Computer-based Adaptive Testing for Assessing Problem-Solving Skills

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Introduction

Problem-solving is one of the skills that engineering programs strive to instill in their graduates. In typical engineering programs, students are expected to gain this skill by observing instructors solving example problems and by practicing with homework assignments that are similar to example problems. These problems can be elementary problems, complex problems, or open-ended problems. Since complex problems and open-ended problems can be solved by breaking them down to a series of elementary problems, it is essential that students master the basic skills required for solving elementary problems.

In recent times, employers, professional organizations, and accreditation agencies have been expressing concern about the poor problem-solving skills of engineering graduates [1-4]. The national performance of engineering graduates in the Fundamental of Engineering (FE) exam conducted by the National Council of Examiners for Engineers and Surveyors (NCEES) affirms this concern. Figure 1, for example, shows a statistically significant declining trend in the percentage of questions answered correctly by civil engineering graduates in the FE exam. Considering that the problems in the FE Exam are elementary problems and that it is a summative evaluation of engineering education and is a prerequisite for professional licensure, such poor performance is alarming. This paper presents a computer-based system that has the potential to improve and assess problem-solving skills of engineering students.

Literature Review

The importance of conceptual knowledge as one of the prerequisites for expert-like problem-solving has been recognized in several studies [5-11]. Dufresne et al [9, 11] have proposed a model for problem solving, identifying three key knowledges: i) concept knowledge, ii) operational/procedural knowledge, and iii) problem-state knowledge. According to this model, the conceptual knowledge of an expert is richly clustered and hierarchically arranged with strong bi-directional links with the other two knowledges. In contrast, the novice's conceptual knowledge is poorly clustered and chronologically arranged, with weak, unidirectional, and inappropriate links with the other two knowledges.

Clough and Kauffman [12] have recommended that students should be given opportunities to make repetitive "connections" between concepts in different contexts and applications, to achieve deeper and long lasting understanding that can enhance problem-solving skills. By challenging the students, starting with single-concept problems and gradually progressing to multi-concept problems, and by making repetitive connections between the different concepts, students are able to apply concepts learned in different places and times to solve problems in new contexts. This can be achieved by solving a problem first and then adding “surface” modifications and extensions to it to explore students’ understanding of the underlying concepts.

Following the above recommendations, we have developed a computerized problem-based tutorial to help students cultivate expert-like problem solving skills. This tutorial challenges the students with problems that require application of gradually increasing number of different concepts to arrive at the solution. The tutorial includes graduated hints and complete solutions that enable the students to work on their own. In contrast to the traditional single-concept, end-of-the-chapter “exercise” problems often found in textbooks, these multi-concept problems encompass not only concepts from all the chapters completed to that point in a course, but also concepts from related courses completed by the students up to that point.

Example of computer-based approach

As an example, we present the computerized problem-based tutorial developed by us for use in one of our hydraulic engineering courses. This course is the second one in a two-course sequence, required of all civil engineering students. The first course covers hydrostatics (hydraulic properties, pressure, forces, buoyancy) and non-viscous fluid flow in pipes (continuity equation, energy equation) etc; the second one covers dimensional analysis, similitude, viscous fluid flow, hydraulic machines, flow over immersed bodies, and open channel flow. We have conducted formative and summative evaluations of our system over the past four years. Based on student feedback on this approach as well as on their performance, we have modified and refined the program over three semesters as detailed here.

When this system was implemented the first time, each assignment had three problems, and the students were given one chance to try each assignment. Mid-semester student evaluations during this period were highly critical of the system. Many of them were nervous to attempt the computer-based assignments, and felt that the scoring was harsh. While the average students found the problems to be quite different from the textbook examples and too difficult to solve, the top students were able to complete the assignments without much difficulty.

Based on student feedback, the program was extensively modified. The tutorial now includes a complete set of assignments for the semester, along with review notes and worked examples; and modules for log in, response analysis, feedback, scoring, performance tracking, and recording. In addition, each problem also has graduated “Hints”, that students can ask for, if necessary.

Each Assignment includes a review of 4 new concepts (C1 to C4) followed by a Concept Quiz and 5 Problems (P1 to P5). Each of the 5 problems has five “surface variations” (V1 to V5) where the problem statement, the numerical data, the required result, and the correct response choice are changed dynamically for each session. The first problem (P1) requires application of two of the four concepts (C1 and C2) and the second problem (P2) requires application of the other two concepts (C3 and C4). The third problem (P3) requires application of all the four concepts (C1 to C4) and the fourth (P4) and fifth (P5) problems require application of all four concepts covered in this assignment as well as concepts learned previously in this course, the first course, as well as other prerequisite courses (e.g. statics). All the problems are multiple-choice type with four choices (A, B, C, and D) each. Students have the option of asking for “Hints” before making a selection, but will lose 20% of the points for that problem for doing so.

Once a selection is made, immediate response is provided, and if necessary, students can view the complete solution.

In any assignment, all the students are first offered Problem P3. Depending on their performance in this problem they will be directed to either Problem P1 or P4. If they solve Problem P3 correctly without requesting Hints, they are given 100 points for it and are offered Problem P4. If they solved Problem P4 also correctly without requesting Hints, they get 100 points and continue with problem P5. On successful completion of problem P5 without the use of Hints, they receive an average score of 100 for that Assignment. If they solved P3 incorrectly without requesting Hints, the solution is presented, and they are allowed to try another version of P3 again after reviewing the on-line notes. Alternatively, if they requested Hints for Problem P3 and solved it correctly, they are given 80 points for Problem P3 and are then offered Problem P4. If students failed to solve Problem P3 correctly after reviewing the Hints, the solution is presented and they are directed to the appropriate section in the on-line review notes. From there, they are directed to Problem P1 and sequentially to the next four Problems. On completion of an assignment, if the student is not satisfied with the average for that Assignment, the student can redo that Assignment following the above cycle until the student is satisfied with the score. An outline of the program flow is shown in Figure 2.

Students are now allowed unlimited number of attempts for each assignment within a week, but each assignment has to be attempted at least twice, even if a perfect score of 100 points is received in the first attempt. The average score of the top two attempts is taken as the score for that assignment. This motivated the students to return to the program as often as they wished, so that they could achieve the highest scores that they were satisfied with. Because of the dynamic variation of the problems, and the randomly picked versions (V1 to V5) of each problem (P1 to P5), all the students had repetitive opportunities to try “different” problems each time they attempted an assignment.

The program keeps track of the progress of each student through an assignment. Information such as time spent, number of attempts, number of problems answered in the first attempt, frequency of failure to solve a problem, etc. This information has enabled the instructor to identify students who were having chronic difficulties as well as topics that were not well understood by majority of the students. Using such information, the instructor was able to improve teaching and learning.

RESULTS

Student Evaluations: Based on end-of-semester student surveys conducted by an external evaluation team, the students now appreciate the benefits of this system as summarized in Figure 3. The records show that the revised system is appealing to a wide range of students and promoted voluntary participation; several students returned to theses assignments voluntarily even after they scored perfect scores in the two attempts that were required. Figure 4 shows that over 90% of the students made one or more voluntary attempts over and above the minimum number of attempts even after achieving perfect scores, and more than 15% of them made over 3 voluntary attempts.

Performance in "Test Problems": We have used "Test Problems" to assess students' improvement in solving multi-concept-problems and to evaluate the validity of the computerized tutorial in assessing problem-solving skills. Each semester, we have used two Test Problems in the final exam; one of these problems (Test Problem TP-A) integrates several concepts discussed individually and in limited combinations throughout the semester in similar applications; the other problem (Test Problem TP-B) also involves several of the concepts discussed during the semester but, applied to a completely new application that the students had never seen before. The final exam is a traditional paper and pencil test, where a standard grading procedure has been used to grade these test problems over the semesters.

The Test Problem TP-A remained essentially the same over the semesters, but with surface modifications. Figure 5 shows this problem where, the properties of the fluid flowing in the pipe, and those of the manometric fluid and the sphere are given; it is required to calculate the diameter of the particle that can be supported as shown for a given manometric reading. The problem requires application of several concepts such as density-specific gravity-specific weight relationships; elevation-pressure relationships in manometers; continuity equation, Bernoulli equation, buoyancy, drag etc, some of which had been discussed in the first course.

During the course of the semester, the students had opportunities to tackle elementary problems incorporating the above concepts as well as some of the features of TP-A. Examples of such simple problems are presented in Figure 6. Even though all the students had been exposed to such problems, their performance in the Test Problem TP-A had been rather unsatisfactory in the past. Several students found TP-A very challenging and could not solve it in a logical and efficient manner. Since implementing the computer-based testing/tutoring system, we have noticed significant improvement in student performance in this problem. The score distribution in TP-A in the two semesters before implementing the computer-based system (71 students) is compared against that in the four semesters after implementation (185 students) in Figure 7. In terms of average grade point average (GPA), these results correspond to 2.3 ± 0.18 before implementation versus 2.8 ± 0.09 after implementation, implying better performance in solving this Test Problem.

The Test Problem TP-B was an entirely new one each semester. One such problem based on pumped storage power plants included several concepts: dimensional analysis to determine the non-dimensional terms for rotary machines; similitude to predict lab results to full scale; calculations to determine head loss due to friction and power; and, use of performance curves for pump selection.

Since our goal is to improve and assess problem solving skills, the performance in the Test Problems is used to provide preliminary evidence for the *validity* of the computerized tutorial in meeting this criterion. Figure 8 shows the correlation between the average score of the computerized assessments and the average score in the two Test Problems. The consistency in the correlation between the two over four semesters ($r^2 = 0.80$ to 0.88) as well as the high overall validity coefficient of 0.795 supports the criterion-related validity of the approach [13].

CONCLUSIONS

A computerized adaptive tutorial and assessment approach incorporating the findings from the literature has been developed. Based on student feedback, the approach has been refined and modified over three semesters. The current version has been in use during the last four semesters in a hydraulic engineering course. Data collected so far confirms that this approach is appealing to the students and has promoted voluntary participation. Compared to the students who did not use this approach, those who did were able to solve new problems correctly and efficiently. Preliminary validation data indicates that the approach is effective in assessing the problem-solving skills of these students.

BIBILIOGRAPHY

1. Maul G. P. and Gillard, J. S., "Teaching problem-solving skills", Computers in Ind. Engrg., 31, 17-20, 1996.
2. Taylor, P. A., Woodhouse, K. A., and Bouchard, C. G. K., Developing problem-solving skills: The McMaster problem-solving program, *Jour. Engrg. Educ.*, vol 86, p 75-91, 1997.
3. Woods, R. D., Hrymak, A. H., Marshall, R. R., Wood, P. E., Crowe, C. M., Hoffman, T. W., Wright, J. D., Taylor, P. A., Woodhouse, K. A., and Bouchard, C. G. K., Developing problem-solving skills: The McMaster problem-solving program, *Jour. Engrg. Educ*., vol 86, p 75-91, 1997.
4. ABET 2000- Engineering Criteria 2000, Accreditation Board for Engineering and Technology (ABET), Baltimore, MD, 1996.
5. Chie, M. T. H., Feltovich, P. J., and Glaser, R., Categorization and representation of physics problems by experts and novices, *Cognitive Sci.,* 5, 121-152, 1981.
6. McDermott, L. C., Research on conceptual understanding in mechanics, Physics Today, 37, 24-32, 1984.
7. Heller, P., Keith, R., and Anderson, S., Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving, *Am. J. Phys*., 60, 627-636, 1992.
8. Heller, P. and Hollabaugh, M., Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups, *Am. J. Phys*., 60, 637-668, 1992.
9. Dufresne, R. J., Gerace, W., Hardiman, P. T., and Mestre, J. P., Constraining novices to perform expert like problem analyses: Effects on schema acquisition, *The Jour. of the Learning Sci*., 2, 307-331, 1992.
10. Nakieh M. B. and Mitchell, R. C., Concept learning versus problem solving, *Jour. of . Chem. Educ*., 70, 190-192, 1993.
11. Dufresne, R. J., Gerace, W., and Leonard, W. J., Solving physics problems with multiple representations, *The Phys. Teacher*, 35, 270-275, 1997.
12. Clough, M. P. and Kauffman, K. J. Improving engineering education: A research-based framework for teaching, *J. Engrg. Educ*., p 527-534, 1999.
13. Wiersma, W. and Jurs, S. G., Educational Measurement and Testing, 2nd Ed., Allyn & Bacon, Boston, MA, 1990.

BIOGRAPHICAL INFORMATION

Dr Nirmala Khandan holds the John Clark Professorship in the Civil Engineering Department at New Mexico State University. He received his MS and PhD degrees from Drexel University in Environmental Engineering. He has received several awards for teaching and research. His current research is focused o n educational materials development, teaching, and learning.

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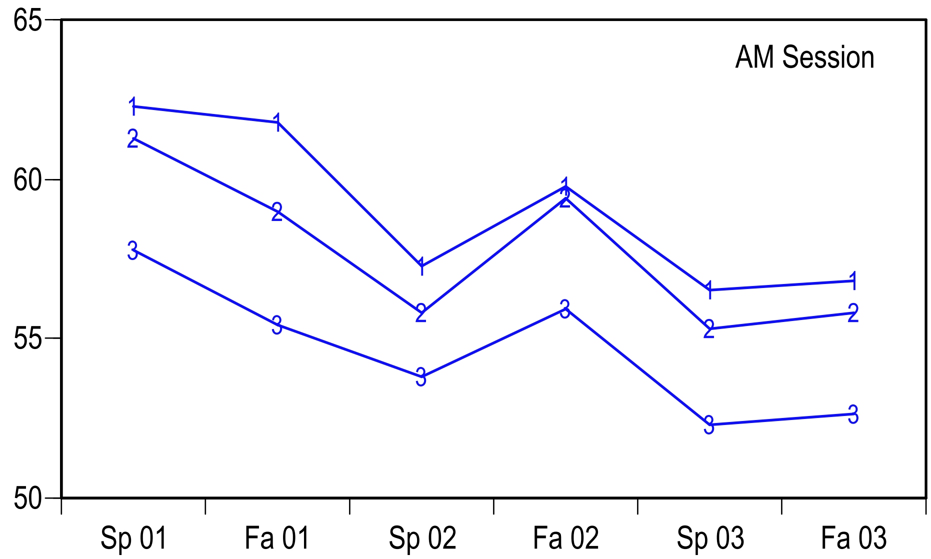


Figure 1. Average % of questions correctly answered by
ABET-accredited civil engineering programs

1- Carnegie Research/PhD Extensive Institutions; 2- Carnegie Research/PhD Intensive Institutions; 3- Carnegie MS Comprehensive Institutions.

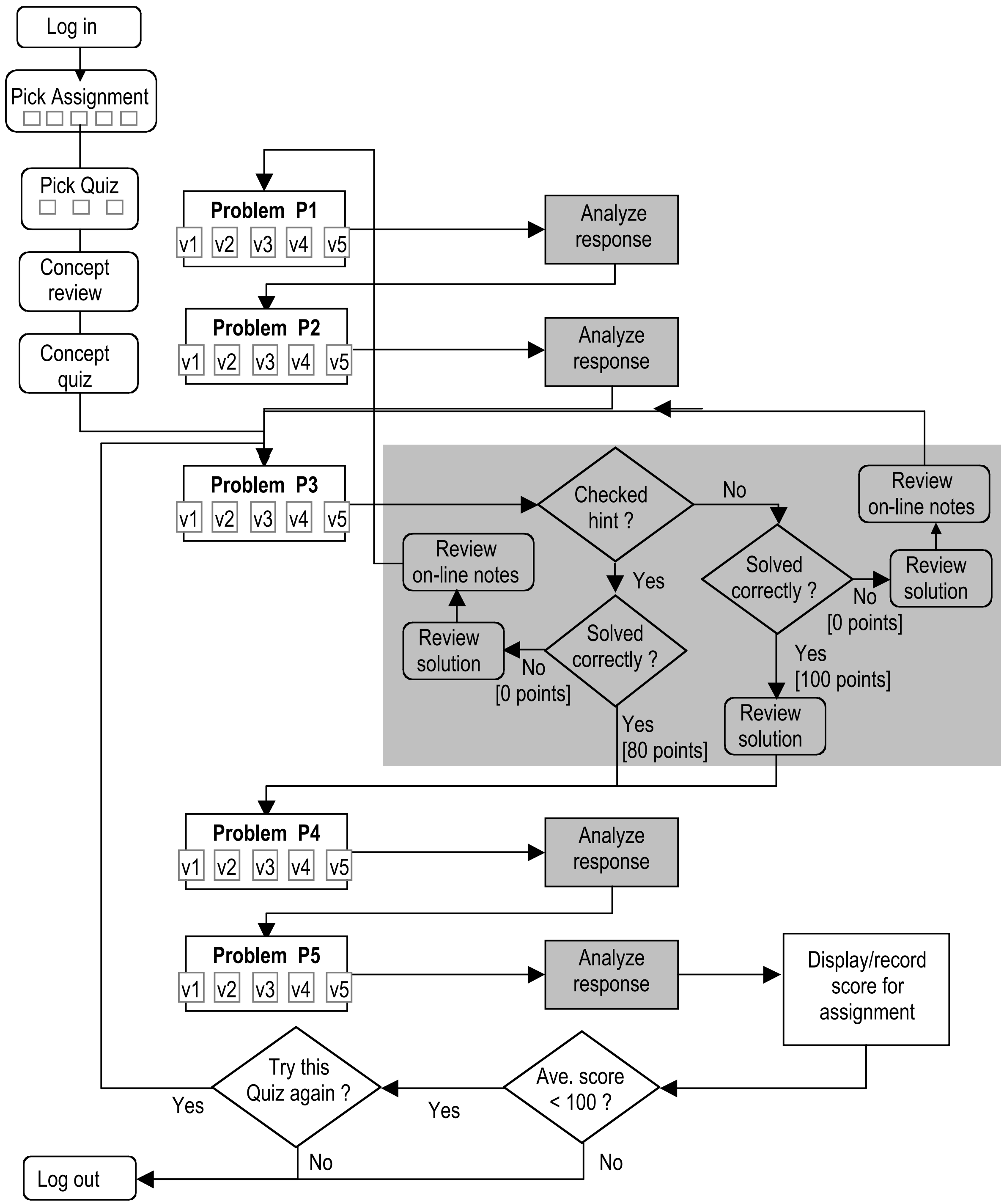


Figure 2. Schematic of Computer-based Tests/Tutorials Program

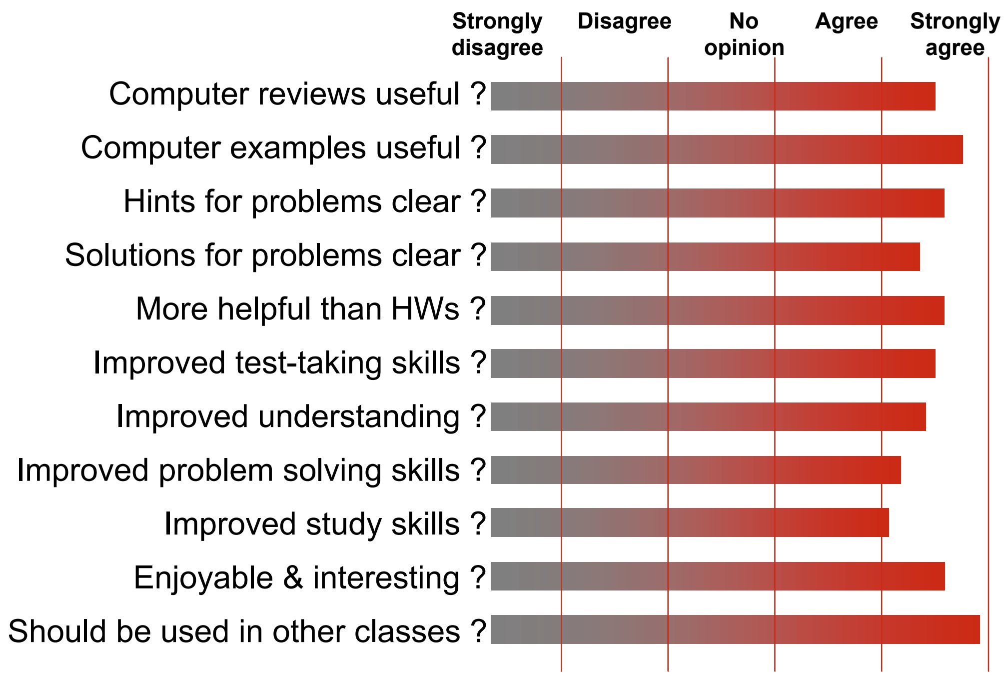


Figure 3. Results of Student Surveys
(Strongly disagree = 0; Disagree = 1; No Opinion = 2; Agree = 3; Strongly agree = 4)

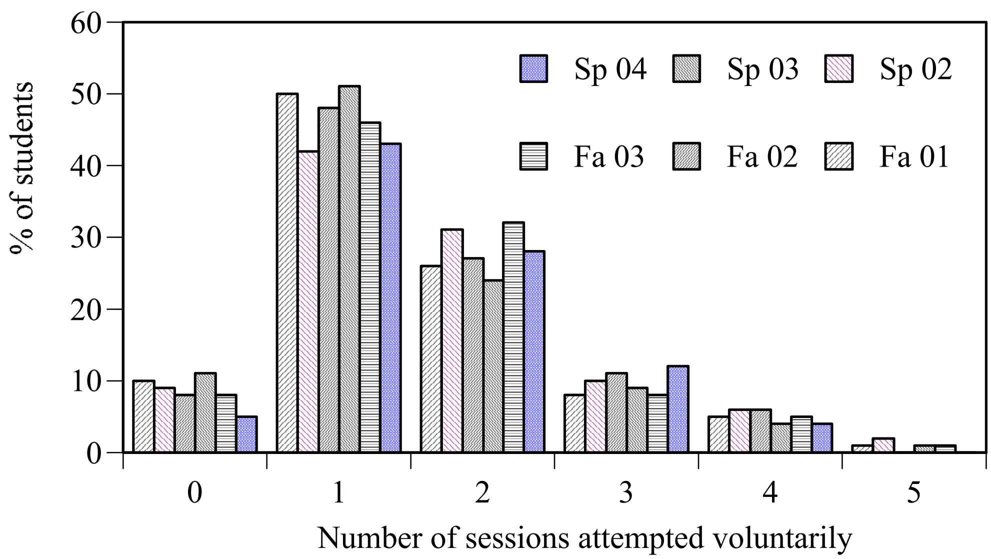


Figure 4. Voluntary Participation in Computer-based Tutorials

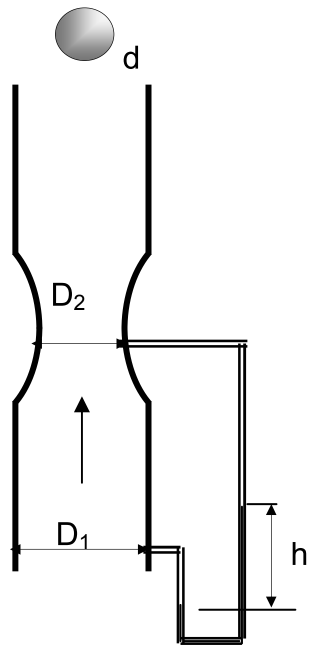
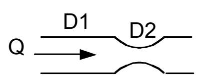
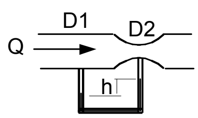
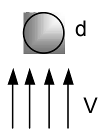
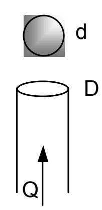
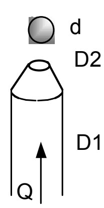


Figure 5. Test Problem, TP-A

Problem schematic	Concepts	Problem variations	
		Given	Find
	Continuity equation	V1, D1, D2	V2
		D1/D2	V1/V2
		Q, D1, D1/D2	V2
	Manometry	h, D1, D2, γ_m	Q
	Continuity equation	Q, D1/D2, sp gr_m	h
	Energy equation	Q, h, D1, ρ_m	D2
	Drag equation	d, ρ_f, ρ_s, μ	V
	Buoyancy equation	d, sp gr_f, sp gr_s, μ	V
	Force balance	V, γ_f, γ_s, μ	d
	Continuity equation	Q, D, ρ_f, ρ_s, μ	d
	Drag equation	d, D, sp gr_f, sp gr_s, μ	Q
	Buoyancy equation	d, Q, γ_f, γ_s, μ	D
	Force balance	Q, D, γ_f, ρ_s, μ	d
	Continuity equation	Q, D2, D1, ρ_f, ρ_s, μ	d
	Drag equation	d, D2/D1, ρ_f, ρ_s, μ	Q
	Buoyancy equation	Q, D2/D1, ρ_f, d, μ	ρ_s
	Force balance	Q, D2/D1, sp gr_f, ρ_s, μ	Q

Notation: V= velocity; D = diameter; Q = flow rate; γ = specific weight; ρ = density;

sp gr = specific gravity; μ = viscosity; d = diameter of sphere; h = manometric reading

Subscripts: m- manometer; f- fluid; s- sphere.

Figure 6. Simple and multi-concept problems with surface modifications

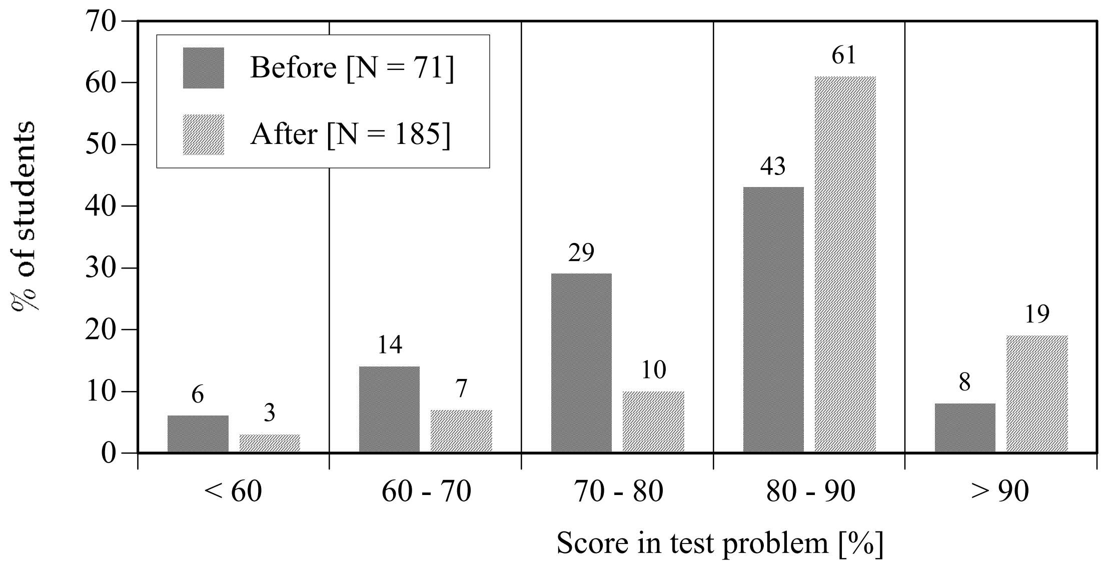


Figure 7. Performance in the “Test Problem TP-A”

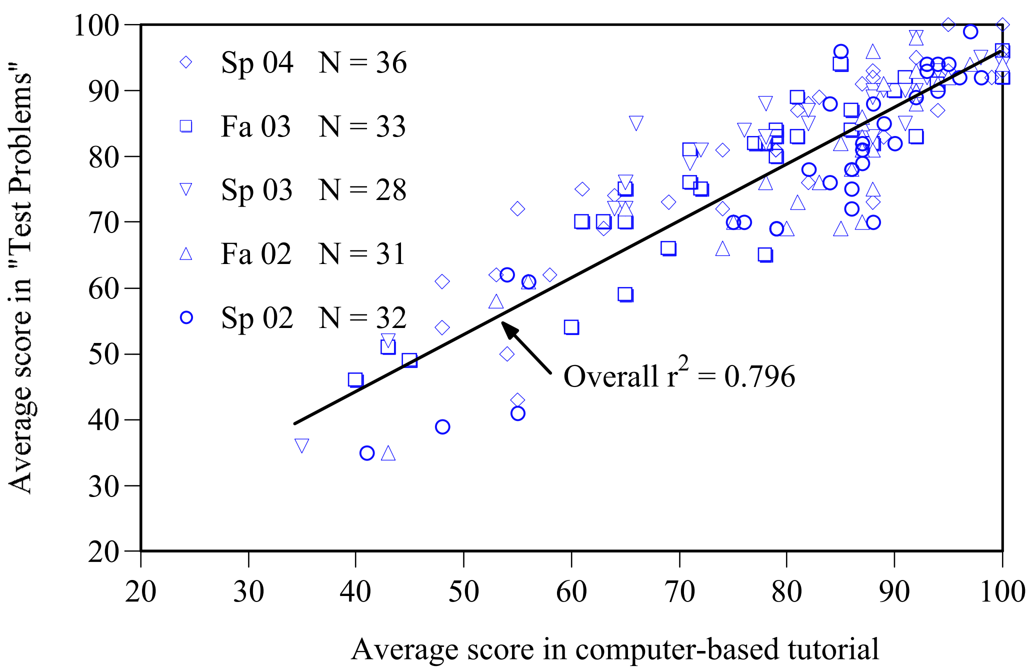


Figure 8. Correlation between
average score in computer-based assessment and score in test problem