Evidence for the Efficacy of Student-active Learning Pedagogies

Jeffrey E. Froyd
Research Professor
Director of Faculty and Organizational Development
Texas A&M University
froyd@tamu.edu
Version: 22 April 2007

Summary

Although many resources have been published on improvements in student retention and/or learning as a result of using what can be referred to as student-active pedagogies, the resources are published in a variety of journals or on various websites. As a result, it may be difficult for an individual to locate and assemble these resources to support an argument in favor of using these alternative pedagogies. Over a period of eight years, including my time as the Project Director for the Foundation Coalition, one of the Engineering Education Coalitions supported by NSF, I have tried to assemble many of these resources in one place for easy reference.

Cooperative and Small-group Learning Pedagogies

Springer, L., Stanne, M. E., and Donovan, S. S. (1999). Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: A meta-analysis. *Review of Educational Research*, *69*(1), 21–51.

Abstract: Recent calls for instructional innovation in undergraduate science, mathematics, engineering, and technology (SMET) courses and programs highlight the need for a solid foundation of educational research at the undergraduate level on which to base policy and practice. We report herein the results of a meta-analysis that integrates research on undergraduate SMET education since 1980. The meta-analysis demonstrates that various forms of small-group learning are effective in promoting greater academic achievement, more favorable attitudes toward learning, and increased persistence through SMET courses and programs. The magnitude of the effects reported in this study exceeds most findings in comparable reviews of research on educational innovation and supports more widespread implementation of small-group learning in undergraduate SMET.

Quote: The 0.51 effect of small-group learning on achievement reported in this study would move a student from the 50th percentile to the 70th on a standardized (norm-referenced) test. Similarly, a 0.46 effect size on students' persistence is enough to reduce attrition from SMET courses by 22%.

Hake, R. R. (1998). Interactive-Engagement vs. Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses. *American Journal of Physics, 66*(1), 64–74

Abstract: A survey of pre/post test data using the Halloun-Hestenes Mechanics Diagnostic test or more recent Force Concept Inventory is reported for 62 introductory physics courses enrolling a total number of students N = 6542. A consistent analysis over diverse student populations in high schools, colleges, and universities is obtained if a rough measure of the average effectiveness of a course in promoting conceptual understanding is taken to be the average normalized gain <g>. The latter is defined as the ratio of the actual average gain (%<post> – %<pre>) to the maximum possible average gain (100–%<pre>). Fourteen "traditional" (T) courses (N = 2084) which made little or no use of interactive-engagement (IE) methods achieved an average gain <g>$_{\text{T-ave}}$ = 0.23 ± 0.04 (std dev). In sharp contrast, forty-eight courses (N = 4458) which made substantial use of IE methods achieved an average gain <g>$_{\text{IE-ave}}$ = 0.48 ± 0.14 (std dev), almost two standard deviations of <g>$_{\text{IE-ave}}$ above that of the traditional courses. Results for 30 (N = 3259) of the above 62 courses on the problem-solving Mechanics Baseline test of Hestenes-Wells imply that IE strategies enhance problem-solving ability. The conceptual and problem-solving test results strongly suggest that the classroom use of IE methods can increase mechanics-course effectiveness well beyond that obtained in traditional practice

Wage, K. E., Buck, J. R., Wright, C. H. G., and Welch, T. B. (2005). The Signals and Systems Concept Inventory. *IEEE Transactions on Education, 48*(3), 448–461

Abstract: The signal processing community needs quantitative standardized tools to assess student learning in order to improve teaching methods and satisfy accreditation requirements. The Signals and Systems Concept Inventory (SSCI) is a 25-question multiple-choice exam designed to measure students' understanding of fundamental concepts taught in standard signals and systems curricula. When administered as a pre- and postcourse assessment, the SSCI measures the gain in conceptual understanding as a result of instruction. This paper summarizes the three-year development of this new assessment instrument and presents results obtained from testing with a pool of over 900 students from seven schools. Initial findings from the SSCI study show that students in traditional lecture courses master approximately 20% of the concepts they do not know prior to the start of the course. Other results highlight the most common student misconceptions and quantify the correlation between signals and systems and prerequisite courses.

Buck, J. R., and Wage, K. E. (2005). Active and Cooperative Learning in Signal Processing Courses. *IEEE Signal Processing Magazine, 22*(2), 76–81

Abstract: None

Quote: Pedagogical research in physics has found that (g) is robust to variations in instructor experience, student background, class size, and university ranking [2], [3]. Hake's major conclusion was that 14 traditional lecture format classes achieved normalized gain (g) = 0.23 ± 0.04, while 48 IE (or ACL) courses achieved (g) = 0.48 ± 0.14, nearly two standard deviations better than lecture courses. Subsequent papers have reported similar performance for IE methods in physics courses [4]. In our study using the SSCI, we found results strikingly similar to those reported by Hake. We computed (g) for 20 signals and systems courses. The 15 lecture format courses had normalized gain (g) = 0.20 ± 0.07, while the five ACL courses for which we have data achieved (g) = 0.37 ± 0.06. The gain for these ACL courses is more than two standard deviations above the lecture courses.

Crouch, C.H., and Mazur, E. (2001). *Peer Instruction: Ten years of experience and results. American Journal of Physics, 69*(9), 970–977

Abstract: We report data from ten years of teaching with Peer Instruction (PI) in the calculus- and algebra-based introductory physics courses for nonmajors; our results indicate increased student mastery of both conceptual reasoning and quantitative problem solving upon implementing PI. We also discuss ways we have improved our implementation of PI since introducing it in 1991. Most notably, we have replaced in-class reading quizzes with pre-class written responses to the reading, introduced a research-based mechanics textbook for portions of the course, and incorporated cooperative learning into the discussion sections as well as the lectures. These improvements are intended to help students learn more from pre-class reading and to increase student engagement in the discussion sections, and are accompanied by further increases in student understanding.

Wright, J.C., Millar, S.B., Kosciuk, S.A., Penberthy, D. L., Williams, P.H., and Wampold, B.E. (1998). A Novel Strategy for Assessing the Effects of Curriculum Reform on Student Competence. *Journal of Chemical Education, 85*(8), 986–992

Abstract: A new strategy has been developed to credibly assess the effects of curriculum reform on student competence. In order to implement the strategy, a comparative assessment was performed between the students in a section of a course with active learning and those in a reference section. The comparison used 25 faculty to conduct oral interviews that assessed student competence using each faculty member's definition of competence. Qualitative research methods were also employed to identify the reasons for any differences. The results show substantial differences in the students' reasoning and self expression skills that we believe are directly attributable to their structured active learning experiences.

Quote: Although SAL [structured active learning] students outperformed RL [responsive lecturing] students in all subcategories, the assessors in the meta-awareness subgroup found the largest differences between sections—almost ½ the maximum possible differences. [This difference is statistically significant.] This finding indicates that the major reason for the large difference in student competence was the thinking process that students displayed during the oral examination. In the analysis and agility subgroups, the differences became smaller but were still 25% of the maximum possible difference. The differences are not significant, however, because of the small number of assessors in each category. In the analogy subgroup, the differences are still smaller and are not significant

Prince, M. (2004). Does Active Learning Work? A Review of the Research. *Journal of Engineering Education, 93*(3), 223–231

Abstract: This study examines the evidence for the effectiveness of active learning. It defines the common forms of active learning most relevant for engineering faculty and critically examines the core element of each method. It is found that there is broad but uneven support for the core elements of active, collaborative, cooperative and problem-based learning.

Quote: The reported results are consistently positive. Indeed, looking at high quality studies with good internal validity, the already large effect size of 0.67 shown in Table 2 for academic achievement increases to 0.88. In real terms, this would increase a student's exam score from 75 to 85 in the "classic" example cited previously, though of course this specific result is dependent on the assumed grade distribution. As seen in Table 2, cooperation also promotes interpersonal relationships, improves social support and fosters self-esteem.

Quote: In summary, there is broad empirical support for the central premise of cooperative learning, that cooperation is more effective than competition for promoting a range of positive learning outcomes. These results include enhanced academic achievement and a number of attitudinal outcomes. In addition, cooperative learning provides a natural environment in which to enhance interpersonal skills and there are rational arguments and evidence to show the effectiveness of cooperation in this regard.

Johnson, D. W., Johnson, R. T., and Smith, K. A. (1998). Cooperative Learning Returns to College: What Evidence Is There That It Works? *Change*, 30(4), 26–35

Abstract: None

Quote: Between 1924 and 1997, over 168 studies were conducted comparing the relative efficacy of cooperative, competitive, and individualistic learning on the achievement of individuals 18 years or older. These studies indicate that cooperative learning promotes higher individual achievement than do competitive approaches (effect size = 0.49) or individualistic ones (effect size = 0.53). Effect sizes of this order describe significant, substantial increases in achievement. They mean, for example, that college students who would score at the 50^{th} percentile level when learning competitively will score in the 69^{th} percentile when learning cooperatively; students who would score at the 53^{rd} percentile level when learning individualistic ally will score at the 70^{th} percentile when learning cooperatively.

Bowen, C. W. (2000). A Quantitative Literature Review of Cooperative Learning Effects on High School and College Chemistry Achievement. *Journal of Chemical Education, 77*(1), 116–119

Abstract: This paper has two purposes. First, the reader is given an overview on how quantitative literature reviews (meta-analyses) can be conducted to give overall estimates of the quantitative impact an instructional treatment has on a specific student outcome. The second purpose is to illustrate how such a literature review is carried out by examining studies on using cooperative learning to teach chemistry at the high school and college levels. This analysis extends earlier reported work on effects of cooperative learning on achievement in college-level science, mathematics, and engineering and technology (SMET) courses. The analysis shows that while median student performance in a traditional course is at the 50th percentile, the median student performance in a cooperative learning environment is 14 percentile points higher.

Felder, R. M., Felder, G. N., and Dietz, E. J. (1998). A Longitudinal Study of Engineering Student Performance and Retention. V. *Comparisons with Traditionally-Taught Students. Journal of Engineering Education, 98*(4), 469–480

Abstract: In a longitudinal study at North Carolina State University, a cohort of students took five chemical engineering courses taught by the same instructor in five consecutive semesters. The courses made extensive use of active and cooperative learning and a variety of other techniques designed to address a broad spectrum of learning styles. Previous reports on the study summarized the instructional methods used in the experimental course sequence, described the performance of the cohort in the introductory chemical engineering course, and examined performance and attitude differences between students from rural and urban backgrounds and between male and female students [1–4]. This paper compares outcomes for the experimental cohort with outcomes for students in a traditionally-taught comparison group. The experimental group outperformed the comparison group on a number of measures, including retention and graduation in chemical engineering, and many more of the graduates in this group chose to pursue advanced study in the field. Since the experimental instructional model did not require small classes (the smallest of the experimental classes had 90 students) or specially equipped classrooms, it should be adaptable to any engineering curriculum at any institution.

Terenzini, P. T., Cabrera, A. F., Colbeck, C. L., Parente, J. M., and Bjorklund, S. A. (2001). Collaborative Learning vs. Lecture/Discussion: Students' Reported Learning Gains. *Journal of Engineering Education, 90*(1), 123–130

Abstract: This study examined the extent to which undergraduate engineering courses taught using active and collaborative learning methods differ from traditional lecture and discussion courses in their ability to promote the development of students' engineering design, problem-solving, communication, and group participation skills. Evidence for the study comes from 480 students enrolled in 17 active or collaborative learning courses/sections and six traditional courses/sections at six engineering schools. Results indicate that active or collaborative methods produce both statistically significant and substantially greater gains in student learning than those associated with more traditional instructional methods. These learning advantages remained even when differences in a variety of student pre-course characteristics were controlled.

Bonsangue, M. (1994). An efficacy study of the calculus workshop model. *CBMS Issues in Collegiate Mathematics Education, 4,* Providence, RI: American Mathematical Society, 117–137

Active Learning Pedagogies

Burrowes, P. A. (2003). A Student-Centered Approach to Teaching General Biology That Really Works: Lord's Constructivist Model Put to a Test. *The American Biology Teacher, 65*(7), 491–502

Abstract: None

Quote: Exams were taken on computer sheets and graded electronically. Grades achieved by students in experimental (constructivist teaching) and control (traditional teaching) groups were contrasted graphically (Figure 7) and the mean test scores were compared statistically by students' T-tests using Minitab 12 software. The first partial exam was offered after six weeks of instruction and included content on the cell as the functional unit of life (atoms, molecules, the cell membrane, organelles, energy transformations, cellular respiration, and photosynthesis). Although average scores of students in the experimental group were significantly better than in the control group ([Mean] = 65% versus 58%; T = 2.65, P = 0.004, n = 204), and they attained more As and Bs, and fewer Fs, the differences are not as impressive as later in the semester (Figure 7). The second exam was given 12 weeks into the semester, and evaluated knowledge on the continuity of life (mitosis, meiosis, DNA structure and replication, protein synthesis, and inheritance). Results of this exam showed grade improvement in both groups (Figure 7); however, the mean score of students in the experimental group was significantly higher than that of students in the control section ([Mean] = 72% versus 67%; T = 2.41, P = 0.009, n = 192). The outcome of the third exam (evolution and origin of life) was striking because performance of students in the experimental group approximated an ideal normal distribution of grades (Figure 7). Although students' achievement in the control group improved, students in the experimental section still did significantly better ([Mean] = 74% versus 68%; T = 3.05, P = 0.001 n =190).

Quote: This study provides substantiated evidence that teaching in a constructivist, active learning environment is more effective than traditional instruction in promoting academic achievement, increasing conceptual understanding, developing higher level thinking skills, and enhancing students interest in biology. In their final course evaluations, students in the experimental section commented that they enjoyed this class much more than their traditional classes, felt they had learned more, made valuable friendships in their collaborative groups and – particularly important to me – they never fell asleep! Thus, I am convinced that constructivism works better for our generation of students, and I will never return to a traditional style of teaching. Although the constructivist method of instruction requires a greater investment of time and effort from the professor for preparation, organization, and grading, the majority of this investment is made the first semester of teaching. During subsequent semesters, effort/payback increases dramatically, as less time is required. For example, with experience, I have become more efficient at formulating questions and coming up with ideas for problems, scenarios, and case studies, which help students develop their own knowledge of the material. Additionally, help from trained teaching assistants in grading, book-keeping, and organizational tasks associated with instruction can reduce some of the workload required of the instructor.

Laws, P., Sokoloff, D., and Thornton, R. (1999). Promoting Active Learning Using the Results of Physics Education Research. UniServe Science News, 13, Retrieved 4 September 2006 from http://science.uniserve.edu.au/newsletter/vol13/sokoloff.html

Redish, E. F., Saul, J. M., and Steinberg, R. N. (1997). On the effectiveness of active-engagement microcomputer-based laboratories. *American Journal of Physics, 65*(1), 45–54

Abstract: One hour active-engagement tutorials using microcomputer-based laboratory (MEL) equipment were substituted for traditional problem-solving recitations in introductory calculus-based mechanics classes for engineering students at the University of Maryland. The results of two specific tutorials, one on the concept of instantaneous velocity and one on Newton's third law were probed by using standard multiple-choice questions and a free-response final exam question. A comparison of the results of 11 lecture classes taught by six different teachers with and without tutorials shows that the MBL tutorials resulted in a significant improvement compared to the traditional recitations when measured by carefully designed multiple-choice problems. The free-response question showed that, although the tutorial students did somewhat better in recognizing and applying the concepts, there is still room for improvement.

Cummings, K., Marx, J., Thornton, R., and Kuhl, D. (1999). Evaluating innovations in studio physics. *American Journal of Physics*, *67*(supplement 1 to no. 7), S38–S44

Abstract: In 1993, Rensselaer introduced the first Studio Physics course. Two years later, the Force Concept Inventory (FCI) was used to measure the conceptual learning gain [g] in the course. This was found to be a disappointing 0.22, indicating that Studio Physics was no more effective at teaching basic Newtonian concepts than a traditional course. Our study verified that result, [g(FCI,98)] = 0.18+/-0.12(s.d.), and thereby provides a baseline measurement of conceptual learning gains in Studio Physics I for engineers. These low gains are especially disturbing because the studio classroom appears to be interactive and instructors strive to incorporate modern pedagogies. The goal of our investigation was to determine if incorporation of research-based activities into Studio Physics would have a significant effect on conceptual learning gains. To measure gains, we utilized the Force Concept Inventory and the Force and Motion Conceptual Evaluation (FMCE). In the process of pursuing this goal, we verified the effectiveness of Interactive Lecture Demonstrations [[g(FCI)] =0.35+/-0.06(s.d.) and [g(FMCE)] = 0.45+/-0.03 (s.d.)] and Cooperative Group Problem Solving ([g(FCI)] = 0.36 and [g(FMCE)] = 0.36), and examined the feasibility of using these techniques in the studio classroom. Further, we have assessed conceptual learning in the standard Studio Physics course [[g(FCI,98)] = 0.18+/-0.12(s.d.) and [g(FMCE,98)] = 0.21+/-0.05 (s.d.)]. In this paper, we will clarify the issues noted above. We will also discuss difficulties in implementing these techniques for first time users and implications for the future directions of the Studio Physics courses at Rensselaer.

Hoellwarth, C., Moelter, M. J., and Knight, R. D. (2005). A direct comparison of conceptual learning and problem solving ability in traditional and studio style classrooms. *American Journal of Physics*, *73*(5), 459–462

Abstract: We present data on student performance on conceptual understanding and on quantitative problem-solving ability in introductory mechanics in both studio and traditional classroom modes. The conceptual measures used were the Force Concept Inventory and the Force and Motion Conceptual Evaluation. Quantitative problem-solving ability was measured with standard questions on the final exam. Our data compare three different quarters over the course of 2 years. In all three quarters, the normalized learning gain in conceptual understanding was significantly larger for students in the studio sections. At the same time, students in the studio sections performed the same or slightly worse on quantitative final exam problems.

Beichner, R. J., Saul, J. M., Abbott, D. S., Morse, J. J., Deardorff, D. L., Allain, R. J., Bonham, J. W., Dancy, M. H., and Risley, J. S. (2007). The Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP) Project. Retrieved August 27, 2007, from http://www.compadre.org/Repository/document/ServeFile.cfm?ID=4517&DocID=183

Abstract: The primary goal of the SCALE-UP Project is to establish a highly collaborative, hands-on, computer-rich, interactive learning environment for large, introductory college courses. North Carolina State University and a group of more than two-dozen collaborating schools are folding together lecture and lab with multiple instructors in a way that provides an effective, economical alternative to traditional lecture-oriented instruction. The project involves the development of the pedagogy, classroom environment, and teaching materials that will support this type of learning. It includes the development, evaluation, and dissemination of new curricular materials in physics, chemistry, and biology. Here we will focus on the calculus-based introductory physics part of the effort. In comparisons to traditional instruction we have seen significantly increased conceptual understanding, improved attitudes, successful problem solving, and higher success rates, particularly for females and minorities. This chapter highlights the development of the SCALE-UP pedagogy, classroom environment, and teaching materials for calculus-based introductory physics at North Carolina State University.

Summary: SCALE-UP pedagogy is characterized by the following common elements: (i) cooperative learning ("classroom renovated to emphasize group work with 2-3 groups of 3-4 students each per table"), (ii) active learning ("the majority of class time is spent on learning physics through activities done by groups of 3-4 students each", "the activities tend to be short (5-20 minutes) and followed by a class discussion"), (iii) research-based ("activities are based-on or at least informed by [physics education research] (PER)" (iv) classrooms that integrate "lecture and group work including experiments" with the following features: students work in groups of 2–4 students, access to computers and internet, access to equipment to perform experiments, facilitate class discussions, and share work among peers.

Quote: The SCALE-UP class demonstrated better improvement in conceptual understanding than Lecture/Laboratory classes by achieving higher normalized gains for the Mechanics semester pre/post force and motion concept tests at Coastal Carolina University (CCU), North Carolina State University (NCSU), University of Central Florida (UCF), University of New Hampshire (UNH), and Rochester Institute of Technology (RIT).

Quote: They report a 2-3x improvement in normalized gain on pre/post conceptual learning assessments such as the Force Concept Inventory, the Force and Motion Conceptual Evaluation, Conceptual Survey of Electricity and Magnetism, and the Electric Circuit Conceptual Evaluation [see Figures 5 and 6].

Quote: Failure rates are drastically reduced (typically 50%), especially for women and minorities [see Figure 7 and Table 6]

Michael, J. (2006). Where's the evidence that active learning works? *Advances in Physiology Education*, *30*, 159–167

Abstract: Calls for reforms in the ways we teach science at all levels, and in all disciplines, are wide spread. The effectiveness of the changes being called for, employment of student-centered, active learning pedagogy, is now well supported by evidence. The relevant data have come from a number of different disciplines that include the learning sciences, cognitive

psychology, and educational psychology. There is a growing body of research within specific scientific teaching communities that supports and validates the new approaches to teaching that have been adopted. These data are reviewed, and their applicability to physiology education is discussed. Some of the inherent limitations of research about teaching and learning are also discussed.

Knight, J. K., and Wood, W. B. (2005). Teaching More by Lecturing Less. *Cell Biology Education, 4,* 298–310.

Abstract: We carried out an experiment to determine whether student learning gains in a large, traditionally taught, upper-division lecture course in developmental biology could be increased by partially changing to a more interactive classroom format. In two successive semesters, we presented the same course syllabus using different teaching styles: in fall 2003, the traditional lecture format; and in spring 2004, decreased lecturing and addition of student participation and cooperative problem solving during class time, including frequent in-class assessment of understanding. We used performance on pretests and posttests, and on homework problems to estimate and compare student learning gains between the two semesters. Our results indicated significantly higher learning gains and better conceptual understanding in the more interactive course. To assess reproducibility of these effects, we repeated the interactive course in spring 2005 with similar results. Our findings parallel results of similar teaching-style comparisons made in other disciplines. On the basis of this evidence, we propose a general model for teaching large biology courses that incorporates interactive engagement and cooperative work in place of some lecturing, while retaining course content by demanding greater student responsibility for learning outside of class.

Quote: The most compelling support for superiority of the interactive approach came from comparisons of normalized learning gains calculated from pretest and posttest scores in the traditional and interactive classes (Table 4). Normalized learning gain is defined as the actual gain divided by the possible gain, expressed as a percentage [100 × (posttest - pretest)/(100 - pretest); (Fagan et al., 2002)]. Normalization allows valid comparison and averaging of learning gains for students with different pretest scores. A comparison of the F’03 and S’04 courses showed a significant 16% difference (p = .001) in average learning gains, corresponding to a 33% improvement in performance by students in the more interactive S’04 course. Learning gains of greater than 60% were achieved by substantially more students in the interactive class (43/70) than in the traditional class (19/72) (Figures 2, 3). Both ‘‘A’’ and ‘‘B’’ students made higher gains in the interactive course, while ‘‘C’’ students achieved about the same learning gain range in both semesters (Figure 2).

Freeman, S., O’Connor, E., Parks, J. W., Cunningham, M., Hurley, D., Haak, D., Dirks, C., and Wenderoth, M. P., (2007). Prescribed Active Learning Increases Performance in Introductory Biology. *Cell Biology Education, 6,* 132–139.

Abstract: We tested five course designs that varied in the structure of daily and weekly active-learning exercises in an attempt to lower the traditionally high failure rate in a gateway course for biology majors. Students were given daily multiple-choice questions and answered with electronic response devices (clickers) or cards. Card responses were ungraded; clicker responses were graded for right/wrong answers or participation. Weekly practice exams were done as an individual or as part of a study group. Compared with previous versions of the same course taught by the same instructor, students in the new course designs performed better: There were significantly lower failure rates, higher total exam points, and higher scores on an identical midterm. Attendance was higher in the clicker versus cards section; attendance and course grade were positively correlated. Students did better on clicker questions if they were graded for right/wrong answers versus participation, although this improvement did not translate into increased scores on exams. In this course, achievement increases when students get regular practice via prescribed (graded) active-learning exercises.

Problem-based Learning Pedagogies

Prince, M. J., and Felder, R. M. (2006). Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases. *Journal of Engineering Education, 95*(2), 123–138.

Abstract: Traditional engineering instruction is deductive, beginning with theories and progressing to the applications of those theories. Alternative teaching approaches are more inductive. Topics are introduced by presenting specific observations, case studies or problems, and theories are taught or the students are helped to discover them only after the need to know them has been established. This study reviews several of the most commonly used inductive teaching methods, including inquiry learning, problem-based learning, project-based learning, case-based teaching, discovery learning, and just-in-time teaching. The paper defines each method, highlights commonalities and specific differences, and reviews research on the effectiveness of the methods. While the strength of the evidence varies from one method to another, inductive methods are consistently found to be at least equal to, and in general more effective than, traditional deductive methods for achieving a broad range of learning outcomes.

Quote: Individual studies have found a robust positive effect of PBL [problem-based learning] on skill development [1, 65, 66], understanding the interconnections among concepts [65], deep conceptual understanding [67], ability to apply appropriate metacognitive and reasoning strategies [68], teamwork skills [69], and even class attendance [70], but have not reached any firm conclusion about the effect on content knowledge. A longitudinal study of the effectiveness of the McMaster PBL program in chemical engineering demonstrated its superiority to traditional education in the development of key process skills [55]. PBL has also been shown to promote self-directed learning [71] and the adoption of a deep (meaning-oriented) approach to learning, as opposed to a superficial (memorization-based) approach [21, 46, 72].

Prince, M., and Felder, R. (2007). The Many Faces of Inductive Teaching and Learning. *Journal of College Science Teaching, 36*(5), 14–20

Tag: This study examines the effectiveness and implementation of different inductive teaching methods, including inquiry-based learning, problem-based learning, project-based learning, case-based teaching, discovery learning, and just-in-time teaching.

Dochy, F., Segers M., Van den Bossche, P., and Gijbels, D. (2003). Effects of Problem-Based Learning: A Meta-Analysis. *Learning and Instruction, 13*, 533–568

Abstract: This meta-analysis has two aims: (a) to address the main effects of problem based learning on two categories of outcomes: knowledge and skills; and (b) to address potential moderators of the effect of problem based learning. We selected 43 articles that met the criteria for inclusion: empirical studies on problem based learning in tertiary education conducted in real-life classrooms. The review reveals that there is a robust positive effect from PBL on the skills of students. This is shown by the vote count, as well as by the combined effect size. Also no single study reported negative effects. A tendency to negative results is discerned when considering the effect of PBL on the knowledge of students. The combined effect size is significantly negative. However, this result is strongly influenced by two studies and the vote count does not reach a significant level. It is concluded that the combined effect size for the effect on knowledge is non-robust. As possible moderators of PBL effects, methodological factors, expertise-level of students, retention period and type of assessment method were investigated. This moderator analysis shows that both for knowledge- and skills-related outcomes the expertise-level of the student is associated with the variation in effect sizes. Nevertheless, the results for skills give a consistent positive picture. For knowledge-related outcomes the results suggest that the differences encountered in the first and the second year disappear later on. A last remarkable finding related to the retention period is that students in PBL gained slightly less knowledge, but remember more of the acquired knowledge.

Quote: For skill development, the results are unequivocal: 14 studies found a positive effect and none found a negative effect, and the weighted average effect size was 0.460(±0.058).

Quote: For knowledge acquisition, seven of the studies analyzed found a positive effect and 15 found a negative effect, with weighted average effect size and 95 percent confidence interval -0.223 (±0.058). When the assessment of knowledge is carried out some time after the instruction was given, the effect of PBL positive.

Gijbels, D., Dochy, F., Van den Bossche, P., and Segers, M. (2005). Effects of Problem-Based Learning: A Meta-Analysis from the Angle of Assessment. *Review of Educational Research, 75*(1), 27–61

Abstract: This meta-analysis investigated the influence of assessment on the reported effects of problem-based learning (PBL) by applying Sugrue's (1995) model of cognitive components of problem solving. Three levels of the knowledge structure that can be targeted by assessment of problem solving are used as the main independent variables: (a) understanding of concepts, (b) understanding of the principles that link concepts, and (c) linking of concepts and principles to conditions and procedures for application. PBL had the most positive effects when the focal constructs being assessed were at the level of understanding principles that link concepts. The results suggest that the implications of assessment must be considered in examining the effects of problem-based learning and probably in all comparative education research.

Quote: Three levels of the knowledge structure in assessment of problem solving: (a) understanding of concepts; (b) understanding of the principles that link concepts; (c) linking of concepts and principles to conditions and procedures for application. PBL had the most positive effects when the focal constructs being assessed were at the level of understanding principles that link concepts.

Vernon, D. T. A., and Blake, R. L. (1993). Does Problem-Based Learning Work? A Meta-Analysis of Evaluative Research. *Academic Medicine*, *68*, 550–563.

Abstract: The purpose of this review is to synthesize all available evaluative research from 1970 through 1992 that compares problem-based learning (PBL) with more traditional methods of medical education. Five separate meta-analyses were performed on 35 studies representing 19 institutions. For 22 of the studies (representing 14 institutions), both effect-size and supplementary vote-count analyses could be performed; otherwise, only supplementary analyses were performed. PBL was found to be significantly superior with respect to students' program evaluations (i.e., students' attitudes and opinions about their programs)--dw (standardized differences between means, weighted by sample size) = +.55, CI.95 = +.40 to +.70 - and measures of students' clinical performance (dw = +.28, CI.95 = +.16 to +.40). PBL and traditional methods did not differ on miscellaneous tests of factual knowledge (dw = -.09, CI.95 = +.06 to -.24) and tests of clinical knowledge (dw = +.08, CI.95 = -.05 to +.21). Traditional students performed significantly better than their PBL counterparts on the National Board of Medical Examiners Part I examination--NBME I (dw = -.18, CI.95 = -.10 to -.26). However, the NBME I data displayed significant overall heterogeneity (Qt = 192.23, p < .001) and significant differences among programs (Qb = 59.09, p < .001), which casts doubt on the generality of the findings across programs. The comparative value of PBL is also supported by data on outcomes that have been studied less frequently, i.e., faculty attitudes, student mood, class attendance, academic process variables, and measures of humanism. In conclusion, the results generally support the superiority of the PBL approach over more traditional methods.

Capon, N., and Kuhn, D. (2004). What's So Good About Problem-Based Learning? *Cognition and Instruction*, *22*(1), 61–79

Abstract: In a systematically designed and controlled experiment conducted in a naturalistic instructional setting, we examined adult students' learning of two concepts. Two intact classes taught by the same instructor were assigned to 1 of 2 conditions. In 1 class, instruction was problem based for 1 concept. For a second concept, lecture/discussion was the exclusive method. In the other class, matching of concept and method (problem based or lecture/discussion) was reversed. Two forms of assessment of learning occurred 6 and 12 weeks following instruction. At the initial assessment, the lecture/discussion group showed superior learning for 1 concept and the groups performed equivalently for the other concept. At the later assessment, however, the 2 groups showed equivalent ability to access each of the concepts, but each group showed superior explanation of the concept for which they had experienced problem-based learning. Results support the hypothesis of integration of new information with existing knowledge structures activated by the problem-based experience as the mechanism by which problem-based learning produces its benefits.

Inquiry-based Learning Pedagogies

Prince, M. J., and Felder, R. M. (2006). Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases. *Journal of Engineering Education*, *95*(2), 123–138.

Abstract: Traditional engineering instruction is deductive, beginning with theories and progressing to the applications of those theories. Alternative teaching approaches are more inductive. Topics are introduced by presenting specific observations, case studies or problems, and theories are taught or the students are helped to discover them only after the need to know them has been established. This study reviews several of the most commonly used inductive teaching methods, including inquiry learning, problem-based learning, project-based learning, case-based teaching, discovery learning, and just-in-time teaching. The paper defines each method, highlights commonalities and specific differences, and reviews research on the effectiveness of the methods. While the strength of the evidence varies from one method to another, inductive methods are consistently found to be at least equal to, and in general more effective than, traditional deductive methods for achieving a broad range of learning outcomes.

Farrell, J. J., Moog, R. S., and Spencer, J. N. (1999). A Guided Inquiry General Chemistry Course. *Journal of Chemical Education*, *74*(4), 570–574

Abstract: A first-year general chemistry course based on constructivist principles and the learning cycle has been developed. Through the use of cooperative learning techniques, students are active participants in the learning process. No lectures are given; students follow guided inquiry worksheets to develop and understand the course concepts. Groups of about four students are formed and the instructor moves among the groups, serving as a facilitator. The laboratory is designed in the same way as the classroom component of the course. The students form hypotheses and collect data, leading to further refinement of the hypotheses and to formation of chemical concepts.

Quote: the sections taught according to the principles of guided inquiry have experienced a decrease in the W, D, F rate from 21.9% (420 students, Fall 1990–Spring 1994) to 9.6% (438 students, Fall 1994–Fall 1997).3 In the Guided Inquiry (GI) sections, the withdrawal rate is 2.3% and only 1 out of 438 students has received a grade of F in these sections. In contrast, students taught by these same instructors previously had a W rate of 9.3% and 3.6% failed. Final exams given to the GI students that were substantially similar to exams given in the past showed that GI students scored as high as or higher than students who had taken a more traditional course from the same instructor.

Lewis, S. E., and Lewis, J. E. (2005). Departing from Lectures: An Evaluation of a Peer-Led Guided Inquiry Alternative. *Journal of Chemical Education*, *82*(1), 135–139

Abstract: To improve a large-enrollment general chemistry course based on conventional lectures, we instituted a reform combining peer-led team learning with a guided inquiry approach, together called peer-led guided inquiry (PLGI). For one group of first-semester general chemistry students, a PLGI session was combined with two lectures per week, and this group was compared to a control group that had the usual three lectures per week. Students were compared based on performance on identical course exams and on a final exam from the ACS Examinations Institute given at the end of the semester. The experimental group was found to perform better than the control group overall, in spite of experiencing one fewer lecture each week. Also, attendance at the PLGI sessions was found to have a significant positive impact on student performance, even when controlling for students' SAT mathematics and verbal scores. This method of evaluating reform effects for institutions with several large sections of introductory chemistry courses is recommended.

Quote: the experimental group consistently outperformed the control group on the course exams and on the final exam

Quote: The results from this analysis indicate that a student who attends PLGI [peer-led guided inquiry] sessions can be expected to perform better on exams than another student at the same SAT level.

Other results for the Process Oriented Guided Inquiry Learning (POGIL) project are available at http://www.pogil.org/effectiveness/.

Challenge-based Learning Pedagogies

Roselli, R. J., and Brophy, S. P. (2006). Effectiveness of Challenge-Based Instruction in Biomechanics. *Journal of Engineering Education, 95*(4), 311–324.

Abstract: Studies were designed to determine the effectiveness of challenge-based instruction (CBI) versus traditional lecture-based instruction. Comparisons were made over a three-year period between student performance on knowledge-based questions in courses taught with taxonomy-based and challenge-based approaches to instruction. When performance on all questions was compared, CBI classes scored significantly better than control classes on 26 percent of the questions, while control classes outperformed CBI classes on eight percent of the questions, but there was no significant difference in overall performance. However, students in CBI classes performed significantly better than students in control classes on the more difficult questions (35 percent versus four percent). We attribute these differences to additional opportunities available in CBI classrooms for learners to examine their conceptual understanding. Student surveys indicate a slight preference for the challenge-based approach. We believe that the challenge-based approach is effective and has the potential to better prepare students for the workplace and for life-long learning.

Peer-Led Team Learning Pedagogies

Tien, L. T., Roth, V., and Kampmeier, J. A. (2001). Implementation of a Peer-Led Team Learning Instructional Approach in an Undergraduate Organic Chemistry Course. *Journal of Research in Science Teaching, 39*(7), 606–632

Abstract: This study focuses on the implementation of a peer-led team learning (PLTL) instructional approach for all students in an undergraduate organic chemistry course and the evaluation of student outcomes over 8 years. Students who experienced the student-centered instruction and worked in small groups facilitated by a peer leader (treatment) in 1996–1999 were compared with students who experienced the traditional recitation section (control) in 1992–1994. Quantitative and qualitative data show statistically significant improvements in student performance, retention, and attitudes about the course. These findings suggest that using

undergraduate leaders to implement a peer-led team learning model that is built on a social constructivist foundation is a workable mechanism for effecting change in undergraduate science courses.

McCreary, C. L., Golde, M. F., and Koeske, R. (2006). Peer Instruction in the General Chemistry Laboratory: Assessment of Student Learning. *Journal of Chemical Education, 83*(5), 804–810

Abstract: We report the first systematic comparison of conventional and workshop labs. A natural experiment proved possible because students sign up for labs without knowing the type of instruction they will receive. A reliable grading system was developed to characterize students' written responses to the final lab exam, and an independent rater used it to assess student learning. Assessments of learning were made without knowledge of students' instructional condition. Compared to students in conventional sections, students in workshop sections showed superior learning and critical thinking skills, and gave answers that were longer and of greater clarity. Possible reasons for these improvements are discussed.

Quote: In fact, for nearly every measure of performance quality and written communication included in the study, participation in the Workshop labs tended to enhance students' learning relative to that indicated by test performance for students in the conventionally taught labs, with the differences often reaching statistical significance.

Other results from the Peer-Led Team Learning Workshop Project are available at http://www.sci.ccny.cuny.edu/~chemwksp/ResearchAndEvaluationComparisons.html

Workshop Groups

Born, W. K., Revelle, W., and Pinto, L. H. (2002). Improving Biology Performance with Workshop Groups. *Journal of Science Education and Technology, 11*(4), 347– 365

Abstract: This 2-year quasi-experiment evaluated the effect of peer-led workshop groups on performance of minority and majority undergraduate biology students. The workshop intervention used was modeled after a program pioneered by Treisman (1992). Majority volunteers randomly assigned to workshops ($n = 61$) performed significantly better than those assigned to the control group ($n = 60$, $p < 0.05$) without spending more time studying. Workshop minority students ($n = 25$) showed a pattern of increasing exam performance in comparison to historic control minority students ($n = 21$), who showed a decreasing pattern ($p < 0:05$). Volunteers ($n = 121$) initially reported that biology was more interesting and more important to their futures than to nonvolunteers' ($n = 435$, $p < 0.05$). Volunteers also reported higher levels of anxiety related to class performance ($p < 0.05$). The relationship of anxiety to performance was moderated by volunteer status. Performance of volunteers was negatively associated with self-reported anxiety ($r = –0.41$, $p < 0.01$). Performance of nonvolunteers was unrelated to self-reported anxiety ($r = –0.02$). Results suggest elevated anxiety related to class performance may increase willingness to participate in activities such as workshop interventions. In addition, students who volunteer for interventions such as workshops may be at increased risk of performance decrements associated with anxiety. Even so, workshop programs appear to be an effective way to promote excellence among both majority and minority students who volunteer to participate, despite the increased risk of underperformance associated with higher levels of anxiety

Undergraduate Research Experiences

Seymour, E., Hunter, A.-B., Laursen, S. L., and Diatonic, T. (2004). Establishing the Benefits of Research Experiences for Undergraduates in the Sciences: First Findings from a Three-Year Study. *Science Education, 88*, 493–534

Abstract: Descriptions of student-identified benefits of undergraduate research experiences are drawn from analysis of 76 first-round student interviews gathered at the end of summer 2000 at four participating liberal arts colleges (Grinnell, Harvey Mudd, Hope, and Wellesley). As part of the interview protocol, students commented on a checklist of possible benefits derived from the literature. They also added gains that were not on this list. Students were overwhelmingly positive: 91% of all statements referenced gains from their experiences. Few negative, ambivalent, or qualified assessments of their research experiences were offered. The benefits described were of seven different kinds. Expressed as percentages of all reported gains, they were personal/professional gains (28%); “thinking and working like a scientist” (28%); gains in various skills (19%); clarification/confirmation of career plans (including graduate school) (12%); enhanced career/graduate school preparation (9%); shifts in attitudes to learning and working as a researcher (4%); and other benefits (1%).

Lopatto, D. (2004). Survey of Undergraduate Research Experiences (SURE): First Findings. *Cell Biology Education*, *3*, 270–277.

Abstract: In this study, I examined the hypothesis that undergraduate research enhances the educational experience of science undergraduates, attracts and retains talented students to careers in science, and acts as a pathway for minority students into science careers. Undergraduates from 41 institutions participated in an online survey on the benefits of undergraduate research experiences. Participants indicated gains on 20 potential benefits and reported on career plans. Over 83% of 1,135 participants began or continued to plan for postgraduate education in the sciences. A group of 51 students who discontinued their plans for postgraduate science education reported significantly lower gains than continuing students. Women and men reported similar levels of benefits and similar patterns of career plans. Ethnic groups did not significantly differ in reported levels of benefits or plans to continue with postgraduate education.

Hunter, A.-B., Laursen, S. L., and Seymour, E. (2007). Becoming a Scientist: The Role of Undergraduate Research in Students’ Cognitive, Personal, and Professional Development. *Science Education, 91*, 36–74

Abstract: In this ethnographic study of summer undergraduate research (UR) experiences at four liberal arts colleges, where faculty and students work collaboratively on a project of mutual interest in an apprenticeship of authentic science research work, analysis of the accounts of faculty and student participants yields comparative insights into the structural elements of this form of UR program and its benefits for students. Comparison of the perspectives of faculty and their students revealed considerable agreement on the nature, range, and extent of students’ UR gains. Specific student gains relating to the process of “becoming a scientist" were described and illustrated by both groups. Faculty framed these gains as part of professional socialization into the sciences. In contrast, students emphasized their personal and intellectual development, with little awareness of their socialization into professional practice. Viewing study findings through the lens of social constructivist learning theories demonstrates that the characteristics of these UR programs, how faculty practice UR in these colleges, and students' outcomes—including cognitive and personal growth and the development of a professional identity—strongly exemplify many facets of these theories, particularly, student-centered and situated learning as part of cognitive apprenticeship in a community of practice.

Russell, S. H., Hancock, M. P., and McCullough, J. (2007). Benefits of Undergraduate Research Experiences. *Science, 316*, 548–549

Quote: "We found that UROs [undergraduate research opportunities] increase understanding, confidence, and awareness (5–8). Most (88%) of the respondents to the NSF follow-up survey reported that their understanding of how to conduct a research project increased a fair amount or a great deal, 83% said their confidence in their research skills increased, and 73% said their awareness of what graduate school is like increased.

Lack of Growth in Valued Learning Outcomes in Traditional Curricula

Litzinger, T., Wise, J., Lee, S., Bjorklund, S. (2003). Assessing Readiness for Self-directed Learning, *Proceedings, ASEE Annual Conference & Exposition*, Retrieved from http://www.asee.org/acPapers/2003-1429_Final.pdf, 2 July 2003

Abstract: None

Quote: Figure 1 presents the average SDLRS scores for the five groups of students in the study, who were grouped by semester standing according to academic year from first year (1&2) to "supersenior" year (9&10). The average scores range from 217 to 228, corresponding to percentile ranks, based on SDLRS results for adults, of 50% and 68%, respectively. Although the data suggest a slight upward trend, the trend proved not to be statistically significant based upon an analysis of variance (ANOVA). Thus the cross-sectional study did not find evidence of an increase in readiness for self-directed learning, even for students in the later semesters who are taking elective courses and their capstone courses.

Woods, D. et al. (1997). Developing Problem Solving Skills: The McMaster Problem Solving Program. *Journal of Engineering Education, 86*(2), 75–92

Abstract: This paper describes a 25-year project in which we defined problem solving, identified effective methods for developing students' skill in problem solving, implemented a series of four required courses to develop the skill, and evaluated the effectiveness of the program. Four research projects are summarized in which we identified which teaching methods failed to develop problem solving skill and which methods were successful in developing the skills. We found that students need both comprehension of Chemical Engineering and what we call general problem solving skill to solve problems successfully. We identified 37 general problem solving skills. We use 120 hours of workshops spread over four required courses to develop the skills. Each skill is built (using content-independent activities), bridged (to apply the skill in the content-specific domain of Chemical Engineering) and extended (to use the skill in other contexts and contents and in everyday life). The tests and examinations of process skills, TEPS, that assess the degree to which the students can apply the skills are described. We illustrate how self-assessment was used.

Quote: During the four-year undergraduate engineering program studied, 1974-1978, the students had worked over 3000 homework problems, they had observed about 1000 sample solutions being worked on the board by either the teacher or by peers, and they had worked many open-ended problems.36 In other words, they showed no improvement in problem solving skills despite the best intentions of their instructors. Caillot[37] and Meiring[26] confirm these findings.

Fowler, D., Maxwell, D., and Froyd, J. (2003). Learning Strategy Growth Not What Expected After Two Years through Engineering Curriculum. *Proceedings*, *ASEE Annual Conference & Exposition*, Retrieved from http://www.asee.org/acPapers/2003-534_Final.pdf, 2 July 2003

Abstract: As the pace of technological development continues to increase, consensus has emerged that undergraduate science, technology, engineering and mathematics (STEM) curricula cannot contain all of the topics that engineering professionals will require, even during the first ten years of their careers. Therefore, the need for students to increase their capability for lifelong learning is receiving greater attention. It is anticipated that development of this capability occurs during the undergraduate curricula. However, preliminary data from both first-year and junior engineering majors may indicate that development of these competencies may not be as large as desired. Data was obtained using the Learning and Study Skills Inventory (LASSI), an instrument whose reliability has been demonstrated during the past fifteen years. The LASSI is a ten-scale, eighty-item assessment of students' awareness about and use of learning and study strategies related to skill, will and self-regulation components of strategic learning. Students at Texas A&M University in both a first-year engineering course and a junior level civil engineering course took the LASSI at the beginning of the academic year. Improvements would normally be expected after two years in a challenging engineering curriculum. However, data on several different scales appears to indicate that improvements are smaller than might be expected.