculum, with the result that teachers met with their students anywhere from



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two to ten times a week over anything from two to 40 weeks. In Year 1, the total number of minutes spent on SENSE IT ranged from 270 to 1680, with an average of 700; in Year 2, the total number ranged from 240 to 4200, with an average of 1138. The amount of time spent specifically on water quality varied as well, with about half reporting that they spent a considerable amount of time on it and the other half reporting that they spent a limited amount of time.

PROJECT IMPACT

The background surveys showed that the content covered by SENSE IT was new to both teachers and students, while the pedagogy (group work, open-ended investigations) was not a common practice among most of the teachers or common to the experience of most of the students. Implementing a complex set of problem-based learning modules was therefore likely to be a challenge for the teachers and learning the concepts and skills embedded in the curriculum was likely to be a challenge for the students. This turned out to be particularly the case in Year 1, so it is not surprising that the results improved considerably from the first to the second year.

Teacher Ratings

The teachers responded to an end-of-implementation survey after each implementation—which for teachers who were integrating SENSE IT into more than one course meant one survey for each course. These end-of-implementation surveys asked questions about the implementation, including the subjects covered in the class, the type of students, what had gone well, what the issues had been, which sensors had been used, etc. (In addition, the evaluators visited all the teacher workshops and selected teachers were interviewed at the end of Year 1.)

In the post-implementation survey, the teachers were asked to rate how SENSE IT had helped their students in various academic areas, using a scale of 1 to 5, with 5 being the highest. The overall ratings for both student learning and student enjoyment were high, with the few teachers (2–3 each year) who gave lower ratings explaining them as being the result of their own failure to teach well. In terms of specific ratings, in both years most teachers felt that the curriculum had helped their students learn about sensors, but this was even more the case in Year 2 than in Year 1—possibly because they themselves knew more and also because their students built more sensors. They also rated it even more highly in Year 2 than in Year 1 for engaging students, for helping their students learn about the environment, and for helping them learn the principles of electricity, and about the same for all other items. Again, it is likely that this is because the teachers felt better prepared for all of these. (see Table 1 below.) Fewer in both years felt that



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	Year 1 (n=41)	Year 2 (n=32)
Helped your students learn the role of sensors	85%	91%
Engaged your students	76%	84%
Helped your students understand how sensors work	76%	78%
Helped your students learn about the environment	56%	72%
Helped your students learn to work well in groups	71%	69%
Helped your students learn the principles of electricity	54%	66%
Reinforced your students' existing math skills	61%	56%
Gave your students new math skills	32%	34%

Table 1: Percent of teachers who gave the highest ratings (4-5) for each course taught in each year.

SENSE IT had helped their students with math—but this varied depending on the emphasis in the class.

In addition, the teachers saw many other benefits in using the SENSE IT curriculum with their students, ranging from the very specific to the more general. In part, their view of the benefits depended on the course that SENSE IT was integrated into, but most wrote about the general benefit that came from giving their students an opportunity to engage in a hands-on project that was tied to real-world problems. In fact, it was notable how many of their comments included the phrase “hands-on.” They had comments such as these:

- “They were able to see how the material they have been learning in class could be used to solve a real world problem.”
- “It was a hands-on experience for them. They truly enjoyed being able to create their own sensors and see how they are used in the real world. They thought it was “cool” that they got to record their own data.”
- “It provided hands-on learning which the majority of the students who take my class really need to stay focused. Knowing that they would actually test what they had built in a real-life situation, it provided motivation to learn additional material.”

They also liked how the project tied science and math together in a way that made them relevant for their students:



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- “The greatest benefits of this SENSE IT curriculum include: applying math skills in a meaningful context; seeing how Regents Physics content and skills are applied in the ‘real world’; and connecting physics, math and technology to new content (water quality).”
- “It helped us connect science and math into real world problems. Our students do much better when given hands-on experience.”
- “Students saw a real life application of linearizing data -- something I had introduced at the beginning of the year.”
- “This curriculum was hugely beneficial. One of the great challenges in any field of teaching is providing relevance (especially to 14 year olds who may not want to do math at 9:00AM!). The relevance of this curriculum and project were strongly apparent to the students from day one and they seemed to really enjoy it.”

Student Ratings

The students were also asked to respond to a post-implementation survey that asked about their experience with SENSE IT. The first question asked them to rate SENSE IT in terms of how much they felt they had learned and how much they felt they had enjoyed it, in their case using a rating scale from A to F, including + and -. The high school students' ratings were high for both (85 percent gave an A or B for enjoyment and about 75 percent gave it an A or B for learning), but the middle school students' ratings were higher (over 98 percent gave it an A or B for learning and 80 percent for enjoyment). Males were slightly more enthusiastic than females.

When asked what they liked most about the project, the items mentioned most frequently by the high school students in both years referred to the hands-on aspects—the building (mentioned by 60 percent of the students in Year 2), the soldering (mentioned by 59 percent), and the fact that it was “hands-on” (also mentioned by 50 percent). The middle school students also liked the building (mentioned by 63 percent) but their second highest choice was working in groups (mentioned by 57 percent) and their third was the fact that the project was hands-on (54 percent).

Their dislikes tell a great deal about why they like hands-on projects rather than more traditional forms of learning. In Year 1, the high schools students' complaints focused on the instructions, which they thought were unclear, too difficult to read, or involved too much reading. In Year 2, after the curriculum modules had been revised on the basis of the Year 1 experience, the most-mentioned complaints were not related to the reading but to the math, which was mentioned by 45 percent of the students, followed by analyzing data and using Excel (40 percent and 39 percent respectively). The Year 2 middle school students also had the math, analyzing data, and using Excel at the top of their “liked least” lists (50 percent, 44 percent, and 38 percent respectively), but for them, reading the instructions came in second (mentioned by 46 percent).



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Student Learning

Assessing the impact of a complex and multi-part curriculum that is used in so many different situations is a challenge. However, since a key goal of ITEST, and of STEM education projects in general, is to reach all students, whether male or female, middle school or high school, academically higher or lower achieving, and in wealthy or poorer schools, the analysis will focus on these groups in terms of changes in the key content knowledge and skills embedded in the curriculum related to algebra, electricity, water quality, and understanding of sensors. The analysis will focus on the Year 2 results, since that was the year in which there were pre- and post-test for both algebra and electricity and the year in which assessments for water quality and understanding of sensors were introduced, but comparisons with Year 1 will be mentioned where relevant.¹ The algebra and electricity tests consisted of five multiple-choice questions for each area, some of which involved calculations and some of which included interpretations of diagrams, while the water quality assessment included questions designed to assess the students' understanding of the relationship between water quality and sensor-collected data (temperature, turbidity, etc.). Finally, a digital pile sort activity was used to assess student understanding of sensors.² In all instances, high school and middle school are compared, since the middle school students' scores on the pre-tests were always considerably lower than the high school students' scores. However, analysis showed that there were few differences by region or by gender, so neither of these is considered. To determine SES, we used the percent of students receiving free and reduced lunch, a common measure of the socioeconomic status of students in a school in New York State. Since the state considers schools that have over 39.15 percent of their students receiving free or reduced lunch as low SES schools, all students in those schools were therefore considered to be lower SES—approximately 11 percent of the high school students and 50 percent of the middle school students. Weaker students were defined as those who scored below the mean on each pre-test—approximately 40 percent of high school students and 55 percent of middle school students.

SES

There were 828 matched pairs of electricity tests in Year 1 and 721 in Year 2 (542 high school students and 179 middle school students). There was no algebra pre-test in Year 1 but there were 727 matched pairs of algebra assessments in Year 2 (557 high school students and 170 middle school students).

¹In Year 1, there was an algebra readiness (pre) assessment only and a pre- and post-electricity assessment, with three questions each. In Year 2, a post-assessment was added for algebra and the number of questions on each assessment increased to five, with each question mapped to a specific concept or skill.

²Pile sorts are sets of cards that students are asked to sort into piles. In this case, the cards had pictures of objects and the students were asked to sort them into piles of objects that they believed had sensors, did not have sensors, and that they were not sure about. The pile sort was tested with printed cards and then digitized as an online Flash-based activity (see Figure 14). Although the teachers had the option of using the printed cards, they all used the digital version.



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Although there was a significant correlation between the students' post-test scores for algebra and electricity ($r = .43, p < .01$), they are analyzed separately because they call on very different skills and background knowledge, raising the possibility that a student could do well in one but not the other.

As noted above, the teachers felt that the students struggled with the math needed for SENSE IT. In Year 1, students in higher SES schools had higher algebra pre-test scores than students in lower SES schools and this was the case in Year 2 as well. However, in Year 2 the results of an analysis of covariance at the high school level indicated that there was a significant interaction between SES and the covariate (pre-test scores), $F(1, 553) = 5.78, p = .02$ ($p < .05$). Therefore, an analysis of covariance was not the appropriate test here. Instead, a one-way analysis of variance was performed. The results show that although students in higher SES schools did significantly better on the algebra pre-test, $F(1, 590) = 13.03, p = .000$ ($p < .001$), this was not the case for the algebra post-test ($p > .05$). As Figure 7 shows, the scores of students in higher SES schools declined while those in lower SES schools increased, thus narrowing the gap. It should be noted that the reasons for the decline are unclear, but may be related to a lack of focus for these students—most of whom were seniors—at the end of the year. For electricity, on the other hand, the gap at the start, although narrower than that for algebra, remained ($p > .05$). Note that all scores have been converted to a scale of 100 so can be read as percents.

At the middle school level, in contrast, students in lower SES schools did *better* than students in higher SES schools on the pre-tests for both assessments (see Figure 8). However, while the results

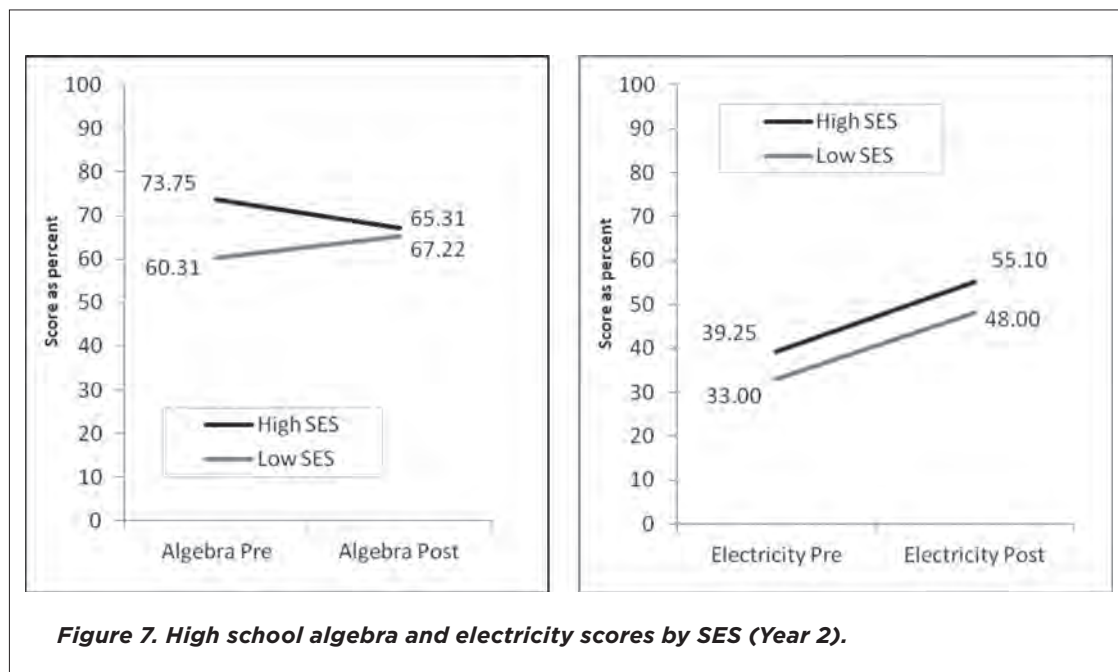


Figure 7. High school algebra and electricity scores by SES (Year 2).



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of two separate analyses of covariance show that the two groups were not significantly different on the algebra post-test, students in lower SES schools performed significantly better than those in higher SES schools on the electricity post-test, $F(1, 176) = 51.08, p = .000 (p < .01)$, widening the gap between them.

Weaker compared to stronger students

There was a similar pattern when weaker and stronger students are compared. Weaker and stronger students were defined according to whether they scored above or below the mean scores for each test: high school algebra (71.82), high school electricity (38.43), middle school algebra (47.84), and middle school electricity (29.37).

At the high school level, the results of an analysis of covariance for the algebra tests showed a significant interaction between the factor (weaker vs. stronger students) and the covariate (pre-algebra scores), $F(1, 553) = 4.61, p = .02 (p < .05)$. Since an analysis of covariance was therefore not the appropriate test, a one-way analysis of variance was performed. The results show that the stronger students did significantly better on both the pre- and post-algebra tests, $F(1, 590) = 1715.48, p = .000 (p < .001)$ and $F(1, 555) = 127.65, p = .000 (p < .001)$, respectively. However, as Figure 9 shows, the gap narrowed—with the weaker students improving on the post-test while the stronger students performed less well.

For electricity, there was also a significant interaction between the factor (weaker vs. stronger students) and the covariate (pre-electricity scores), $F(1, 538) = 4.85, p = .03 (p < .05)$. Therefore, a

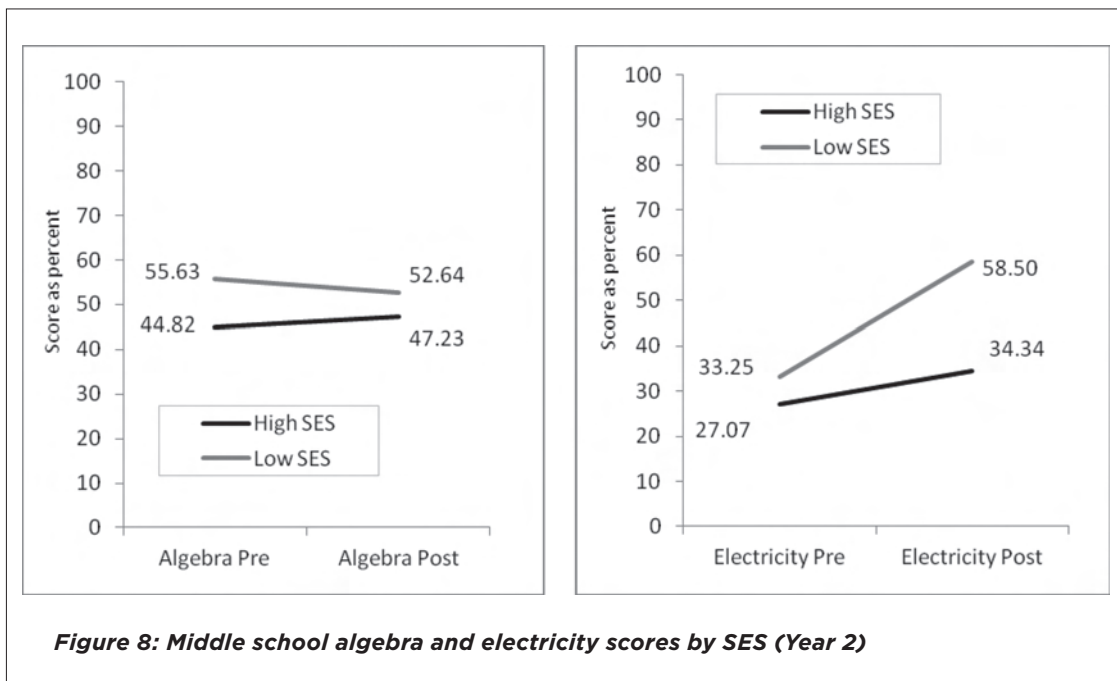
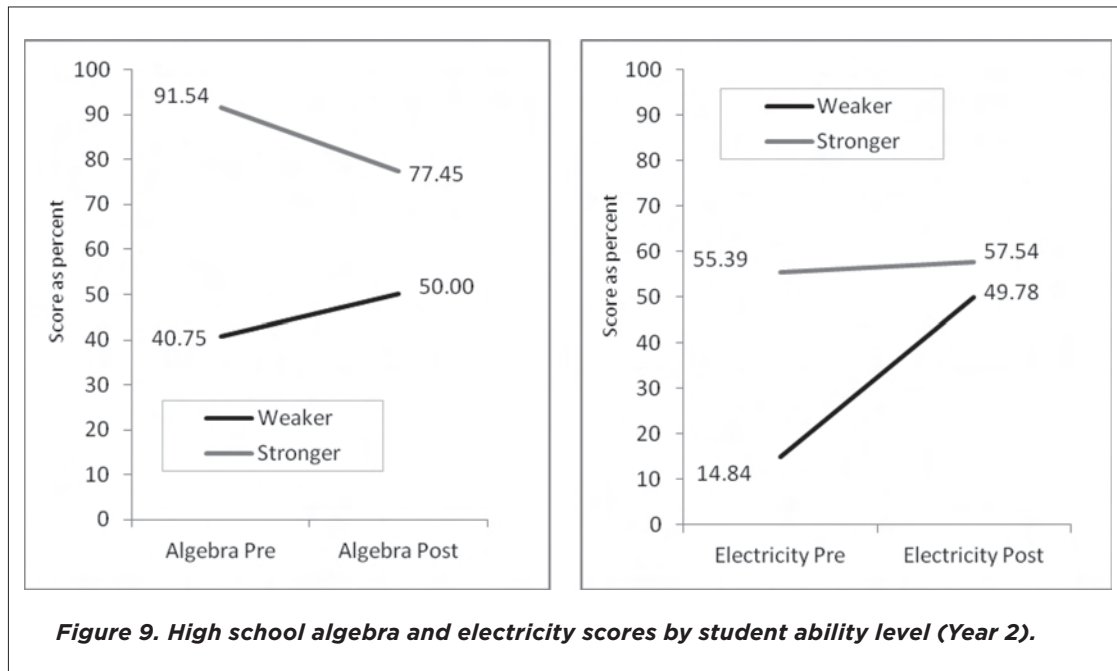


Figure 8: Middle school algebra and electricity scores by SES (Year 2)



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one-way analysis of variance was again performed. The results show that in this case as well, the stronger students did significantly better on both the pre- and post-tests, $F(1, 570) = 993.67, p = .000$ ($p < .001$) and $F(1, 540) = 9.22, p = .003$ ($p < .01$), respectively. Again, however, the weaker students improved far more than the stronger students and the gap narrowed (see Figure 9).

At the middle school level, the results of separate analyses of covariance indicated that although the two groups did not differ on the post-tests for either algebra or electricity, they did differ significantly on both pre-tests, $F(1, 192) = 508.10, p = .000$ ($p < .001$) and $F(1, 188) = 433.59, p = .000$ ($p < .001$), respectively. In other words, as Figure 10 shows, once again the gap narrowed for the weaker students.

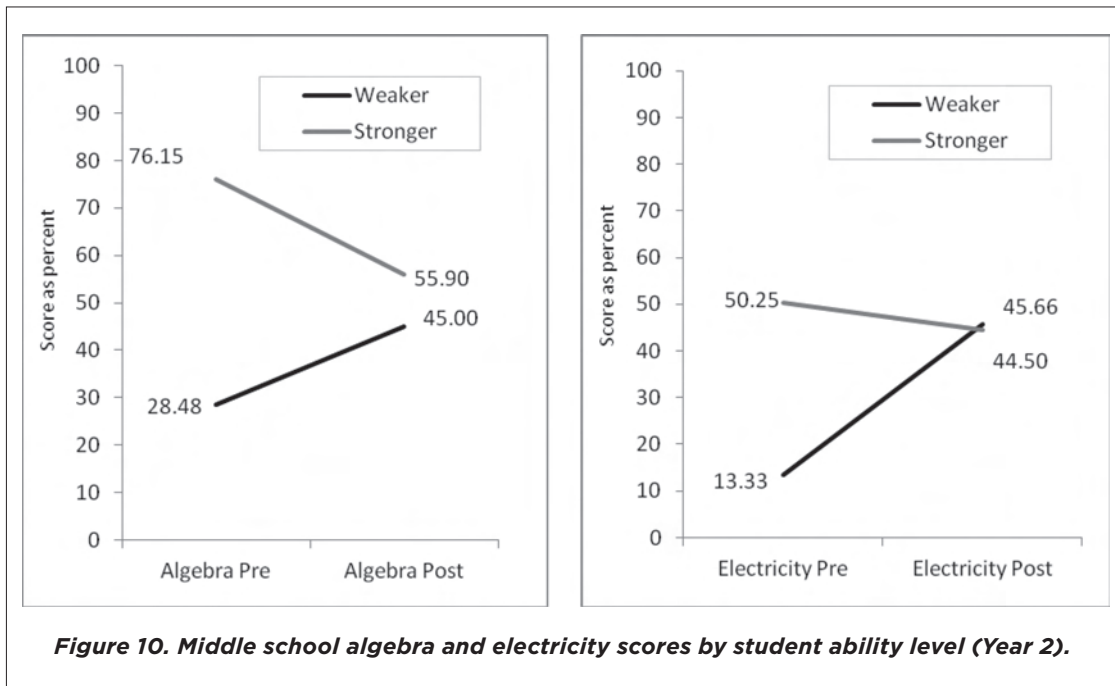
We can summarize these findings as follows:

For SES

- For high school algebra, the gap between higher SES and lower SES students *narrowed*.
- For high school electricity, the gap was not as great at the beginning but it *did not narrow*.
- For middle school algebra, lower SES students scored higher than higher SES students on the pre-test and the difference between them did not change.
- For middle school electricity, lower SES students scored higher than higher SES students on the pre-test but they also *increased more*.

For weaker compared to stronger students

- For high school algebra, the gap between the weaker and stronger students *narrowed*.



- For high school electricity, the gap between the weaker and stronger students *narrowed*, and to a greater extent than for algebra.
- For middle school algebra, the gap between the weaker and stronger students *narrowed*.
- For middle school electricity, the gap between the weaker and stronger students *closed completely*.

Taken together, these results suggest that participating in SENSE IT can lead to higher scores for all but higher SES and academically stronger high school students, and that participation can particularly benefit students in lower SES schools and weaker students in all schools. The impact on students by SES group was less clear-cut than the impact by ability level, possibly because SES was a school-level attribute and may not have applied to the particular students in SENSE IT classrooms. However, the fact that the project had the greatest impact on the algebra and electricity scores of the weaker students was an important benefit of SENSE IT participation.

Water quality

The students were given a post-only assessment on the use of sensor data in determining water quality. There was a bank of 10 questions, two of which were required, with five being the minimum number of questions each teacher was asked to use. A decreasing percent of the students answered each question, from 100 percent for the first two questions (relating to the use of the temperature sensor) down to only 28 percent for the two questions relating to the depth sensor. Scores were



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converted to a scale of 100, so that for a student who answered five questions, each would be worth 20 percent, while for one who answered ten questions, each would be worth 10 percent.

The results of two separate analyses of variance, for middle school and high school, showed that, at the high school level, students in higher SES schools did significantly better on the water quality assessments, $F(1, 501) = 22.44, p = .000 (p < .001)$, but at the middle school level, students in lower SES schools scored significantly higher, $F(1, 125) = 18.76, p = .000 (p < .001)$ (Figure 11).

When we compare weaker and stronger students, we find that the stronger students did better at both the middle and high school levels, whether the two groups were defined by their algebra pre-test scores, $F(1, 490) = 85.43, p = .000 (p < .001)$ or by their electricity pre-test scores, $F(1, 477) = 4.48, p = .04 (p < .05)$. The differences using the electricity pre-test scores are shown in Figure 12.

Not all teachers focused on relating sensor use to water quality—many of the Physics and Engineering teachers, for example, did not feel that water quality fit well with their content. It seemed likely, therefore, that time spent rather than SES or student ability might make the difference between lower and higher scores on the water quality assessments. Teachers reported if they had spent “a great deal of time,” “a considerable amount of time,” “a limited amount of time,” and “no time” on water quality issues. At the high school level, those who spent at least a limited amount of time scoring significantly higher than those who spent no time $F(3, 499) = 5.53, p = .001 (p < 0.1)$. In addition, those who spent a great deal of time scored significantly higher than those that spent limited or no time, but did not differ significantly from those who spent a considerable amount of time (see Figure 13).

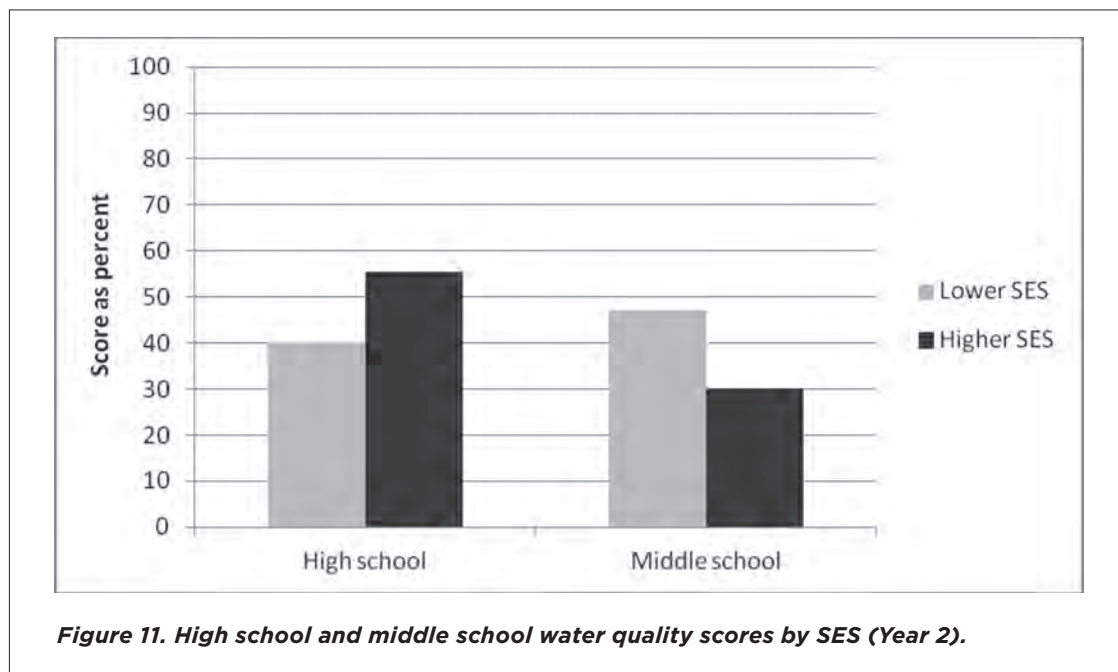
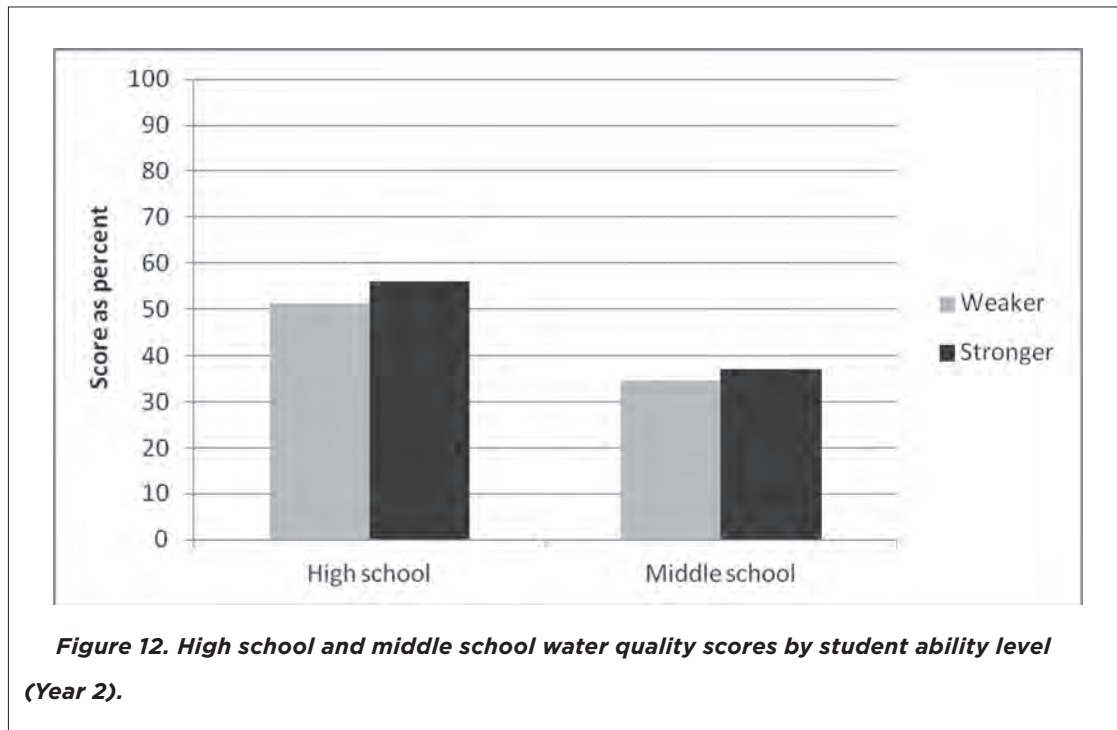


Figure 11. High school and middle school water quality scores by SES (Year 2).



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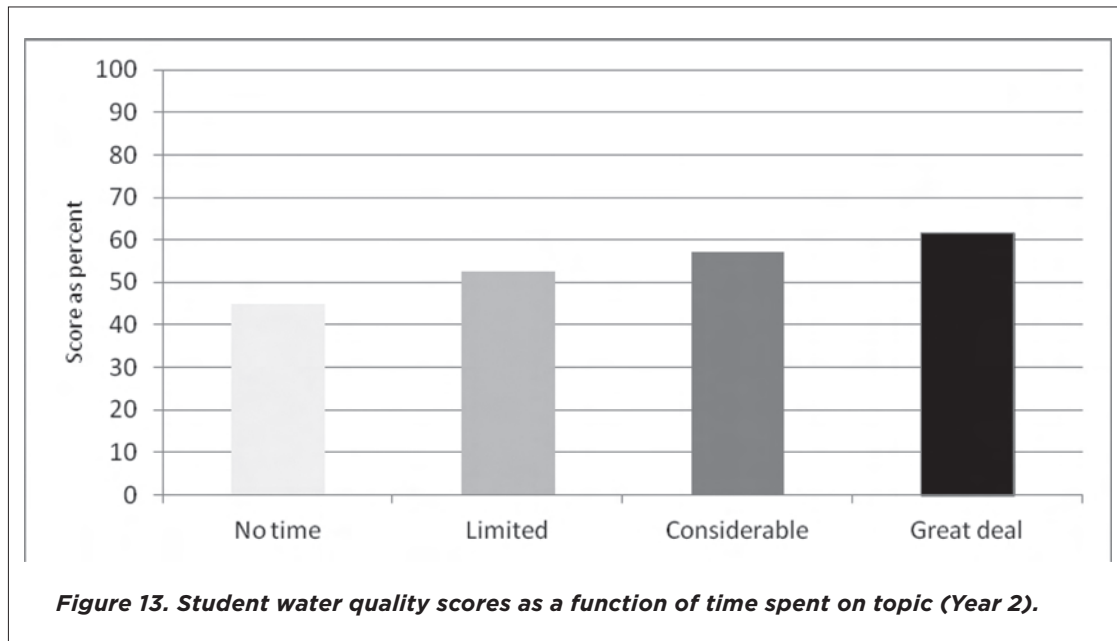


There was also a more subtle impact in terms of student awareness of environmental issues, at least for some students. In Year 1, the teachers had been unsure if their students' awareness of environmental issues had changed as a result of the project, with 46 percent saying yes and 49 percent not sure. In Year 2, in contrast, 72 percent said yes and only 25 percent said they were not sure. The response depended in part on the course that SENSE IT was taught in, with the Environmental Science teachers being much more likely to make the connection than the Physics teachers. Here are some of the ways they described how they did this:

- “My students are more aware of the problems with water quality and the ability to apply technology to help, identify, quantify, and in some cases help solve environmental problems.”
- “They are certainly more aware of issues near us and of how dangerous improper waste removal is. In fact some students want to make a complaint about the red soot a factory near them is emitting.”
- “Few were aware of the AuSable River Watershed, in which they all live. They became more interested in how humans impact the quality of the AuSable River water.”
- “I don't think they gave the Hudson River any thought at all. Also I don't think they had any idea how many factors affect the quality of the water. I hope they are more aware of some of the issues affecting their water supply and the Hudson River estuary.”



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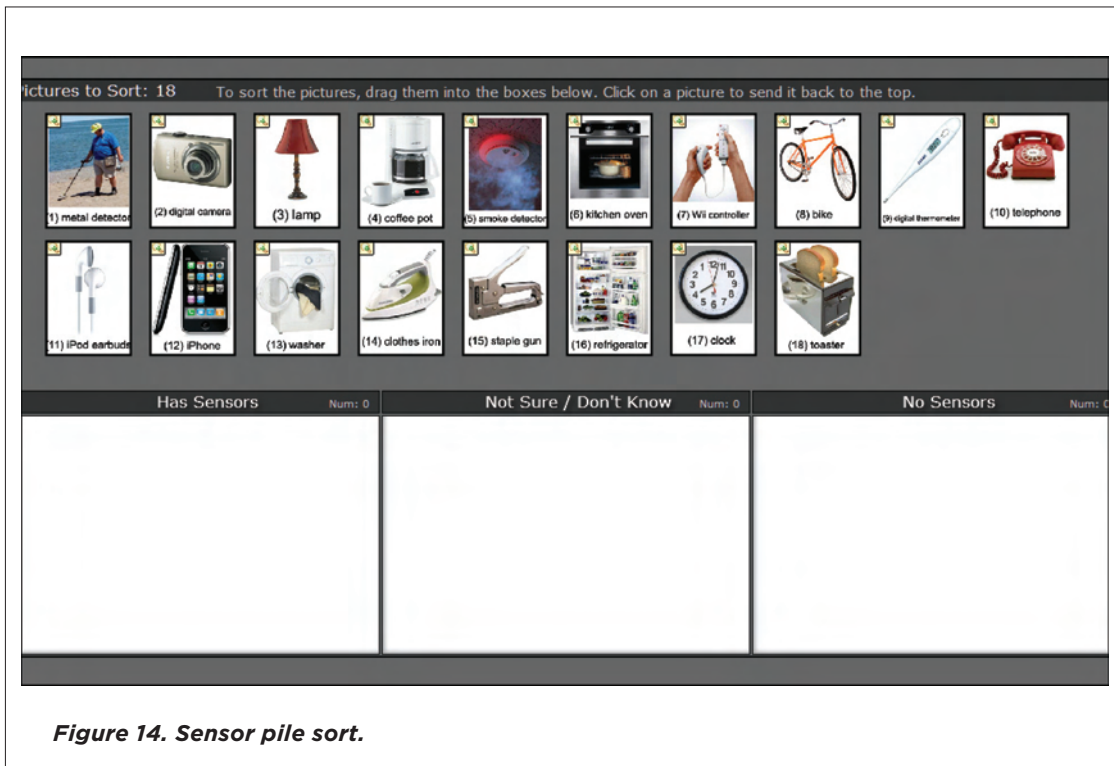
- “I would have not discussed environmental issues in my Physics classes. However, I found that bringing these issues into the classroom was a great idea as it makes material we learn relevant.”

This increased emphasis on the water quality aspect of the curriculum was also evident in the student responses to a question that asked what environmental issues they saw in their communities. As noted earlier, on the baseline survey their most common responses were pollution and littering. This was again the case on the post-implementation surveys, but by then students were more than twice as likely to list not just pollution, but water pollution in particular.

Understanding of sensors

The teachers reported that SENSE IT had helped the students understand the role of sensors in monitoring the environment, but this appreciation did not translate immediately into the students' ability to define what a sensor does. After participating in SENSE IT, 50 percent of high school students and over 80 percent of middle school students were unable to answer a question on the post-implementation survey that asked them to describe what a sensor does—and most of those who did answer only included the sensor's ability to read or gather data, not to convert it.

This finding was confirmed by a second assessment of student understanding of sensors, introduced in Year 2. This was a pile sort (Figure 14), an online Flash-based activity that asked the students to sort (by dragging and dropping) eighteen cards, twelve of which had pictures (with captions) of items that have sensors and six of which had pictures of items that do not have sensors. Not all



classes did the pile sort, primarily because of lack of access to computer labs, with the result that there were 562 matched sets of pile sorts from 22 schools.

It was easy for the students to sort some of the cards into the sensor pile, but they had trouble with items that control for temperature but do not appear to measure it (for example, a toaster or a clothes iron). On the other hand, a majority of students believed that anything mechanical must have a sensor in it, such as iPod ear buds or a telephone.

In addition, there was not as much change from pre to post as was hoped. While 54 percent of the students' scores increased, 28 percent decreased and 18 percent did not change. As we have found in previous projects (McGrath, Lowes, McKay, Sayres & Lin, 2012; McGrath & Lowes, 2011), students who can succeed in building and deploying complex artifacts do not necessarily learn the underlying principles. The students' inability to define what a sensor does and the pile sort results suggest that students need more explicit instruction if they are to understand fully the role that sensors play in everyday life.

It seemed possible that students in engineering-related courses ($N = 84$) would have a better grasp of how sensors work than students in other science courses (earth science, biology, general science, etc., $N = 478$) and also that students who built more than one sensor would improve more. A two-way analysis of covariance was performed to see if the two factors together affected student



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scores on the post pile-sort activity. The results showed that while there was a significant difference for those in engineering-related classes between those who built one sensor and those who built more than one, this was not the case for those in other types of classes, $F(1, 557) = 6.40$, ($p < .05$). In other words, students in engineering-related classes better understood what a sensor was when they built more than one sensor, but this did not make a difference for students in the other classes.

The Link Between Teacher Performance and Student Results

At the beginning of the Year 1 summer institute, the teachers took the electricity and algebra pre-tests and the electricity post-test. This was partly to familiarize them with the process and partly to assess their background knowledge. In Year 2, when there were both algebra and electricity pre- and post-tests, the teachers did both. Since it seemed likely, based on findings from other projects (Macalalag, Tirthali, McGrath, McKay & Lowes, 2011; Macalalag, Lowes, Guo & McKay, 2010), that teachers who knew the material well would be better able to teach it, we used these results to explore the relationship between teacher and student performance.

In Year 1, when we had only post-test scores for electricity, we grouped the teachers into those with high post-test scores and those with low post-test scores. We found that the post-test scores of students whose teachers had high scores were significantly higher than the post-test scores of students whose teachers had low scores.

In Year 2, when we had both electricity and algebra pre- and post-test scores, we found a similar relationship between student and teacher scores. To refine the analysis, we broke the teachers into three groups (Low, Medium, High) based on their algebra post-scores. Although the student scores declined, they declined most for the teachers in the Low group (see Figure 15).

To confirm this, a linear regression was performed. It showed that the Year 2 teachers' algebra post-test scores were indeed a significant predictor of their students' Year 2 algebra post-test scores, $F(2, 688) = 7.06$, $p = .001$ ($p < .01$).

For electricity, in Year 2 most of the teachers got all the answers correct on the pre- and post-test—undoubtedly the result of their work in Year 1—so these scores were not useful as covariates. However, the teachers' Year 1 electricity post-test scores remained significant predictors of their students' Year 2 post-test scores, with those having low scores in Year 1 being the only group whose Year 2 students' scores decreased (see Figure 16).

Again, the results of a linear regression showed that the teachers' electricity post-test scores in Year 1 were a significant predictor of the students' electricity post-test scores (in Year 2), $F(2, 439) = 4.46$, $p = .01$ ($p < .05$).

The relationship between teacher and student scores is also evident when we look at the weaker compared to the stronger students by school level. Thus for high school algebra, there was a

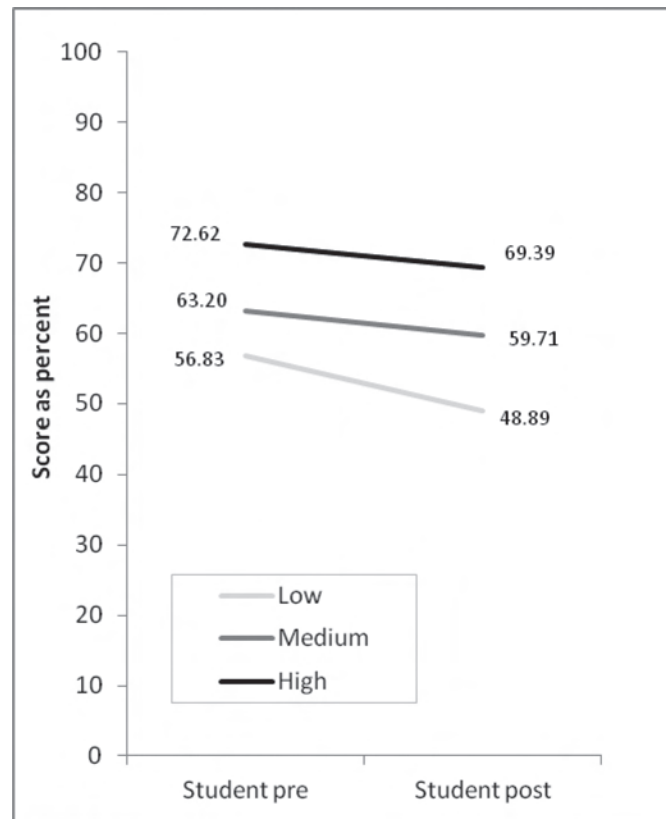


Figure 15. All Students: Relationship between teacher and student algebra scores (Year 2).

significant difference in the students' algebra post-test scores depending on their teachers' algebra post-test scores, $F(2, 518) = 3.18$, $p = .042$ ($p < .05$). Not only did both weaker and stronger students have lower scores if their teachers' scores were low, but weaker students did particularly poorly when this was the case (see Figure 17).

The same was true for electricity at the high school level, where there was again a significant difference in the students' electricity post-test scores depending on the teachers' (Year 1) electricity post-test score, $F(2, 354) = 4.25$, $p = .015$ ($p < .05$). As with algebra, both weaker and stronger students had lower scores if their teachers' had lower scores, but the weaker students did very poorly when this was the case (see Figure 18).

The same pattern held true for algebra at the middle school level (see Figure 19). There was a significant difference in the students' algebra post-test scores depending on the teachers' algebra post-test scores, $F(2, 164) = 16.17$, $p = .000$ ($p < .001$). However, although in this case the weaker students did particularly poorly if their teachers' scores were low, there was a significant interaction, $F(2, 164) = 4.05$,



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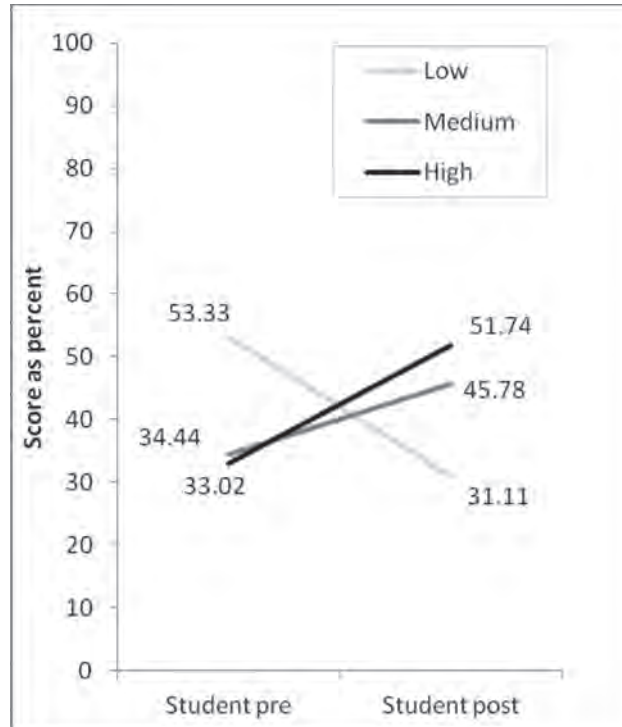


Figure 16. All Students: Relationship between teacher and student electricity scores (Year 2).

$p = .019$ ($p < .05$), suggesting that the effect was not the same for all ability levels. No comparisons could be made for electricity since all the teachers scored 100 on the Year 1 electricity post-test.

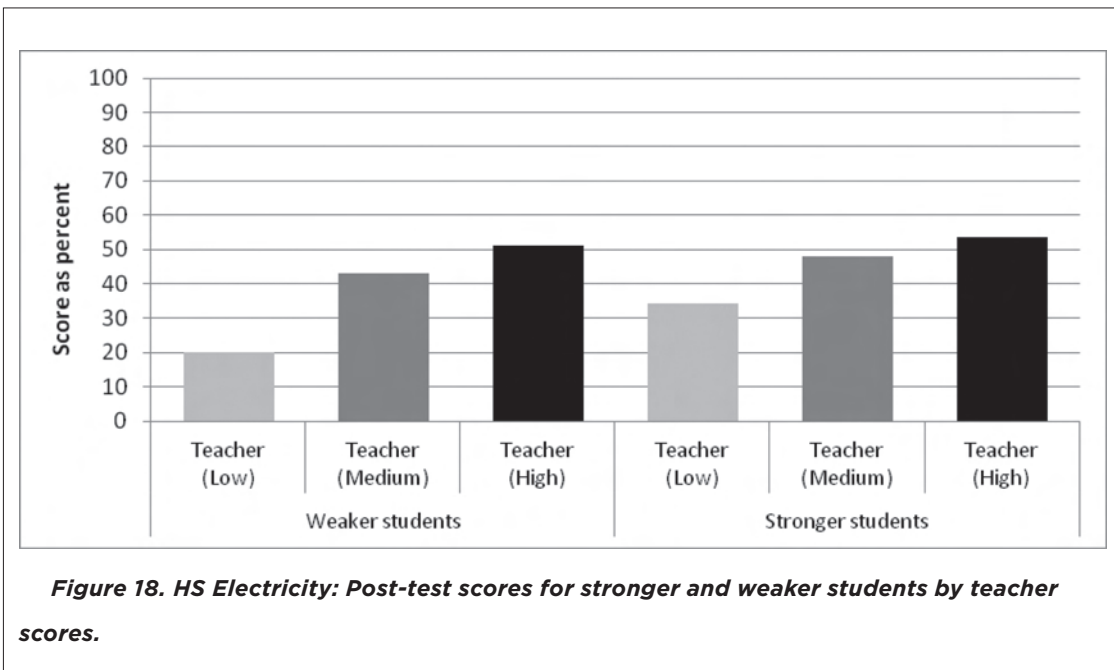
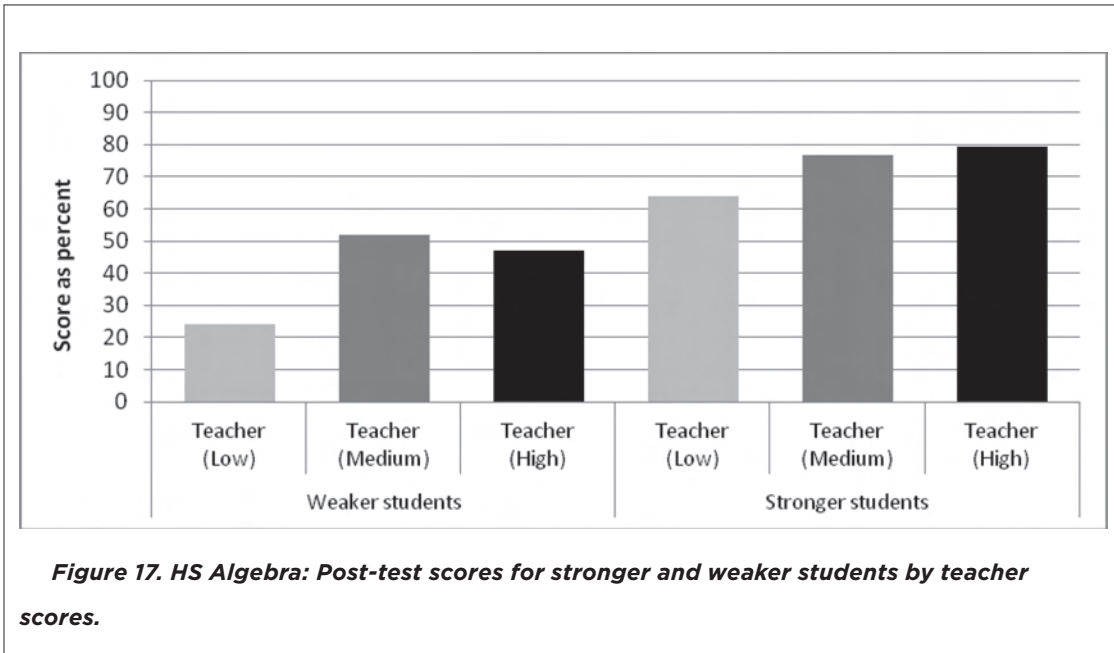
In summary, in all cases for which there was data, the teachers' scores were significant predictors of their students' scores. While for electricity, this equalized the results between weaker and stronger students, for the more complicated concepts in algebra, it meant that the weaker students did particularly poorly.

The Link Between Teacher Practices and Student Results

In both years, teachers were encouraged to discuss the pre-test results for algebra and electricity with their students. In Year 1, however, the teachers would have had to analyze the results themselves or enter them into an online system and few did this early enough to make it useful. In Year 2, the tests themselves were put online, with each class's results immediately available to be shared, in graphical format (Figure 20). As a result, about half the teachers reported that they discussed the results with their students.



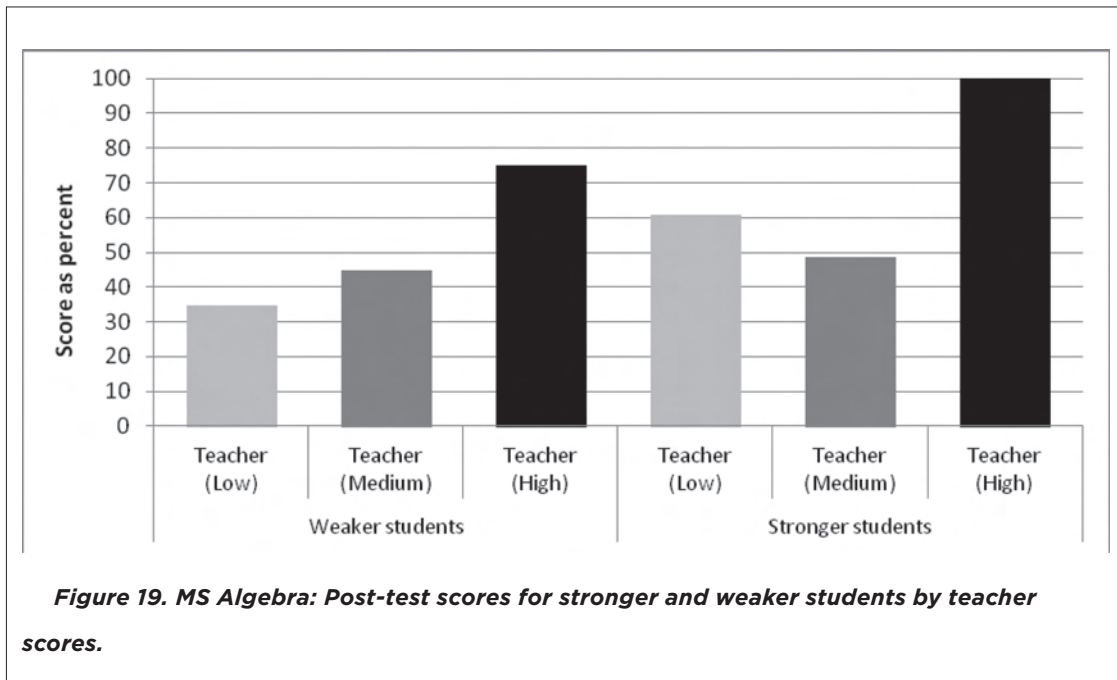
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For algebra at the high school level, the students whose teachers discussed the pre-test results did significantly better than those whose teachers did not, $F(1, 553) = 1.30, p = .000$ ($p < .001$). Furthermore, the difference was larger for the weaker students than for the stronger students (see Figure 21).



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Last Name	Algebra Pre						Algebra Post					
	1	2	3	4	5	%	1	2	3	4	5	%
	c	d	a	b	d	100	b	b	a	b	b	60
	c	b	a	c	d	60	b	b	a	c	c	100
	c	d	a	b	d	100	b	b	a	c	c	100
	c	d	a	b	d	100	b	c	a	d	e	60
	c	b	c	b	c	40	b	b	a	c	e	100
	c	d	a	b	d	100	b	b	a	c	e	100
	c	d	-	b	d	80	b	b	b	c	b	60
	c	d	a	b	d	100	b	b	a	c	e	100
	c	d	a	b	d	100	b	d	a	c	b	60

Figure 20. Graphical results page for algebra tests.

Similarly for electricity at the high school level: The students whose teachers discussed the pre-test results did significantly better than those whose teachers did not, $F(1, 539) = 12.62, p = .000 (p < .001)$, although in this case the difference for the weaker students was not quite as large (Figure 22).

The same was the case for algebra but not for electricity at the middle school level. For algebra, the students whose teachers discussed the pre-test results did significantly better than those whose teachers did not, $F(1, 167) = 4.68, p = .032 (p < .05)$, but for electricity, there was no significant difference between the two groups ($p > .05$).



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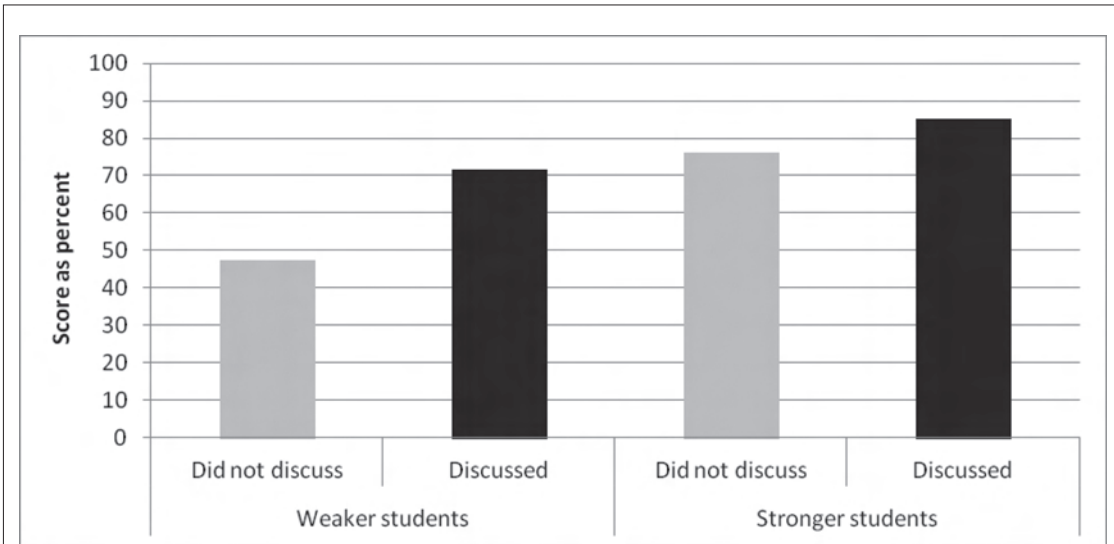


Figure 21. HS Algebra: Impact of teacher discussion of pre-test results on weaker and stronger students.

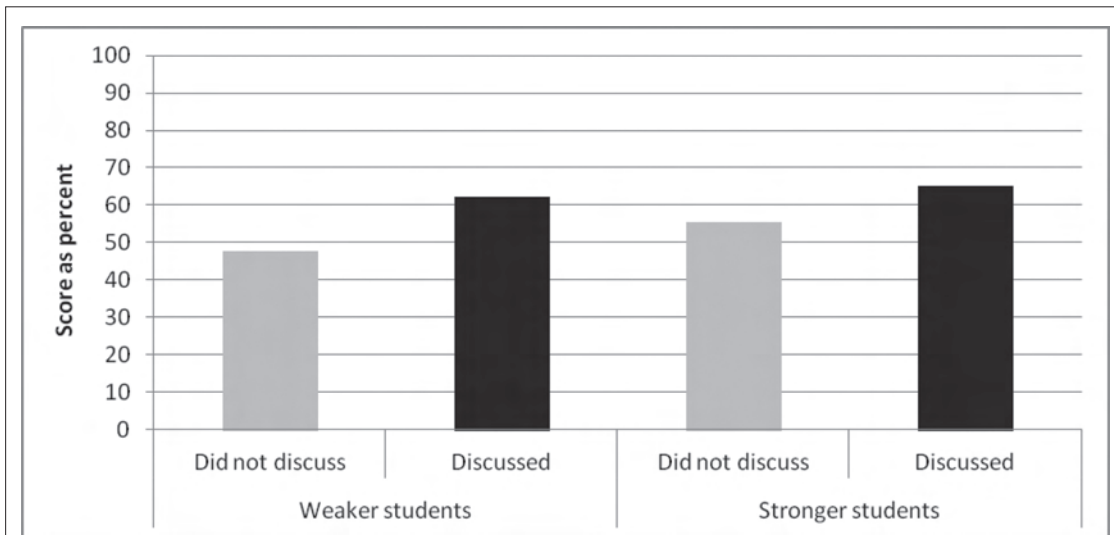


Figure 22. HS Electricity: Impact of teacher discussion of pre-test results on weaker and stronger students.

In summary, discussing the results was correlated with significantly higher scores for both stronger and weaker students for both algebra and electricity at the high school level and for algebra at the middle school level. Even more important, it had the greatest impact on the weaker students, in some cases almost equalizing the scores between the two groups.



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CONCLUSION

SENSE IT offers fully integrated STEM education modules, requiring students to learn and apply principles within science, technology, pre-engineering, and mathematics to construct and deploy water quality sensors. Tracked implementation of SENSE IT in classrooms demonstrates that it is possible, although additional time and effort is required, to have students carry out complex problem-based, hands-on projects within the scope of existing standard curricula and tied to state and national education standards. The applied themes of environmental stewardship and sensor networks provide: 1) a motivating and meaningful scenario for learning a wide range of core math, science, and technology topics and workforce readiness skills, 2) an awareness of the ubiquity of sensors in our world while demonstrating the link between biological, physical and social sciences, 3) a means to encourage learners to look at local water quality and environmental issues and data from a global perspective, and 4) an opportunity to engage students in the use of sensors for environmental monitoring and to learn about potential careers involved with environmental monitoring and management.

Research results indicate that the participating teachers were positive about the benefits of the SENSE IT curriculum for their students, both in terms of how it engaged them and in terms of what they had learned. Teacher responses indicate that this success was in part because they were able to adapt the curriculum to fit into their existing courses and to meet their students' academic levels. In other words, a strength of the curriculum was its flexibility—as shown by the integration of SENSE IT into a wide range of courses with a wide range of students—from upper level high school students to middle school students, from academically advanced students to academically challenged students, from Advanced Placement courses to courses for those students who could not qualify for higher level science. The research results suggest that participating in SENSE IT led to higher scores for all but higher SES and academically stronger high school students, and that SENSE IT participation particularly benefited students in low SES schools and weaker students in all schools.

Although SENSE IT can be taught by teachers in many subject areas, the strong correlation between teacher and student results indicates that teacher preparation is necessary if strong student results are desired. This means that fairly extensive professional development is necessary for teachers not already well versed in the content knowledge and skills embedded in the SENSE IT curriculum.

Based on research results, we hope to grow the SENSE IT program. However, we are also aware that there are too many activities and lessons for the average teacher to use in the classroom and that the two-week summer workshop model requires a time commitment that many teachers cannot make. In order to reach more teachers, it will be necessary to condense and compress both



the professional development experiences and the classroom materials. As we grow the program and network of SENSE IT teachers, we also plan to administer similar evaluation tools to continue understanding the impact of SENSE IT materials on students and teachers. The refined SENSE IT materials will continue to ease classroom implementation issues and increase the numbers of teachers and students exposed to hands-on learning experiences that revolve around the world of sensors, as well as help them prepare students to handle the complex, multidisciplinary challenges awaiting them in the 21st century, technology-focused workplace.

ACKNOWLEDGMENTS

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SENSE IT: Teaching STEM principles to middle and high school students through the design, construction and deployment of water quality sensors



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