

Teaching and learning astronomy in the 21st century

Edward E. Prather, Alexander L. Rudolph, and Gina Brissenden

A national study of teaching and learning in courses that introduce astronomy to nonscience majors shows that interactive learning strategies can significantly improve student understanding of core concepts in astrophysics.

Edward Prather is executive director of the Center for Astronomy Education (CAE) at the University of Arizona's Steward Observatory in Tucson. **Alexander Rudolph** is a professor of physics at California State Polytechnic University in Pomona. **Gina Brissenden** is program director of the CAE.

You're lecturing to your introductory college astronomy class about Newton's law of gravitation. You've carefully explained that the gravitational force depends on the product of the two masses involved and on the inverse square of the distance between them. You've shown a few examples or perhaps videos and animations to help your students connect the abstraction of an equation to the real physical world. You may assign thoughtful homework problems, and you encourage the students to ask questions if they don't understand, either in class or during your office hours. You're known as a good lecturer, and your students always rate you highly at the end of the term. Yet when you give your exam, you're dismayed to see how many of them can't answer straightforward questions of the type you covered in class and assigned as homework. So why does the same thing happen to instructors all over the country?

Astronomy-education researchers have been working to solve that problem and many others facing instructors of astronomy survey courses for nonscience majors. Such courses are commonly called Astro 101. During a series of investigations conducted at the University of Arizona, education researchers have developed conceptual questions used to assess students' understanding of core topics in such courses. Two of the questions are "At what location between the Earth and Moon does the net gravitational force on a spaceship become zero as it travels between the two bodies?" and "Would a waxing gibbous Moon ever be above the horizon during daytime?"

After traditional lecture-based instruction, one student (Jennifer) stated in response to the gravity question, "halfway, because exactly halfway causes the Moon's and Earth's gravitational pulls to cancel out." In response to the lunar-phase question, another student (George) answered, "No, because this phase only occurs when the Sun illuminates it during our nighttime." Those responses indicate that after instruction Jennifer and George still had conceptual and reasoning difficulties common among their peers prior to instruction.¹

By the second time Jennifer and George answered those questions, they had both participated in an interactive learning activity designed to help Astro 101 students confront common misconceptions. After completing the activity on gravity, Jennifer correctly answered, "Closer to the Moon than to Earth, because Earth has a greater force on the space-

ship than the Moon does. But when the spaceship is closer to the Moon, Earth loses some force while the Moon gains some, until their strengths become equal." And George was now able to correctly reason that "this phase is highest in the sky at 9 PM, therefore rising 6 hours earlier at 3 PM and setting at 3 AM. So yes, it would be visible for some short time between 3 PM and 6 PM in the daytime."

Improving scientific literacy

Research on the teaching and learning of Astro 101 has an important role to play in improving our nation's understanding of the scientific process and of the role science plays in society.² Last year, NSF reported that according to its *Science and Engineering Indicators*, only about 25% of the country's adults were scientifically literate. Astro 101 courses reach nearly 250 000 college students each year. An astonishing 10% of all US college students take a survey astronomy course, which makes Astro 101 one of the most popular introductory science courses.³ For many of those students, Astro 101 will be the final science course they take for the rest of their lives. The quality of their astronomy education may therefore have a lasting impact on their scientific literacy and their attitudes toward science.

The overwhelming majority of students taking Astro 101 are nonscience majors. They represent our society's future business leaders, lawyers, journalists, politicians, historians, and — most critically — schoolteachers. As many as 40% of students taking introductory science courses say that they intend to become licensed teachers.⁴ Schoolteachers play a critical role in inspiring and training the next generation of students to join the STEM disciplines: science, technology, engineering, and mathematics. Improving the scientific knowledge, attitude toward science, and teaching skills of prospective teachers must be critical goals for Astro 101 courses. Unfortunately, middle- and high-school teachers often emerge from college unprepared to teach their students about astronomy and space science. With so much at stake, it is clearly in our nation's best interests to improve the teaching and learning of Astro 101.

Over the past 10 years, astronomy-education researchers have made significant gains in their understanding of how students learn the subject. Much of that work has intention-

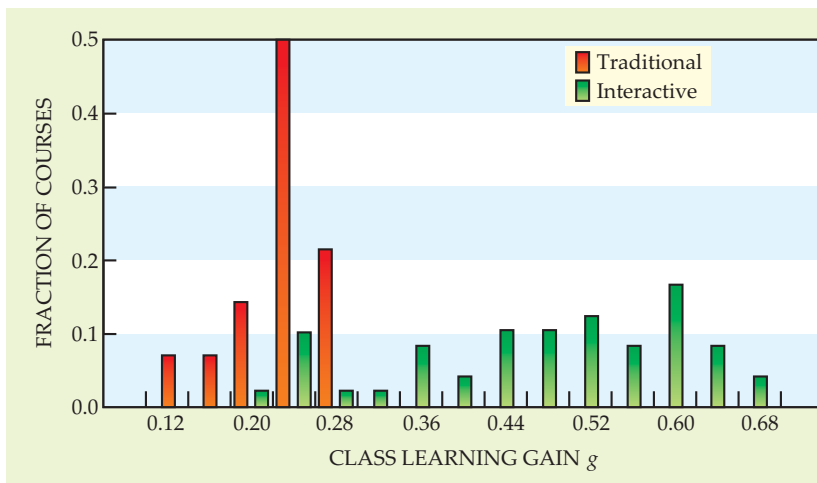


Figure 1. Distributions of learning gain in introductory college-level physics courses taught with different instructional strategies. The class learning-gain parameter g (defined on page **) was measured by testing every student with the 30-questions Force Concept Inventory at the start of the course and then again at its completion.⁷ The red histogram is for traditionally taught classes. The green histogram, for classes using interactive learning strategies, shows that students in those classes significantly outperformed students in more traditional classrooms.

ally followed the successful path blazed over the previous two decades by physics-education researchers. Physics-education research (PER) has shown that interactive learning strategies significantly improve student understanding. Astronomy-education research (AER) has begun to show that carefully adapted versions of those research-validated learning strategies can achieve large gains in the Astro 101 classroom. To determine the effectiveness that new and innovative teaching strategies are having on Astro 101 students, we have conducted a national study involving nearly 4000 students at 31 colleges and universities. Before discussing the key results of our study, we share some highlights from PER that have influenced our work.

Physics education leads the way

Over the past several decades, a number of highly effective research and curriculum-development models have emerged from the PER community.⁵ (See also the PHYSICS TODAY articles by Edward Redish and Richard Steinberg, January 1999, page 24, and by Carl Wieman and Katherine Perkins, November 2005, page 36.) Physics-education researchers have made much progress toward determining what naive misconceptions and reasoning difficulties students have in introductory physics. The results of that research have been used to develop curricula that specifically target those difficulties. The most successful instructional strategies have focused on getting students to become actively engaged in their own learning, as opposed to passively listening to lectures.

A necessary step in the progress of PER was the creation of research-validated assessment instruments that let instructors measure the effectiveness of their instruction. Among the first such assessment instruments was the widely adopted Force Concept Inventory.⁶ The FCI is a collection of 30 multiple-choice questions on the basic concepts of Newton's laws. They are designed to force students to choose between Newtonian concepts and "common-sense" alternatives. The FCI was widely adopted in the physics community because it focused on a topic central to all first-term introductory courses, and also because its simple design enabled instructors to easily measure how much students gained in their understanding.

That wide use allowed Richard Hake in 1998 to report a meta-study of FCI results from 6000 students enrolled in classrooms all over the country.⁷ As a measure of student learning in a particular course, Hake used the normalized learning-gain parameter

$$g = (\langle post\% \rangle - \langle pre\% \rangle) / (100 - \langle pre\% \rangle),$$

where $\langle pre\% \rangle$ and $\langle post\% \rangle$ are class-average scores in answer-

ing the FCI questions before and after the course. The normalization denominator is intended to create a figure of merit that minimizes dependence on the different levels of student understanding at the time of the pre-course test.

As shown in figure 1, Hake's study yielded strong evidence that students in classes that used interactive learning strategies outperform those in traditional lecture-based classrooms. Through many such validation studies, the PER community provided evidence that helped generate acceptance of new instructional modes in the physics community.

... and astronomy follows

The highly successful PER work offered a well-marked path for the AER community to follow in developing effective instructional strategies and assessment instruments for the Astro 101 classroom.⁸ Our long-term goal was to perform the necessary research that would culminate in a national study, similar to Hake's, on the effectiveness of teaching Astro 101. The list of research and development tasks below provides an outline of the essential steps undertaken along the path to this national study:

- ▶ Carry out systematic investigations designed to elicit students' conceptual and reasoning difficulties on fundamental topics common to Astro 101 courses.
- ▶ Develop active-engagement instructional strategies appropriate for the Astro 101 classroom that have been shown to significantly increase student understanding of core topics.
- ▶ Create professional-development programs that help instructors learn how to effectively implement proven instructional strategies.
- ▶ Develop research-validated assessment instruments that instructors can use to measure their students' gain in understanding of topics central to Astro 101.

Although the results from PER were very helpful to the astronomy-education researchers, there are fundamental differences between the two fields. First, the courses and student populations studied in PER and AER are very different. Introductory college physics is aimed at science and engineering majors, while Astro 101 is designed primarily for non-science majors. Second, on a practical level, the development of curricular materials for Astro 101 is constrained by the lack of recitation sessions, labs, and teaching assistants. The lecture portion of the Astro 101 class is commonly the only time instructors meet with their students.

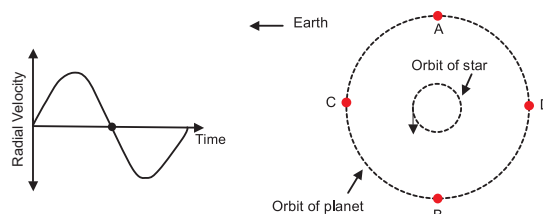
So instructional strategies must resolve conceptual and reasoning difficulties without significant help from the instructor, and they must be designed for use in large lecture

Box. Interactive learning strategies

Think-pair-share (TPS) or peer instruction (PI). Students are initially asked to think individually about a conceptually challenging multiple-choice question and then commit to an answer—usually with flash cards or remote “clickers.” The instructor then leads the students to engage in a discussion with their neighbors, in pairs, to defend their answers. The private discussions are followed by another vote and possibly a full class discussion.^{9,17,18}

The sample TPS question *at right* illustrates how a single question can evoke a conversation involving several topics simultaneously. To reason correctly about this question, the student must be able to interpret both the graph and the diagram, understand Doppler shifts, and understand the coupling of planetary and stellar orbits.

Given the location marked on the star’s radial velocity curve, at which location would you expect the planet to be located?



Lecture-tutorials (LTs). These collaborative learning activities are driven by carefully sequenced Socratic questioning. They are designed to be completed by pairs of students in 10 to 20 minutes, working together in lecture-hall settings after having heard a short lecture on the relevant topic.¹⁸

The questions, posed in ordinary language, are designed to promote small cognitive steps, ultimately guiding the students toward scientific understanding. Initially, students are asked to examine a novel situation that requires them to reflect on information they’ve heard in the lecture. The questions that follow are of increasing difficulty, and the activities involve graphical representations, data tables, and self-checks that encourage students to continuously evaluate their developing ideas.

The *following* example from the end of an LT about look-back time in astronomical observations illustrates the challenge posed by such question sequences.

- 7) The telescope image at the right was taken of the Andromeda Galaxy, which is located about 2.5 million ly away from us. Is this an image showing how the Andromeda Galaxy looks right now, how it looked in the past or how it will look in the future? Explain your reasoning.

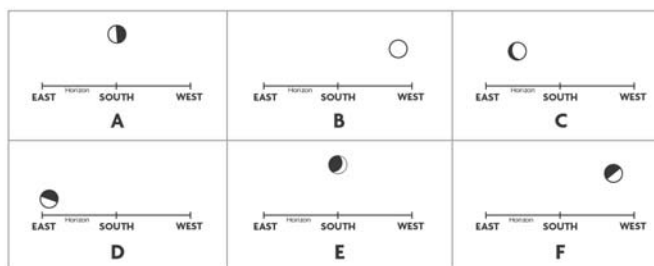


- 8) Imagine that you are observing the light from a distant star that was located in a galaxy 100 million ly away from you. By analysis of the starlight received, you are able to tell that the image we see is of a 10 million year old star. You are also able to predict that the star will have a total lifetime of 50 million years, at which point it will end in a catastrophic supernova.
- How old does the star appear to us here on Earth?
 - How long will it be before we receive the light from the supernova event?
 - Has the supernova already occurred? If so, when did it occur?

Ranking tasks (RTs). Much like the LTs, these collaborative learning activities are designed to be completed by pairs of students after a short lecture. The tasks begin with a series of illustrations providing variations of a basic physical situation. Students examine the different situations to determine their order or ranking. The RT format challenges them with problems in which the path to solution is not immediately obvious. The multiple scenarios engage their minds and force them to think more deeply about the critical features that distinguish one situation from another.

The example *below* presents students with a drawings and questions that require a robust understanding of lunar phases.

In each figure below (A – F) the Moon is shown in a particular phase along with the position in the sky that the Moon would have at one time during the day (or night).



Ranking Instructions: Use the time each Moon phase (A – F) would appear as shown to rank the figures (from earliest to latest), starting from sunrise (6 am).

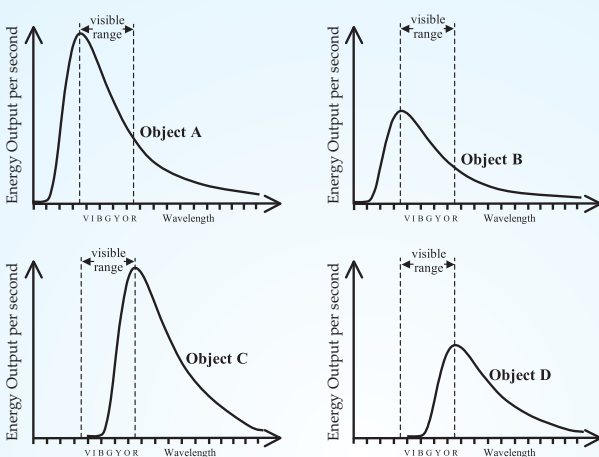
Ranking Order:

Earliest (about 6 am) 1 ___ 2 ___ 3 ___ 4 ___ 5 ___ 6 ___ Latest

Explain your reasoning:

Research on the effectiveness of LTs and RTs has shown that they make it hard for students to rely strictly on memorized answers and mechanical substitution in formulae and that they help students develop mental models more flexible and robust than those they acquire from traditional instruction.¹

Use the spectral curves for objects A-D shown below to answer the next **three** questions. The scale is the same for all four graphs.



24. Which, if any, of the other objects has the same temperature as object B?
- Object A.
 - Object C.
 - Object D.
 - They are all the same temperature.
 - There is insufficient information to answer this question.
25. Which, if any, of the objects could be approximately the same size as object D?
- Object A.
 - Object B.
 - Object C.
 - They could all be the same size.
 - None of the above.
26. Which of these objects is the smallest?
- Object A.
 - Object B.
 - Object C.
 - Object D.
 - More than one of these objects is the smallest.

Figure 2. A sample of three questions from the Light and Spectroscopy Concept Inventory used to measure the learning gain of classes in Astronomy 101 courses.¹¹ To answer these particular questions correctly, the student must understand both Wien's law and the Stefan-Boltzmann law.

proper implementation, researchers at the University of Arizona's Center for Astronomy Education (CAE) have developed a teaching-excellence workshop series with funding from NASA and NSF. Over the past five years, the workshops have been offered at colleges and universities and at national meetings of organizations such as the American Astronomical Society and the American Association of Physics Teachers. The workshops have been attended by more than 1000 college instructors from all types of institutions.

To conduct its own national study, the AER community needed a reliable assessment instrument like the physicists' FCI, but one that covered a central topic of the Astro 101 curriculum. To that end, the Light and Spectroscopy Concept Inventory (LSCI) of questions was created.¹¹ Light is the central carrier of information in astronomy, and a survey of Astro 101 instructors has shown that they consider the nature of light and the electromagnetic spectrum to be the most important topics in their courses.¹² The topic domains of the LSCI are

- The nature of the electromagnetic spectrum, including the interrelationships of wavelength, frequency, energy, and prop-

agation speed.

agation speed.

- Interpretation of Doppler shift as an indication of motion.
- The correlation of peak wavelength and temperature of a blackbody radiator.
- Relationships between luminosity, temperature, and surface area of a blackbody radiator.
- The connection between spectral features and underlying physical processes.

halls with fixed seats. Furthermore, because new strategies require instructors to give up precious class time normally spent lecturing, teaching innovations must be relatively brief. Within the Astro 101 teaching community, three active-engagement strategies have been widely adopted and have been shown to improve students' understanding: Think-pair-share (called peer instruction in the PER community), lecture-tutorials, and ranking tasks (see the box on page **).^{1,9,10} Those strategies are designed to have small groups or pairs of students work together during the standard classroom period, typically following a short 10- to 20-minute lecture.

The LSCI questions, like those of the FCI, were phrased, as much as possible, in ordinary language, and they include "distracters" drawn from common misconceptions. The questions are not easy, and they often require multiple reasoning steps to answer correctly. Three such questions are shown in figure 2. The entire LSCI can be seen at <http://aer.noao.edu/auth/LSCIspring2006.pdf>.

Each strategy represents a different type of interactive learning activity. They target known conceptual difficulties and promote active intellectual engagement. By discussing challenging questions, students get to explore the reasoning behind their answers. In doing so, they improve their reasoning skills and their understanding of core topics. Systematic studies have shown that the strategies can improve students' understanding by two full letter grades beyond what traditional lectures accomplish.^{1,10}

But does it work?

The existence of such research results has encouraged many Astro 101 instructors to start implementing those interactive strategies in their classrooms. To further increase instructor awareness of those strategies and to help ensure their

To bring about a shift in how Astro 101 is taught similar to that motivated by Hake's study of introductory-physics teaching, we conducted a national study in collaboration with instructors who agreed to use the LSCI, to determine the effectiveness of various teaching strategies in Astro 101 classes.¹³ Our 4000-student study covered 69 classes sections at 31 colleges that represented all types of institutions, with a wide range of class sizes and instructional styles—tradi-

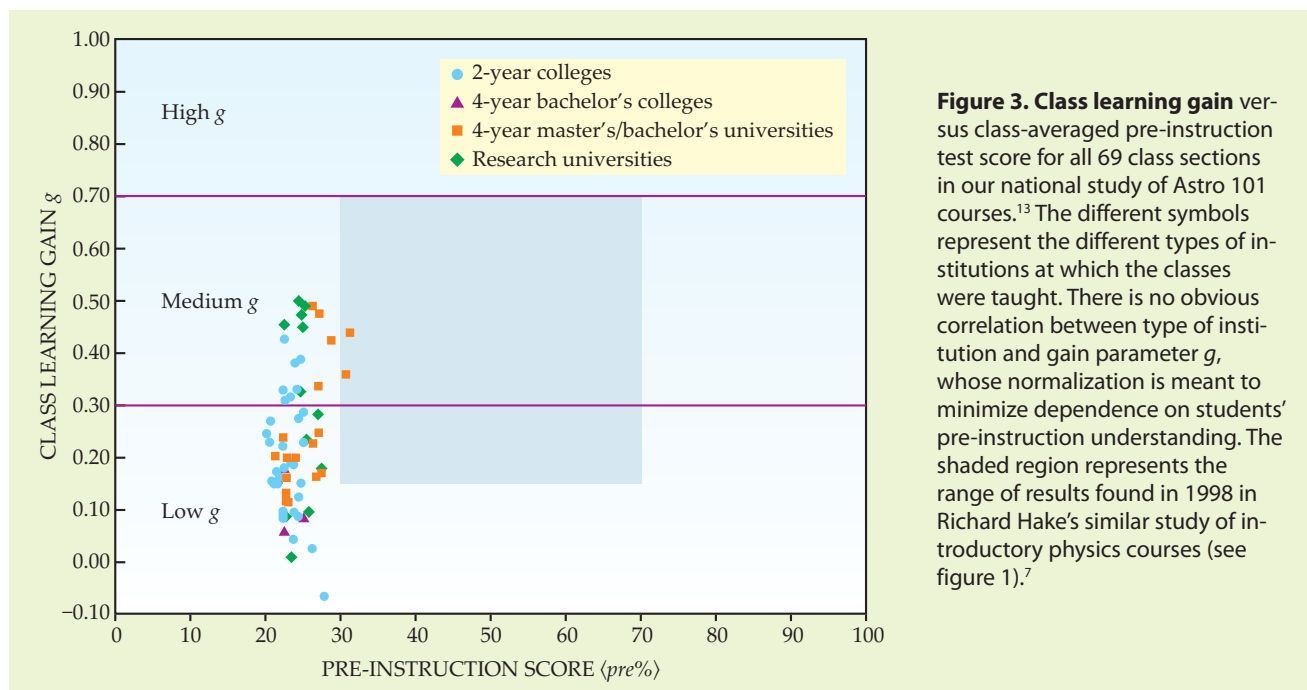


Figure 3. Class learning gain versus class-averaged pre-instruction test score for all 69 class sections in our national study of Astro 101 courses.¹³ The different symbols represent the different types of institutions at which the classes were taught. There is no obvious correlation between type of institution and gain parameter g , whose normalization is meant to minimize dependence on students' pre-instruction understanding. The shaded region represents the range of results found in 1998 in Richard Hake's similar study of introductory physics courses (see figure 1).⁷

tional and interactive.

Figure 3 shows a scatter plot of Hake's learning-gain parameter g , measured with the LSCI astronomy questions, versus class-averaged pre-instruction score for Astro 101 courses in our study, sorted by type of institution. For comparison, the shaded region indicates the range of results for Hake's introductory-physics study. The boundaries at $g = 0.3$ and 0.7 separate the ranges of learning gain that Hake characterized as low, medium, and high.

One striking result is evident. The range of LSCI pre-instruction scores is surprisingly narrow, clustered around 25%, regardless of institution type. That's very different from Hake's study, in which pre-instruction scores ranged from 30% to 70%. That discrepancy illustrates a fundamental difference between the student population taking Astro 101 and that taking introductory college-level physics. Many physics students come to introductory college physics having already taken physics in high school. But Astro 101 students are mostly nonscience majors with little prior knowledge of the basic concepts of light and spectroscopy.

The learning-gain scores in figure 3 vary widely, from almost 0 to 0.5, illustrating that the LSCI is capable of measuring changes in student understanding and, by extension, the effectiveness of teaching about light and spectroscopy in Astro 101. Because the gains appear to be independent of institution type—and also, as we find, of class size¹³—we conclude that neither of those two variables can explain the variation in g . This result suggests that type and effectiveness of instruction are crucial variables. Characterizing introductory-physics classes by whether instructors used any of a variety of interactive learning strategies, Hake had demonstrated that—as measured by g —the interactive classes outperformed the traditional lecture-only classrooms, on average, by about a factor of two.

In our study, we knew that a significant fraction of the instructors were using interactive learning strategies because they were members of the greater national CAE community. We developed a questionnaire for instructors that let us quantify the amount of interactive engagement occurring in each classroom. From each instructor's responses, we calculated a

nominal percentage of time, called the interactive assessment score (IAS), spent on interactive learning strategies during the term. The scores ranged from 0 to 49%, suggesting that our questionnaire was successful at distinguishing different amounts of interactive instruction, and that instructors were not inflating estimates of their classes' interactivity. If they had been, we would surely have seen many estimates of over 49% and none near 0%. Nonetheless, the IAS is only a first-order indicator of allotted time. It provides no details as to the quality of the implementation or engagement in the classroom.

In figure 4, we plot g versus IAS for the 52 Astro 101 classes in our study with at least 25 students. We excluded smaller classes because we believe that the teaching and learning in classes with a very small number of students can be a special case, bordering on personalized instruction. Although the plot shows no simple relationship between learning gain and the level of interactivity, it is notable that no class with an IAS below 25% achieved a gain above 0.30.

By contrast, classes with an IAS above 25% had gains ranging from about 0.05 to 0.5. The average learning gain for those classes was 0.29, more than twice the average gain of 0.13 found for classes with an IAS below 25%. This result is almost identical with that found by Hake for introductory physics. To determine if this dependence on IAS is real, we conducted a statistical-significance test (a t -test) and concluded that there is less than a 10^{-5} chance that the recorded difference in learning gain between the two groups is just a statistical fluke. If this were a medical study of two treatment strategies for a disease, the study would be stopped at this point for ethical reasons, so that every patient could be given the more effective treatment immediately!

To further probe the relationship between interactivity and learning gain, we conducted a multivariate regression analysis to determine how individual differences (for example, personal and family characteristics, academic achievement, and student major) might be correlated with learning gain.¹⁴ The results show that the use of interactive learning strategies is the single most important variable in accounting for the variation in student learning gains, even after control-

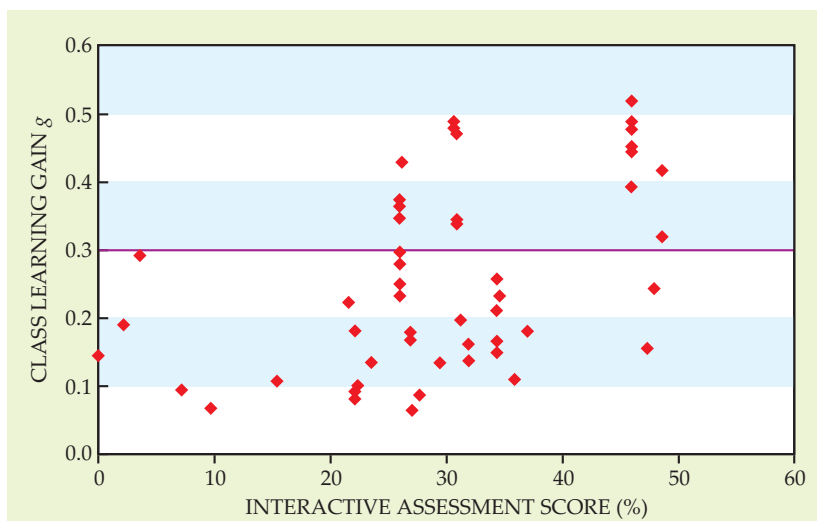


Figure 4. Dependence of class learning gain on interactive assessment score for the 52 class sections in our study with at least 25 students. IAS, a measure of the percentage of class time spent on interactive learning strategies, is determined from each instructor's responses to a questionnaire about time allocation.

ling for individual characteristics. Furthermore, we find that the positive effects of the interactive strategies are the same for strong and weak students, men and women, regardless of ethnicity or primary language. Our results strongly suggest that all students benefit from interactive learning strategies—because those strategies are based on how humans learn.¹⁵

Although our data suggest that spending at least 25% of class time on interactive learning strategies can have a large impact on learning, the broad spread in g for the higher-interactivity classes suggests that the use of such strategies is not enough. The combination of IAS and individual student characteristics used in our multivariate analysis accounts for only 25% of the spread.¹⁴ So, what could account for the rest? The answer may come from research findings on the professional development of instructors which suggest that the quality of implementation of instructional strategies has a significant influence on student learning.¹⁶

Implications

Because of its great popularity among nonscience students and its importance for future schoolteachers, Astro 101 has a central role to play in improving the scientific literacy of our nation. Inspired by the success of PER, the AER community has conducted valuable research on teaching and learning in astronomy. Our work demonstrates that every Astro 101 instructor, regardless of the type of institution or class size, can see benefits in student learning by implementing interactive strategies.

Yet a clear message from our research is that the mere use of such learning strategies is not enough. The quality of implementation is crucial, which points to the importance of professional development. College-level instructors typically receive no significant pedagogical training prior to teaching for the first time. Furthermore, many Astro 101 instructors have had no formal training in astronomy. Of the 250 000 students who take Astro 101 each year, 40% do so in a pure physics department, and another 40% take the course in departments that don't offer degrees in either physics or astronomy.³ Thus a large number of students taking Astro 101 are taking it from an instructor who has little or no formal training in astronomy.

To address such challenges, the CAE has created professional-development workshops designed for Astro 101 instructors with all levels of prior preparation. Those teaching-excellence workshops focus specifically on developing instructors' pedagogical knowledge. They are based on pro-

fessional-development best practices,¹⁶ and they use research-validated techniques that require instructors to practice teaching strategies in a peer-review environment, in which participants offer suggestions and critiques of one another's implementation of interactive learning strategies. Beyond those workshop experiences, the CAE also provides online professional-development resources through our website at <http://astronomy101.jpl.nasa.gov>.

Lack of training is not the only barrier to the effective use of interactive learning strategies. Fundamentally changing how we instructors teach requires work on our part. In addition, there is little requirement that we document our students' learning gains as part of our quest for hiring, promotion, or tenure. Given the amount of work and lack of reward, there can be a natural resistance to change. Thus it is critical for deans, department chairs, other senior faculty, and national organizations to encourage instructors to make the effort to change the way they teach—and reward them for doing so. For example, resources and opportunities should be provided that allow instructors, teaching assistants, and even postdocs to engage in professional-development workshops and that encourage them to implement proven interactive learning strategies in their classrooms.

The ideas of PER and AER are steadily gaining acceptance in physics and astronomy departments nationwide. It is particularly encouraging that many of those who are embracing interactive instructional strategies are early in their careers, which bodes well for the future of Astro 101 instruction. The central role of AER in improving the teaching and learning of astronomy was strengthened by the founding (in 2002) and subsequent growth of the online journal *Astronomy Education Review* (<http://aer.aip.org>), published by the American Astronomical Society.

In addition, members of the CAE recently received an NSF grant to create the Collaboration of Astronomy Teaching Scholars. CATS is a large and growing international community working to increase the number of Astro 101 instructors conducting research in astronomy education. The collaboration also aims to spur the development of research-validated curricula and assessment instruments. With a willingness to challenge ourselves—astronomers and physicists alike—to teach Astro 101 using proven instructional strategies, we can improve the way we teach this critical course and thereby improve the scientific literacy of some 250 000 Americans each year.

Many people have contributed to astronomy education research over the past several decades. We would like to specifically acknowledge the contributions made by members of the Center for Astronomy Education's national community of Astro 101 educators and by members of

the University of Arizona's NSF-funded Collaboration of Astronomy Teaching Scholars program. This research was supported by NSF grants DUE-0715517 and AST-0847170.

References

1. D. W. Hudgins, E.E. Prather, D. J. Grayson, D. P. Smits, *Astron. Educ. Rev.* **5**(1), 1 (2006).
2. B. Partridge, G. Greenstein, *Astron. Educ. Rev.* **2**(2), 46 (2003).
3. A. Fraknoi, *Astron. Educ. Rev.* **1**(1), 121 (2001).
4. F. Lawrenz, D. Huffman, K. Appeldoorn, *J. Coll. Sci. Teach.* **34**, 40 (July 2005).
5. L. C. McDermott, E. F. Redish, *Am. J. Phys.* **67**, 755 (1999).
6. D. Hestenes, M. Wells, G. Swackhamer, *Phys. Teach.* **30**, 141 (1992).
7. R. Hake, *Am. J. Phys.* **66**, 64 (1998).
8. J. M. Bailey, T. F. Slater, *Am. J. Phys.* **73**, 677 (2005).
9. C. H. Crouch, E. Mazur, *Am. J. Phys.* **69**, 970 (2001).
10. E. E. Prather et al., *Astron. Educ. Rev.* **3**(2), 122 (2004).
11. E. Bardar, E. E. Prather, K. Brecher, T. Slater, *Astron. Educ. Rev.* **5**(2), 103 (2007).
12. T. Slater, J. P. Adams, G. Brissenden, D. Duncan, *Phys. Teach.* **39**, 52 (2001).
13. E. E. Prather, A. L. Rudolph, G. Brissenden, W. M. Schlingman, *Am. J. Phys.* **77**, 320 (2009).
14. A. L. Rudolph, E. E. Prather, G. Brissenden, D. Consiglio, V. Gonzaga, *Astron. Educ. Rev.* (in press).
15. J. D. Bransford, A. L. Brown, R. R. Cocking, eds., *How People Learn: Brain, Mind, Experience, and School*, National Academies Press, Washington, DC (1999).
16. J. Gess-Newsome, N. G. Lederman, eds., *Examining Pedagogical Content Knowledge: The Construct and Its Implications for Science Education*, Kluwer Academic, Norwell, MA (1999).
17. E. E. Prather, G. Brissenden, *Astron. Educ. Rev.* **7**(2), 1, (2008).
18. Center for Astronomy Education, "Revisiting Think-Pair-Share: An expanded 'How To' Guide," <http://astronomy101.jpl.nasa.gov/tips/index.cfm?TeachingID=54>. ■