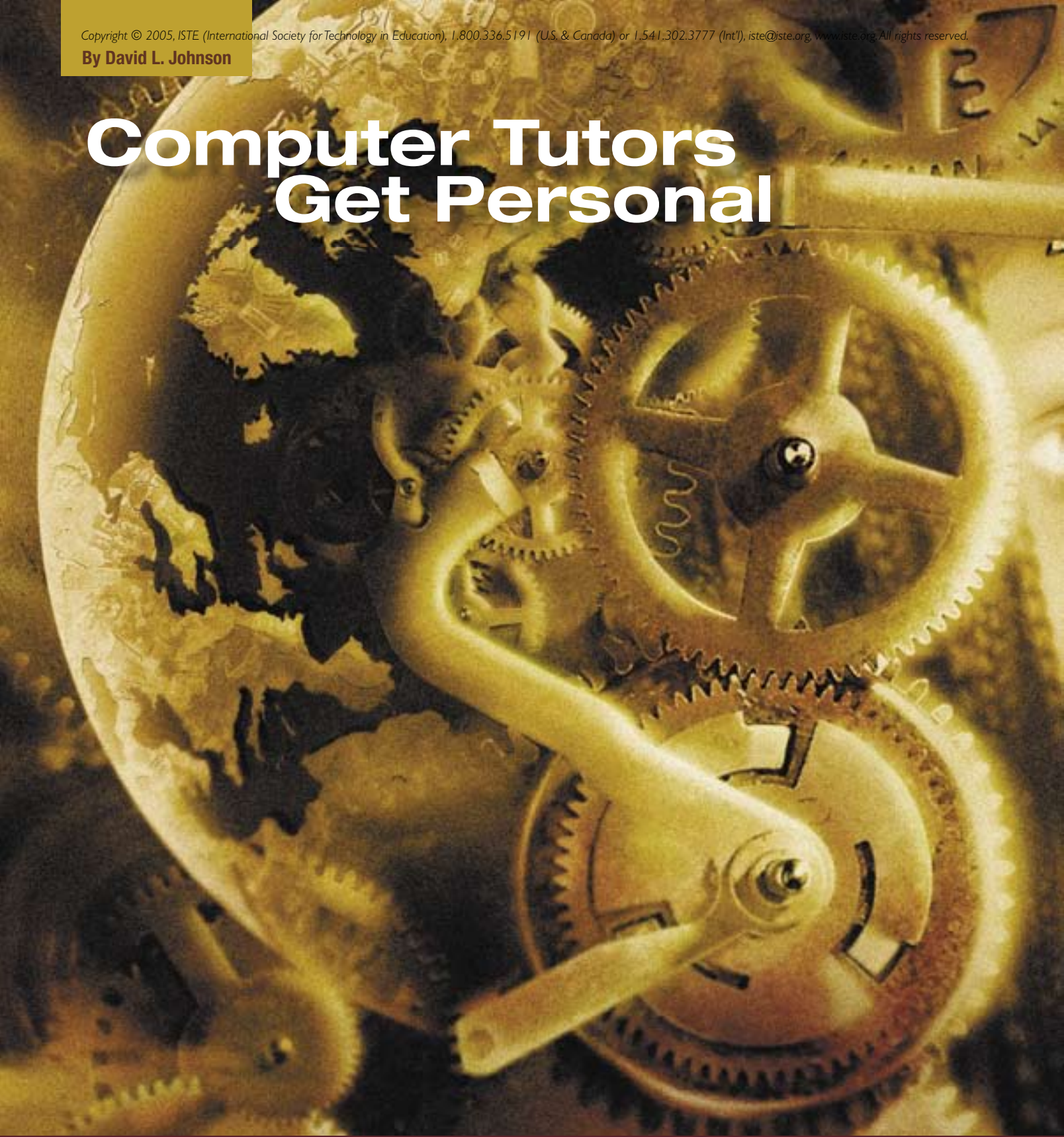
By David L. Johnson

Computer Tutors Get Personal



After decades of research in artificial intelligence (AI) and cognitive psychology, a number of companies have emerged that offer intelligent tutor system (ITS) software to schools. These systems try to mimic the help that a human tutor would provide to an individual student, something nearly impossible for teachers to accomplish in the classroom. They offer new options to identify, remediate, and track students in a very individualized manner.

An ITS can adapt to the student in a way that traditional computer-assisted instruction (CAI) cannot. It is built on the foundations of AI and cognitive psychology. AI uses mathematics to model human reasoning, employing inductive and deductive processes to derive novel answers. Cognitive psychology explains how humans represent and organize knowledge in memory. Many of them are based on Dr. John R. Anderson's adaptive control of thought theory, which posits that all cognitive functions can be represented as a set of production rules. (***Editor's note:*** Find a glossary of these and other terms on p. 17.)

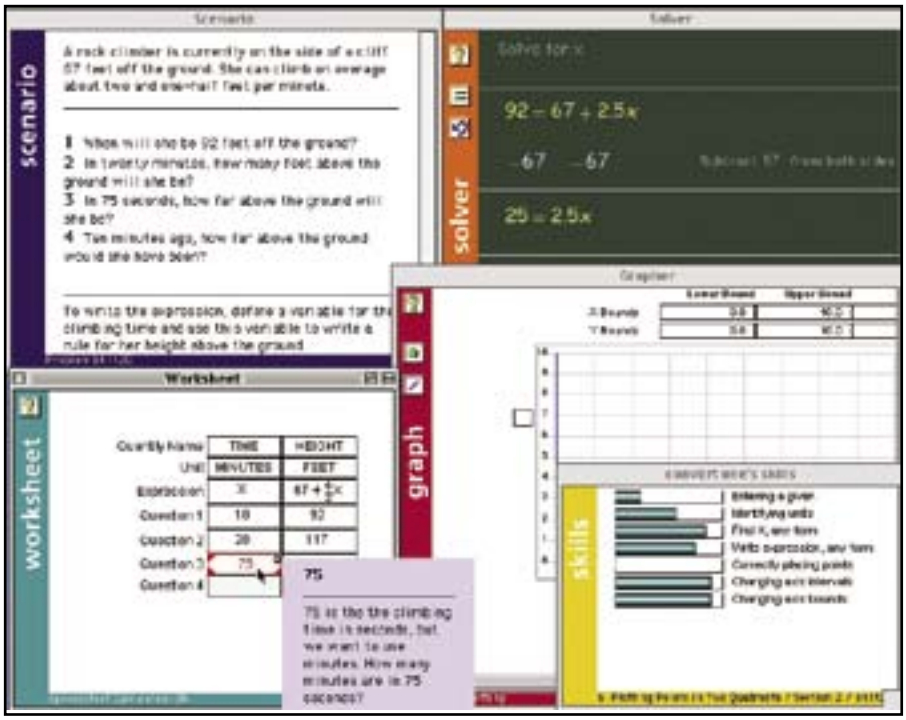
A typical ITS diagnoses what feedback a student needs and what practice problems should follow, based on production rules, not predefined branching sequences. Production rules enable the ITS to anticipate all alternative problem solutions and respond to each one. The program assesses what the student knows in a student skills model. The ITS generates a problem, works out a solution, compares the solution in real time to the student's solution, and performs a diagnosis based on differences between the two. The system then updates the student skills model. This customized diagnosis and remediation differentiates an ITS from CAI.

After millions of dollars of funding by the National Science Foundation, U.S. Department of Education, and the U.S. military, the research is paying off with commercial ITS products that improve student achievement. Carnegie Learning Inc. and Apangea Learning Inc. offer math tutors, and Quantum Simulations, Inc. offers chemistry tutors. All three companies provide intelligent tutoring in different ways, and all are backed by solid research. Carnegie Learning provides personal attention to students in the classroom with a complete curriculum, which includes teacher training, computer tutors for the lab, and textbooks for the classroom. Apangea provides personal attention to students with an Internet-based hybrid tutoring model that leverages intelligent software for about 90% of the work and Internet-based human tutors for the other 10%. Quantum Simulations provides personal attention to students at home with an Internet-based homework tutor that is open-ended, allowing students to enter any problem their teachers assign.

Personal Attention in Class

Carnegie Learning spun out of Carnegie Mellon University as a separate company in 1999 and offers a blended curriculum for math in which 40% of class time is spent in the computer lab using the Cognitive Tutor programs and 60% is spent in the classroom doing class activities.

{ Intelligent tutors can mimic human tutors, providing some of the same benefits as well as unceasingly patient practice and remediation. }



Cognitive Tutor Algebra I provides multiple representations of the problem. A real-world word problem is provided in the top left window. A worksheet to convert textual information into quantities and units is provided in the bottom left window. A graph is provided in the bottom right window, as well as a skills meter summarizing the student's mastery of math skills. A solver to convert information into equations is provided in the top right window. Finally, a hint at the bottom helps direct the student to properly convert units in the worksheet.

Cognitive science researchers at Carnegie Mellon teamed with Pittsburgh public school teachers, such as former Presidential Teacher of the Year Bill Hadley, to develop and refine the mathematics curricula over a 20-year period. The line of tutors employs AI, tracking what students know, tailoring the feedback, and sequencing the next problem.

According to Dr. Steve Ritter, senior cognitive scientist of the company, "What we do is give a complex problem and monitor the process the student uses to solve the problem. We provide multiple representations of the problem, linking graphs with equations with tables with words. We are trying to help students develop robust representations to promote transfer to real-life applications." A worksheet prompts students to think abstractly by converting the problem into quantities and units. A graph promotes visual thinking, and an equation solver prompts students to think in the language of mathemtics.

The cognitive tutors employ model tracing that detects the strategy the student is using to solve the problem. They recognize common student errors and misconceptions and respond appropriately. "We provide an interface where students' thinking becomes more evident so we can detect skill difficulties that they may have," says Ritter. "Merely tracking right or wrong answers won't provide that. A student may get an answer right, but may have taken a circuitous route to get that answer because of a misconception. The objective is to reveal a student's thinking." Feedback enables students to self-correct. A Skillometer visually summarizes the student's mastery of math skills. The bars increase in size and turn gold on mastery.

In the classroom, teachers can spend more time on concepts after consulting a Teachers Toolkit that provides progress reports for individuals and the whole class and a Skills Alert Report listing students who are having difficulty mastering a skill. Carnegie provides activities that use problems similar to those used in the lab.

Mary Ann Stine, director of curriculum and instruction for the Everett (Washington) Public Schools, has witnessed Cognitive Tutor's success. At Cascade High School, they placed students who had already failed Algebra in a class using the Cognitive Tutor. "After Cognitive Tutor, they had a high pass rate of 80–90%," Stine reports. They surveyed the students, and "80% of those students—this is a total of 150 students—said if we could do math like this, we would go on to the next level," says Stine. "It's very powerful to hear them talk about how this really makes sense to them."

Jillian Whaley is a math teacher at Stephen Decatur High School in Worcester County, Maryland, who uses Cognitive Tutor Algebra I with 9th through 12th graders. Not only does the self pacing promote student-to-teacher collaboration, Whalley says, the software also promotes student-to-student collaboration. "The kids help each other. A lot of times you learn best from your peers. There's a lot of math talk going on in the lab; you wouldn't believe it!" The personalized attention seems to work. "It's absolutely amazing to watch their progress," she continues.

Personal Attention out of Class

Based on a 10-year research project undertaken by the U.S. Air Force Research Laboratory and funded in part by the Heinz Endowments, Apangea Learning was founded in 2002. The company sells a hybrid tutoring system for math called SmartHelp that combines intelligent software with online human tutors for 5th through 12th graders. SmartHelp promotes a structured approach to solving math problems. The intelligent tutoring

Glossary

Adaptive Control of Thought (ACT)
This cognitive theory developed by Dr. John R. Anderson of Carnegie Mellon University states that learners acquire cognitive skill by developing procedural knowledge (knowing how to do things). Learners initially process incoming stimuli as declarative knowledge (knowing what the world is like). Learners process declarative knowledge into procedural knowledge while solving a problem. Thereafter, repeatedly performing the procedure strengthens it, allowing the learner to execute the procedure in the future with little conscious thought.

Artificial Intelligence
AI mimics human thought and cognitive processes to solve complex problems.

Cognitive Tutor Authoring Tools
These are a suite of software tools that facilitate the development of computer-based tutors. Carnegie Mellon University created the tools, and the Pittsburgh Science of Learning Center (http://www.learnlab.org) uses them for learning science experiments.

Computer-Assisted Instruction (CAI)
This type of application employs conditional branching after assessing the student's response, either looping the student through built-in remediation or advancing the student to the next problem. Developers construct the branches in advance. In contrast, intelligent tutor systems (ITS) branch students on the fly. Likewise, CAI typically doesn't recognize misconceptions or diagnose student errors and tailor remediation based on these errors as an ITS does.

Consistency Rules
These AI rules, developed by Quantum Simulations Inc., check a student's steps in solving a problem for consistency with an applicable principle or concept in the subject domain, permitting intelligent tutor systems to offer open-ended questions.

Intelligent Tutor Systems (ITS)
These applications use AI software technologies and cognitive psychology models to provide one-on-one instruction. They evaluate student performance, assess the student knowledge and skills, provide instructional feedback, and select appropriate next exercises for the student.

Model Tracing
This is the process of comparing student responses to an expert system. An expert system consists of a set of production rules for the domain of knowledge. Every time the student takes an action, the tutor compares it to a set of actions generated by the expert system. If the student action matches one of the actions predicted by the expert system, the student action is considered correct. Model tracing can identify misconceptions and typical student errors and provide appropriate feedback to the student.

Production Rules
Production rules represent knowledge in cognitive psychology expressed as a set of IF-THEN rules. For example, IF you want to start the car, THEN insert the key on the right side of the steering wheel and turn the key away from you.

Student Skills Model
This represents the procedural skills the tutor perceives that the student has. The tutor compares the student skills model to the expert system to identify differences and to select the next problem for the student to solve.

Available Intelligent Tutor Systems

Apangea Learning Inc. ■ http://www.apangea.com

Modules	*Price*
SmartHelp	$48
SmartHelp LIVE! (includes human tutors online)	$60
Professional Development	No charge
Teacher's Toolkit	No charge

Note: SmartHelp and SmartHelp LIVE! offer 27 tutorial math courses for Grades 5–12. Prices vary, depending on concurrent seat licenses and usage. Annual subscriptions include human tutors online. Alternatively, schools may use their own tutors/teachers online.

Carnegie Learning Inc. ■ http://www.carnegielearning.com

Modules	*Price*
Cognitive Tutor Algebra I	$65
Cognitive Tutor Geometry	$65
Cognitive Tutor Algebra II	$65
Cognitive Tutor Integrated Mathematics	$65
Bridge to Algebra (new course)	$65
Cognitive Tutor Textbook	Included
Teacher's Toolkit	Included
Teacher training	Included (regional onsite training is $2,500/day for up to 25 teachers)
Professional development	$750/teacher/day

Note: Prices vary depending on number of students. $65 is for a typical implementation (50–100 students) and includes textbooks, training, and support.

Quantum Simulations Inc. ■ http://www.quantumsimulations.com

Modules	*Price*
Complete Bundle (Chemistry/Math)	$43
Chemistry Bundle	$31
Mathematics Bundle	$21
Individual Tutor Modules	$9.95

Note: Quantity discounts are available based on volume and multiple-year subscriptions. Chemistry modules include measurement, the elements, ionic compound formulas, mathematics of chemical formulas, equation balancing, oxidation numbers, chemical bonding, chemical reactions, and stoichiometry. Mathematics modules include measurement, ratio and proportion, percentages, scientific notation, and metric units.

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software handles 90%–95% of the work and for the remainder, passes the student to a human tutor onsite or on the Web. The software has been used successfully for remediation in after-school programs, study hall programs, and evening tutoring at home.

The Air Force studied the best practices of human tutors as they helped students with the process of solving problems. From this process methodology, the Air Force developed a line of software for math, science, and writing and tested their approach on 30,000 public school students throughout the United States. Apangea licensed the Air Force technology and developed a unique combination of intelligent software and human tutors for its 27 courses in mathematics. Using a seven-step process, the tutors help build critical skills that teach students how to think about math.

Apangea's vision is to leverage technology to make tutoring affordable and available to every student. "We decided to provide large-scale tutoring programs to schools, where in the past they could only afford to do very small-scale tutoring programs," says Louis Piconi, co-founder and CEO. "We do everything from the assessment at the front end to generating individual learning pathways to delivering the tutoring. After each lesson, kids work through progressively more difficult problems as they show increasing mastery. As they are going through these problems, the tutor is looking over their shoulder and interacting with them based on their demonstrated proficiency for each individual skill."

SmartHelp starts by giving each student a placement exam. The software recommends an individual learning pathway for each student that requires the teacher's approval. Each module consists of individual 10- to 18-minute lessons. Each lesson ends with a quiz to measure understanding before allowing students to progress to the skills-based problem solving session. Struggling students receive tutor-generated feedback as they make mistakes. This feedback is shaped by student proficiency ratings that the Tutor continuously adjusts. When the system can no longer help a student, a human tutor is flagged to provide additional assistance.

SmartHelp generates real-time reports on student progress. The reports are accessible on the Internet minutes after lessons are completed, permitting the administration to track students compared to standards and to adjust the curriculum and classroom instruction if necessary.

Since 2003, Dennis Johnson, superintendent of the Cornell School District in Coraopolis, Pennsylvania, has used SmartHelp in the school district's tutorial programs. He implemented these programs because nearly 25% of the students in the Cornell School District were performing below state standards for math and reading.

Since then, the district has seen significant progress and has met per-

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SmartHelp provides real-time reports to district superintendents who track student progress against standards.

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formance standards on the Pennsylvania System of School Assessments exam for the first time in four years. Approximately 32% of eighth graders tested during the spring of 2004 scored at or above proficient levels, up from 28% in 2003.

Johnson's district sends progress reports to parents every two weeks. "That's key," he says. "You've got to have the capability to generate those reports. You have to keep parents and guardians informed. It's a valuable tool for us to determine if a child has mastered a concept or needs another intervention."

Personal Attention at Home

After $4 million of funding from the U.S. Department of Education, National Science Foundation, and the National Institutes of Health, Quantum Simulations released its line of chemistry and science-related mathematics tutors in 2002. These are the first and only AI-based tutors for these disciplines. Building on the model tracing capabilities developed by the researchers at Carnegie Mellon University, Quantum innovated and created a tutor that allows students to enter their own problems—a switch from a typical tutor, in which the computer generates the problems.

The Quantum Tutors are particularly effective in helping students during private study when no teacher is present to answer their questions. The Tutors show students how to work their problems one step at a time, explaining each step in detail and allowing students to ask questions before moving on to the next step. This facilitates self-explanation, which in turn promotes understanding.

Chemist Dr. Benny Johnson teamed up with his former high school chemistry teacher, Dale Holder, to form the company. Holder has taught chemistry in Kentucky for 40 years and has won numerous teaching awards. They couldn't use a conventional CAI approach because the computer would not know in advance what chemistry problems the students were going to use or what mistakes they were going to make. Therefore, the company developed a breakthrough innovation, called Consistency Rules and received a methodology patent.

The company is nearly finished creating assessment tools that will permit teachers to create their own assessment questions and students to take the assessments online and receive real-time feedback. The Quantum Assessment Advisors will instantly grade the assessment, award partial credit, and for missed questions, transfer the question data back to the Quantum Tutor for remediation. The Advisor will provide data to teachers and administrators summarized by school and by district, with drill-down detail for individual students.

Kevin Willis teaches 12th-grade chemistry in the Carmichaels Area Junior/Senior High School, near Pittsburgh, Pennsylvania. He uses the tutor for homework assignments, "as a take-home teacher," he says. "A lot of times the students don't even know what questions to ask because it's so foreign to them. The tutor helps them ask the questions they need whenever they get stuck."

Willis also uses the tutor in the computer lab for review sessions with another set of homework problems. Rather than working through all the problems on the board, he requires the students to work through the problems on their own with the tutor. "They can ask specific questions of the tutor and get feedback," says Willis. "If they have further questions, I can come around and help them. The value in review and individualized instruction really helps."

Willis has been pleased with the results. "The experience that we had with the Balancing Equations tutor has been amazing. I wasn't a skeptic, because I thought it could work, but I have to admit I was surprised with the results because there was such a large increase for the students who used the tutor." In a trial, one class used the tutor and another did not. Both classes received almost identical scores on a pretest and both showed gains between the pretest and posttest. However, the tutor group scored 12.8 points better than the control group—one whole letter grade. "The difference was astounding," says Willis.

Future Directions

ITS software is extremely time consuming to develop, with estimates of 200–1,000 hours of development time required to produce one hour of instruction. Cognitive Tutor Authoring Tools developed by Carnegie Mellon University show promise, reducing development time to 23 hours per each hour of instruction. The tools are included in the research the Pittsburgh Science of Learning Center will conduct on how people learn. The Center was established in 2004 with a $25 million grant from the National Science Foundation to Carnegie Mellon University, the University of Pittsburgh, and Carnegie Learning.

Providing personalized attention to students through computer technology shows great promise in a way that is almost impossible for teachers to accomplish on their own. Whether in the classroom, after class, or at home, ITS technology has proven to be very successful in remediation and improving standards-based test scores. The technology works for all students, whether they are excelling or struggling, because students can progress at their own pace. ITS software tools help schools achieve results that someday will approach what a human tutor can provide.

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