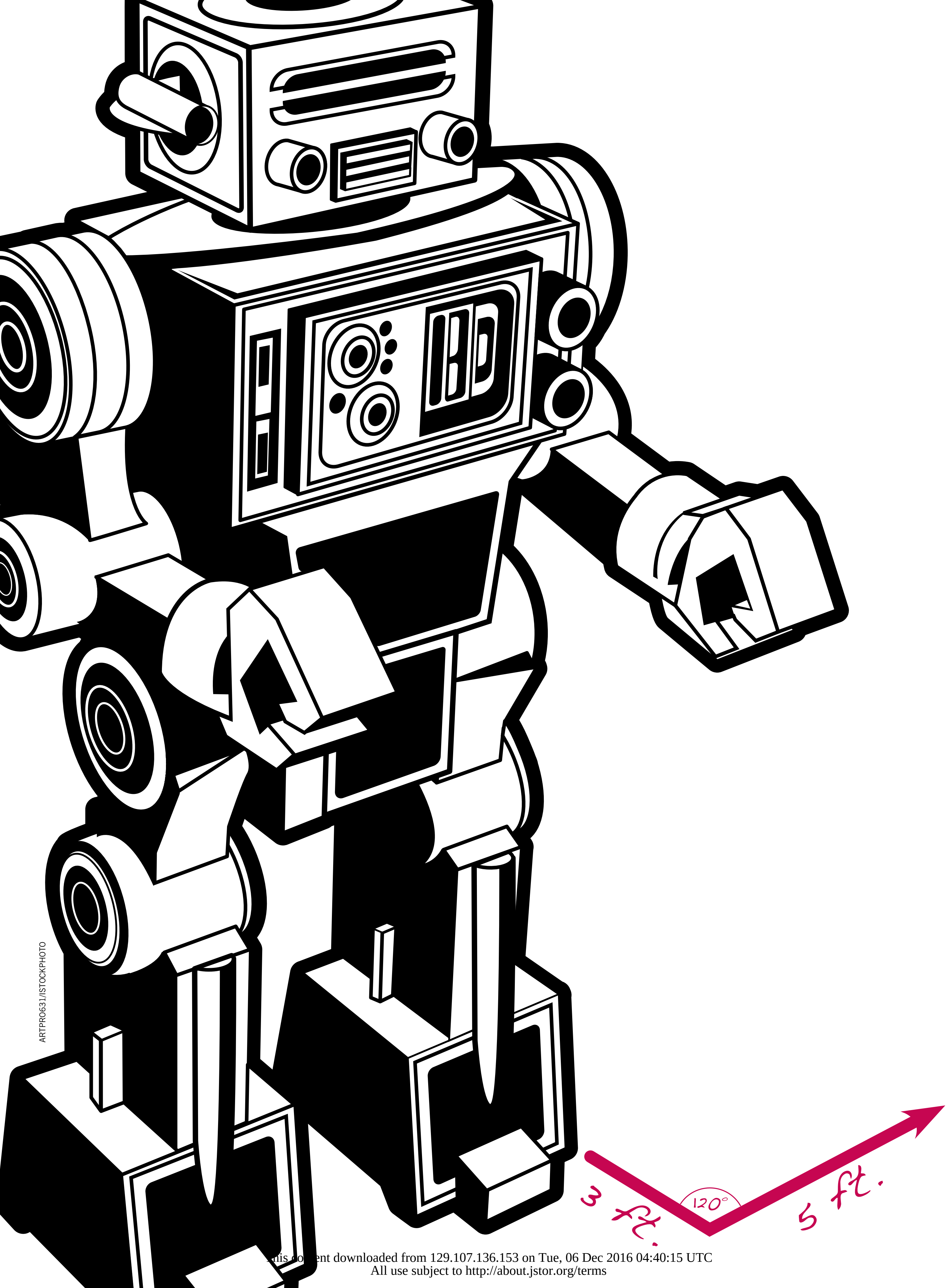

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ROBOTS Bring Math-Powered IDEAS TO LIFE

A compelling contest motivates students and makes mathematics and STEM relevant.

Kasi C. Allen

What if every middle school student learned to create a robot in math class? What if every middle school had a robotics team? Would students view mathematics differently? Would they have a different relationship with technology? Might they see science and engineering as fields driven by innovation rather than memorization? In my experience, robotics provides a compelling context for engaging students in STEM like no other. As students find themselves faced with open-ended problems that demand creativity as well as precision, they experience firsthand how mathematically informed decisions contribute to the quality of their robot, not to mention its functionality.

WHERE'S THE MATH?

Why should mathematics teachers try to incorporate robotics into math instruction? The answer is twofold: (1) Students love robots, and (2) mathematics powers every robot. Without math, a robot cannot take shape, move, or perform a task. From the perspective of the students, much of the mathematics in robotics remains embedded. However, as students explore the materials and as their enthusiasm builds, teachers can make the mathematics both explicit and memorable for a motivated audience.

For example, as students begin to

Where to Find **ROBOTICS MATERIALS**

Although a range of robotics materials are available for purchase in stores and online, this article focuses on LEGO® MINDSTORMS® NXT for the following reasons:

1. The NXT starter kits are relatively affordable (especially given the included sensors and motors) and already in use in a variety of settings nationwide, involving students of all ages, from elementary school through college.
2. Local retailers, such as Target and Wal-Mart, stock LEGO NXT on a regular basis.
3. The LEGO materials are durable as well as versatile, and robotics kits can be expanded and enhanced by adding parts from any LEGO Technic building kit.
4. New users can make a robot, essentially right out of the box, that moves and performs other basic tasks without connecting to a computer because of the built-in functions and plug-in sensors for the NXT programmable brick.
5. Once students begin programming, the software provided is icon-based, intuitive, and easy to use with its drag and drop interface.
6. Teachers can find a wealth of support materials in print, including programming guides and ideas for projects (Erwin 2001; Kelly 2007; Wang 2004).
7. LEGO NXT serves as the building platform for *FIRST*® LEGO League (FLL), an international team-based robotics program that takes place every fall, from mid September to mid December, targeting students in grades 5–8.

experiment with simple structures, such as creating a chassis, as well as other attachments, such as arms and claws, many will initially build quadrilaterals that lack stability, like those shown in **figure 1**. Teachers can ask students to experiment with strategies for making their structures more rigid. Students will often try parallel bracing initially, only to discover that this does not make the structure more stable. However, those who use triangular bracing will get a different result (see **fig. 2a**). Students can then make conjectures about what gives any structure stability. In the LEGO MINDSTORMS NXT environment, students often discover Pythagorean triples. Note that the triangular bracing in **figure 2b** uses a 3-4-5 combination, whereas **figure 2c** shows an example of a 5-12-13 right triangle, another combination readily built with the LEGO materials.

Experimenting with sensors affords even more opportunities to use mathematics. The LEGO MINDSTORMS NXT comes with multiple plug-in sensors as well as a data-logging feature that can be used without any knowledge of programming. All sensors connect directly to the NXT brick, the brain of every LEGO MINDSTORMS robot. The simplest is the **touch sensor**, which works like a button. It closes a circuit when pressed, making it useful as a stop button for moving parts or to stop a robot when it hits an object (a wall, for example). The **sound sensor** enables the robot to hear and react to sound; it measures and records noise levels, as well. The **color sensor** allows the robot to detect light and color, making it possible to follow a line or a path on the ground.

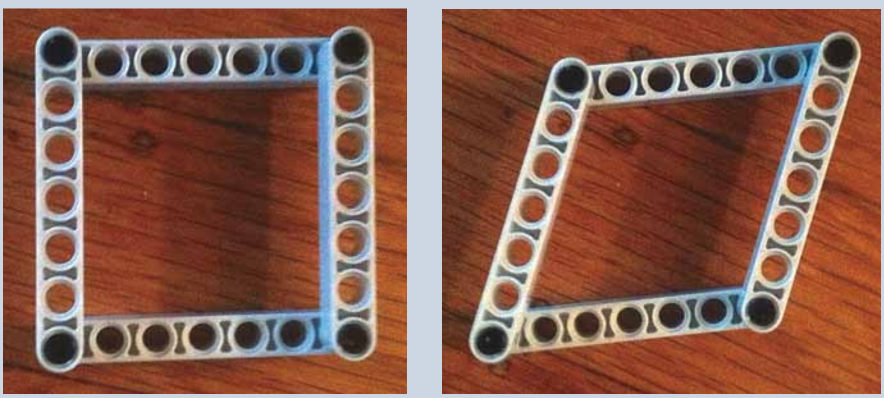
The NXT also comes with three interactive **servo motors**, each with a built-in rotation sensor, giving the robot the ability to move and to know how far it has traveled. The integrated unit can measure the rotation of the motor, accurate to the nearest 2 degrees, ensuring that a robot moves with precision (see **fig. 3**).

Before the start of any programming, students can try different wheels and display the rotation measure on the NXT brick to experiment with the relationship between wheel size and distance traveled in a single rotation (see **fig. 4**).

The last sensor in the kit, and arguably the most technologically advanced, is the **ultrasonic sensor,** which lets a robot measure distance to another object and react to movement. This sensor even looks like a pair of eyes with which the robot can "see" (see **fig. 5**).

In my experience, the presence of the robotics kit in the classroom, initially as a station for students to visit and experiment with, will cultivate an

Fig. 1 Students learn that a quadrilateral (a) without bracing (b) will not hold its shape.



(a) (b)

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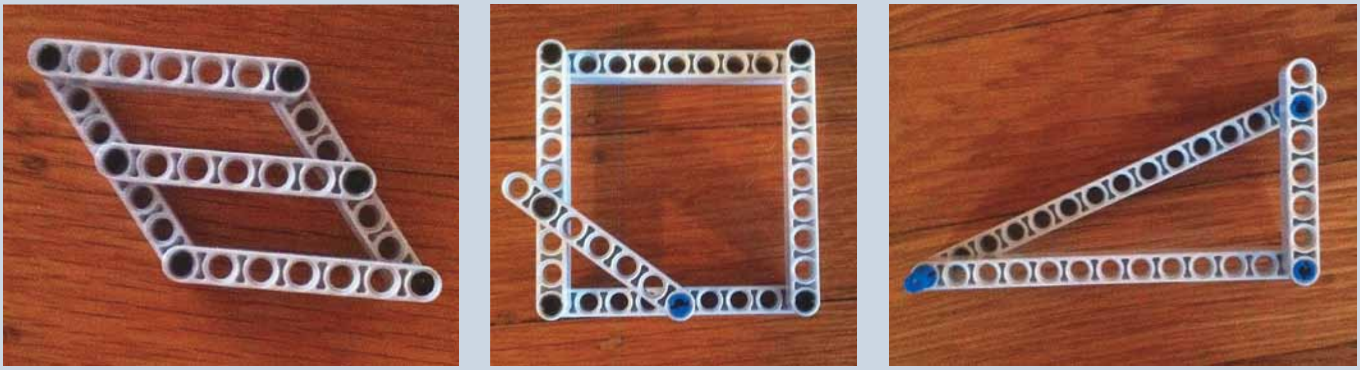
Fig. 2 Students experience the effects of (a) parallel versus (b) triangular bracing and find that the latter strategy will make their shape structurally sound; (c) Pythagorean triples emerge when students construct triangles with the materials provided. At one point, a student noted, “Pythagorean triples are your friend!”



(a) (b) (c)

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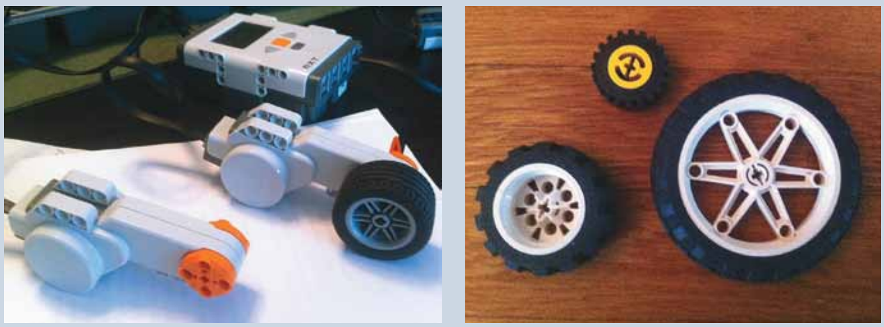
Fig. 3 The NXT brick displays rotation measured in degrees.

Fig. 4 Using servo motors with rotation sensors helps students relate wheel size to distance traveled.



(a) (b)

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interest in learning more. Ultimately, this interest will lead to students writing programs, which is where the mathematics can really come alive. For example, suppose that students wanted their robot to launch via a clap, roll forward 10 inches, make a 90 degree right turn, continue rolling until it hits a black line, and stop. They would need to break this seemingly simple procedure down into smaller steps, which they can “teach” the robot, through programming (see **fig. 6**).

In the process, students would need to determine how far their robot travels with one rotation of the wheels and how many rotations comprise 10 inches. They might talk about the role of wheel size in this calculation (see **fig. 7**). Their icon-based program would require using multiple sensor inputs; defining variables; reasoning proportionally; and determining inequalities to make their robot start, turn, and stop in the exact desired locations.

FIRST ROBOTICS

For more than twenty years, the nonprofit *FIRST*® (For Inspiration and Recognition of Science and Technology) has worked to informally transform

Fig. 5 The ultrasonic sensor serves as the eyes of the robot.

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Fig. 6 A student makes notes for planning a simple program.

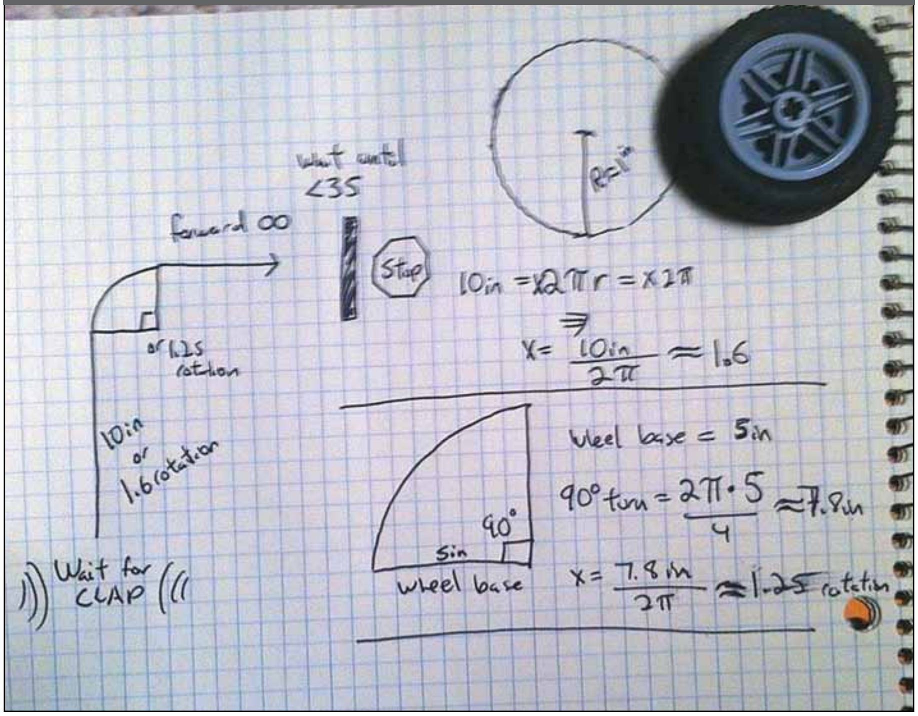


Fig. 7 In this example of student programming, wheel size is a significant consideration.

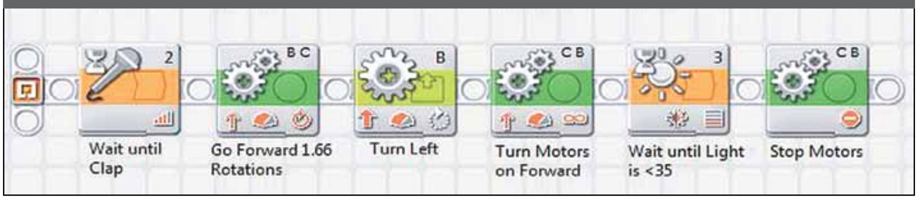
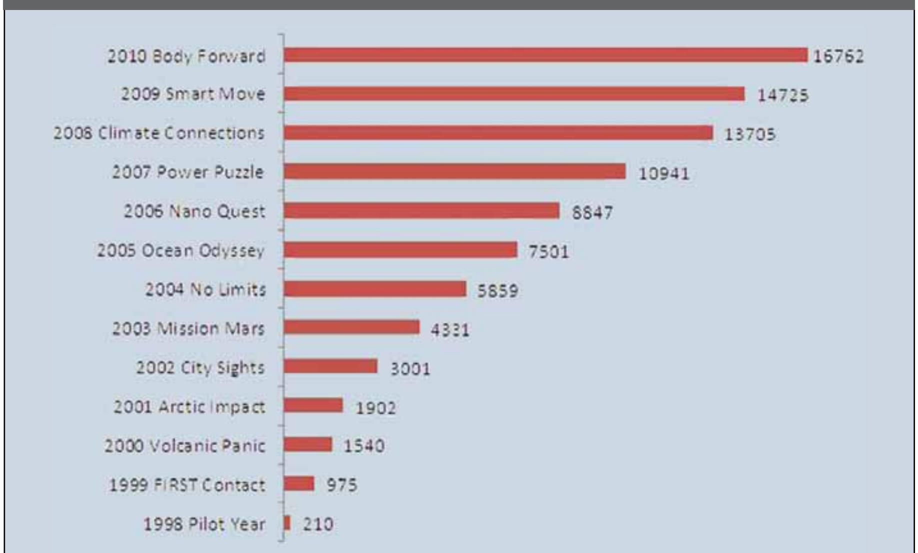


Fig. 8 This chart shows the growth of *FIRST* LEGO League by year, theme, and number of registered teams.



Source: http://firstlegoleague.org/challenge/thechallenge

STEM education by promoting and organizing robotics competitions for students nationwide. Founder Dean Kamen calls these events "Olympics for the mind." Although *FIRST*'s early programs targeted high school students, Kamen (an inventor and innovator, who created the Segway® transporter) quickly recognized the potential benefit of involving students at an earlier age. The result was *FIRST* LEGO® League (FLL®)—a partnership between LEGO and *FIRST*, now international in scale, involving thousands of teams every year, each team composed of up to ten students in fourth through eighth grade. Many FLL teams are based in schools, either as after-school programs or as part of the STEM curriculum. Others are located in youth organizations such as Boys and Girls Clubs or Girl Scouts. Many middle school teachers start teams at their school.

Components of the FLL Robotics Competition

Over a few months, each FLL team creates a fully autonomous robot solely out of LEGO parts. Students write all the programs that enable these robots to move; no remote control is used. Each robot must accomplish a series of related tasks organized around a theme that students research as they prepare for competition. **Figure 8** presents a list of recent themes along with the growing number of registered teams.

The Core Values of the *FIRST* LEGO League play a key role in this experience, transforming students' and adults' views about STEM:

- We are a team.
- We do the work to find solutions, with guidance from our coaches and mentors.
- We know our coaches and mentors do not have all the answers; we learn together.

- We honor the spirit of friendly competition.
- What we discover is more important than what we win.
- We share our experiences with others.
- We display Gracious Professionalism® and Coopertition® in everything we do.

(For more information, see http://www.usFIRST.org/aboutus/gracious-professionalism.)

Building More Than Robots

It's not just about building a robot. It's about building engineers. It's about building people. (*FIRST* student with seven years' experience)

Being aware of and promoting STEM education in the United States means more than helping students learn and experience math and science. It means changing students' perceptions of these disciplines through direct experience and creating situations for students to fall in love with these subjects and all that science, technology, engineering, and mathematics make possible in our world. It also means helping students see themselves as future scientists, tech specialists, engineers, and mathematicians. In my twenty-five years as a mathematics educator, I have encountered nothing that helps light this spark like robotics. This potential spark is the reason I have continued as a *FIRST* robotics volunteer for nearly a decade.

The fourth graders with whom I began my robotics journey have recently graduated high school. Over the years, they have inspired dozens of students to join a *FIRST* team, many of whom are now pursuing or considering STEM careers that they never could have envisioned without their robotics experience. In 2007, the middle school team won the *FIRST* LEGO League World Championship as seventh graders.

Where to Find **ROBOTICS INFORMATION**

With the increasing availability and affordability of robotics materials, especially those designed specifically for educational use, it is possible to give students a robotics experience at the middle school level. Anyone who has worked with youth robotics will confirm that robots help hook students on STEM. As a result, a growing number of organizations have developed and continue to refine instructional materials designed to make robotics more accessible to more teachers and their students across grades K–grade 12. A few examples are these:

- NASA's Robotics: http://www.nasa.gov/audience/foreducators/robotics/lessonplans/index.html
- Carnegie Mellon University's Robotics Academy: http://www.education.rec.ri.cmu.edu/content/educators/research/robot_algebra/index.htm
- Tufts University Center for Engineering Education and Outreach: http://www.ceeo.tufts.edu/

In my twenty-five years as a mathematics educator, I have encountered nothing that helps **LIGHT THIS SPARK** like robotics.

As ninth graders in high school, they started a *FIRST* robotics team at their school. At the varsity level, 120-pound metal robots and state of the art technology were used. I have marveled at every stage of their development at the reduced role of the adults and the growing capacity of the students to direct themselves. The coaches ask questions. We provide guidance and organizational structure. Industry mentors contribute specialized knowledge as the robots become more sophisticated. The adults make sure everyone is safe. However, for the most part, we stand back and watch in awe.

BROADENING STUDENT INTEREST

Over the years, I have collected student quotes as evidence of the impact that FLL and *FIRST* robotics can have on young people, particularly their views about the value of mathematics. Below are a few favorites.

- "Whoa! Forward and reverse are like positive and negative numbers!"
- "That's going to fall over. We need a triangle in there."
- "Before robotics, math was just on paper; now it's 3-D."
- "Pythagorean triples are your friend!"
- "OK, 2:1 means twice as fast. That's so cool!"
- "Honestly, I never knew geometry could be useful."
- "When we use math, we do better."

Particularly powerful for our current work in mathematics education are the connections between the work of a robotics team and the mathematical practices recommended in the Common Core State Standards for Mathematics. The Standards addressed include those listed here, and expanded on in **table 1**:

Table 1 Direct connections are found between the Common Core State Standards for Mathematics (2010) in grades 6–8 and the mathematics embedded in robotics. The table describes only a small sample of the mathematics that comes to life when middle school students participate in robotics programs.

Common Core Standards	Robotics Tasks
Understand ratio concepts and use ratio reasoning to solve problems. (Grade 6) Analyze proportional relationships and use them to solve real-world and mathematical problems. (Grade 7)	Select a wheel size for the robot chassis. Determine the amount of rotation needed to arrive at a specific location. Use gears to slow.
Represent and analyze quantitative relationships between dependent and independent variables. (Grade 6) Use properties of operations to generate equivalent expressions. (Grade 7) Use functions to model relationships between quantities. (Grade 8)	Write number sentences that involve a range of numeric values for light, distance to an object, or rotation—all used to start and stop the robot. Determine the most efficient measures for having the robot move precisely.
Reason about and solve one-variable equations. (Grade 6) Solve real-life and mathematical problems using numerical and algebraic expressions and equations. (Grade 7) Understand the connections among proportional relationships, lines, and linear equations. (Grade 8)	Use wheel size and rotation to experiment with quantities such as speed and power. Determine angles for building attachments that allow the robot to interact with other objects.
Apply and extend previous understanding of numbers to the system of rational numbers. (Grade 6) Solve real-life and mathematical problems using numerical and algebraic expressions and equations. (Grade 7) Work with radicals. (Grade 8) Understand and apply the Pythagorean theorem. (Grade 8)	Create a chassis and mounting system that will allow for stable and convenient attachment of the NXT brick and its sensors. Given a task, determine the robot's strategy and best path.
Draw, construct, and describe geometric figures and describe the relationships among them. (Grade 7) Understand congruence and similarity using physical models. (Grade 8)	Design different robots for different purposes (for example, agility versus stability). Create attachments like claws and scissor lifts.

1. Make sense of problems and persevere in solving them.
2. Reason abstractly and quantitatively.
3. Construct viable arguments and critique the reasoning of others.
4. Model with mathematics.
5. Use appropriate tools strategically.
6. Attend to precision.
7. Look for and make use of structure.
8. Look for and express regularity in repeated reasoning. (CCSSI 2010, pp. 6–8)

If we are serious about implementing these standards for all students, then we must create compelling problem-solving experiences and tasks that support engagement through achievable challenge (Willis 2010). We must also highlight activities that engage students so that they will want to invest in and own the task as well as the mathematics behind it (Middleton and Jansen 2011). Robotics provides such opportunities.

Establishing an FLL program in a school takes this one step further by fostering a culture that combines competition, creativity, and collaboration in a way that encourages everyone to grow. Students see mathematics as a tool that makes all the difference in the quality of their robot. They devise and solve mathematical problems, such as working with proportions, using positive and negative numbers, calculating square roots, writing algebraic expressions and equations, and so on, with enthusiasm. Such tasks might be avoided in another context. However, the robot intrinsically motivates (Bascom 2011). Some students even feel compelled to teach themselves a new mathematical procedure because they need it to solve a problem. As we consider strategies for strengthening STEM education at the middle school level and preparing all students to succeed in a STEM-based future, there is no question that the goal of "robotics in every school" holds undeniable promise as the innovation we need to change lives and to change the world.

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