Chapter 8: Student Performance on Quantitaitve Exam Problems in Two Instructional Modes

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Introduction

In this chapter we compare performance on quantitative exam problems for students in a tutorial class and students in a recitation class. The previous chapter showed that even though almost all the students answered the qualitative question correctly on exam 3, only 49% of the students could answer the corresponding quantitative question correctly. Those results indicate that in certain contexts the tutorial curriculum does not seem to help students make the connection between their qualitative knowledge and their quantitative knowledge. In this chapter we look at performance in two new contexts: heat transfer and physical optics. While the last chapter evaluated the role of the tutorial section in problem-solving, this chapter will evaluate the role of the tutorial and the role of the traditional problem-solving recitation and compare the two.

Research results from The University of Maryland Physics Education Research Group (PERG), as well as results from the University of Washington Physics Education Group (PEG), have shown that tutorials[1] can improve student qualitative understanding of various topics.[2] But there is little published work demonstrating how students perform on more traditional type problems after going through tutorials.[3] The traditional recitation, where a teaching assistant shows students how to solve problems at the board, is usually employed to teach students how to solve problems. If these problem-solving sessions are replaced with conceptual activities such as tutorials, will the students' problem-solving ability degrade? Or will conceptually based exercises foster the development of expert-like problem-solving skills?

As we have demonstrated, students often view quantitative problems differently from qualitative problems. When given a qualitative problem in a class using tutorials, students usually apply the qualitative knowledge that they have developed. When the question is quantitative, even though the underlying physics may be the same, students do not automatically apply a qualitative analysis to the problem. We would therefore like to see whether the tutorial curriculum and the recitation curriculum help students develop coherence between qualitative knowledge and quantitative knowledge.

The two studies discussed in this chapter were conducted in the engineering physics course (Physics 262 and Physics 263) at UMd. The questions were asked as open-ended exam questions in a class with tutorials and in a class with traditional recitations. The first study presented in this chapter is on the topic of heat transfer in which the recitation students had instruction on the material and the tutorial students had none. In our second study a physical optics question was asked in the tutorial class and the recitation class. Students in the tutorial section had more instruction on the topic of physical optics than the students in recitation. We find that students in the two classes performed about the same on the heat transfer problem despite the recitation class spending more time on the material. On the physical optics question students in the tutorial class performed significantly better than the students in the recitation class.

It should be noted that the tutorial curriculum is not designed to improve student problem-solving although it is sometimes assumed that improved problem-solving skills would be a side-effect of improved qualitative understanding. The results from the last chapter and the results from this chapter show that this is only true in certain cases. The last part of this chapter focuses on innovative curricula that use physics education research (PER) to specifically address problem-solving skills. The reform curricula that are presented in this dissertation all use PER as a guide to curriculum development.

Comparison of performance: Two examples

Heat Transfer Problem

To examine the effectiveness of the problem-solving recitation we asked a heat transfer question in the second semester engineering course (Physics 262) at the University of Maryland in two different instructional settings. One section of the Physics 262 class had tutorials, whereas the other class had a traditional recitation. Although the topic of heat transfer was lectured on in both classes and the students were assigned homework on the topic in both classes, the students in tutorial did not cover the topic in the tutorial class. In contrast, the teaching assistant[4] in the recitation class did go over many of the homework problems that were assigned in the recitation and in a review for the exam. We were able to put a heat transfer problem on the

Tipler Problem

Two metal cubes, one copper and one aluminum, with 3 cm edges are arranged as shown below. Find (a) the thermal resistence of each cube, (b) the thermal resistence of the two-cube system, (c) the thermal current I, and (d) the temperature at the interface of the two cubes.

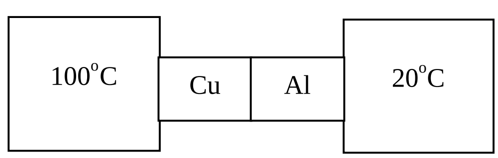


Figure 8 - 1

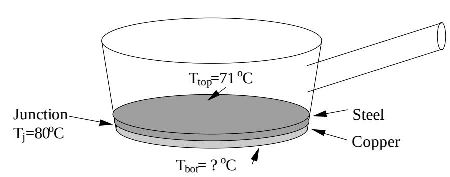
Tipler question on heat transfer asked as part of the homework assignment.

exam in both classes that was similar to a problem both sets of students were given on the homework assignment. The TA for the recitation section solved a similar homework problem in each of his recitation sections. The TA for the course estimated attendance in the recitation section to be between 70% and 80%.

The homework problem that was similar to our exam question came from Tipler's[5] introductory physics text and is shown on the previous page in Figure 8 - 1. If students were benefiting from the recitation we would expect that their performance on the exam question would be better due to the extra exposure to the subject. After the assignments were due in class, a solution to the homework problem was posted for both classes. The exam question was written by the author and is shown in Figure 8 - 2. A solution to the exam problem involves applying the same physics concepts and principles that were applied in the homework question. In addition, students can solve the exam problem by applying steps almost identical to the steps used on the homework problem. The exam problem can be solved in fewer steps if the student applies more conceptual arguments.

The correct solutions to the homework problem and the exam problem are shown in Figure 8 - 3. In the homework question the problem is broken down into four parts. Students are first asked to calculate the resistance of each block, then the equivalent resistance for the two blocks, then the thermal current that flows in the blocks, and finally the temperature at the junction. Students can apply the same four steps to calculate the temperature at the bottom of the pan in the exam problem. A

Suppose the base of a 40 cm^2 pan is made of two different materials each with thickness equal to 0.20 cm. The top side is made of steel [k = 0.46 W/cm*K)] and the bottom side is made of copper [k = 4.01 W/(cm*K)], as shown below.



a) Calculate the temperature of the bottom surface.
b) What is the thermal current through a 1 cm^2 cross section?

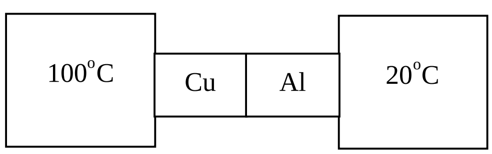
Figure 8 - 2

Heat transfer exam question.

more direct method of solution requires more of a conceptual understanding of the problem. Since the materials are in series, the currents in the two materials are the same, therefore one can obtain the temperature at the bottom of the pan in two steps. An important aspect of this research is examining the methods the students use in solving the problems.

We conducted a careful analysis of student responses after the students (N = 111 in the tutorial class and N = 73 in the recitation class) took the exams. Fewer than 50% of the students answered the exam question correctly in both the recitation and the tutorial class. Some student responses indicate that the students either used a pattern matching approach or solved the problem without a deep conceptual understanding. For example, 13% of the students in the tutorial class (and 11% of the students in the recitation class) incorrectly used the change in temperature between the top and the junction and the equivalent resistance to calculate the current through the base of the pan. In addition 5% (1%) of the students obtained a non-physical answer where the temperature at the bottom was less than the temperature of the junction. In part (b), where the students were asked to calculate the current through a cross section of the pan, 12% (14%) of the students made the mistake of calculating the thermal current through the entire base of the pan. Another common error made by 17% (11%) of the students was to find the thermal current in each material separately and then add the currents.

In part (a) of the exam problem the students are asked to calculate the temperature at the bottom of the pan, whereas in the homework problem students had to calculate the temperature at the junction. The results shown in Figure 8 - 4 show that students in the two sections performed equivalently within the uncertainty of the measurements.



(1) Calculate resistances:

$R_{Cu} = \Delta x / k_{Cu} A$ and $R_{Al} = \Delta x / k_{Al} A$

(2) Calculate R_{eq}:

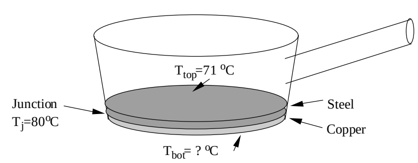
$R_{eq} = R_{Cu} + R_{Al}$

(3) Calculate I:

$I = \Delta T_{lr} / R_{eq}$

(4) Calculate T_j:

$\Delta T_{lj} = I R_{Cu}$



(a) $I_{steel} = I_{Cu}$ and $\Delta T = IR$

And since $R = \Delta x / kA$ we have

$\Delta T_{tj} / R_{steel} = I = 828\,Watts$ and

$\Delta T_{jb} / R_{Cu} = I = 828\,Watts$ so

$T_b = 81^oC$

(b) $828\,Watts / 40\,cm^2 = 20.7\,Watts / cm^2$

Figure 8 - 3

Solutions to the heat transfer homework problem and the exam problem.

This result leads us to question the role of the traditional problem-solving recitation. The recitation seems to have had little effect on the students even after solving multiple problems from the chapter and solving an almost identical problem to the one asked on the exam. Although the students in the tutorial class did not have extra instruction on this material, one might hope that the emphasis on concepts in the tutorial section would improve their performance on this question, but this does not seem to be the case.

Part (b) of the exam is different from anything posed on the homework assignment. On this section of the problem, the recitation class performed slightly better, but not significantly better.

In order to get a better idea of student problem-solving ability we analyzed the responses in greater detail, looking for the methods used in solving the problem. As was mentioned earlier, a solution to the exam question could be obtained in two steps instead of the four steps that were done in the problem assigned for homework.

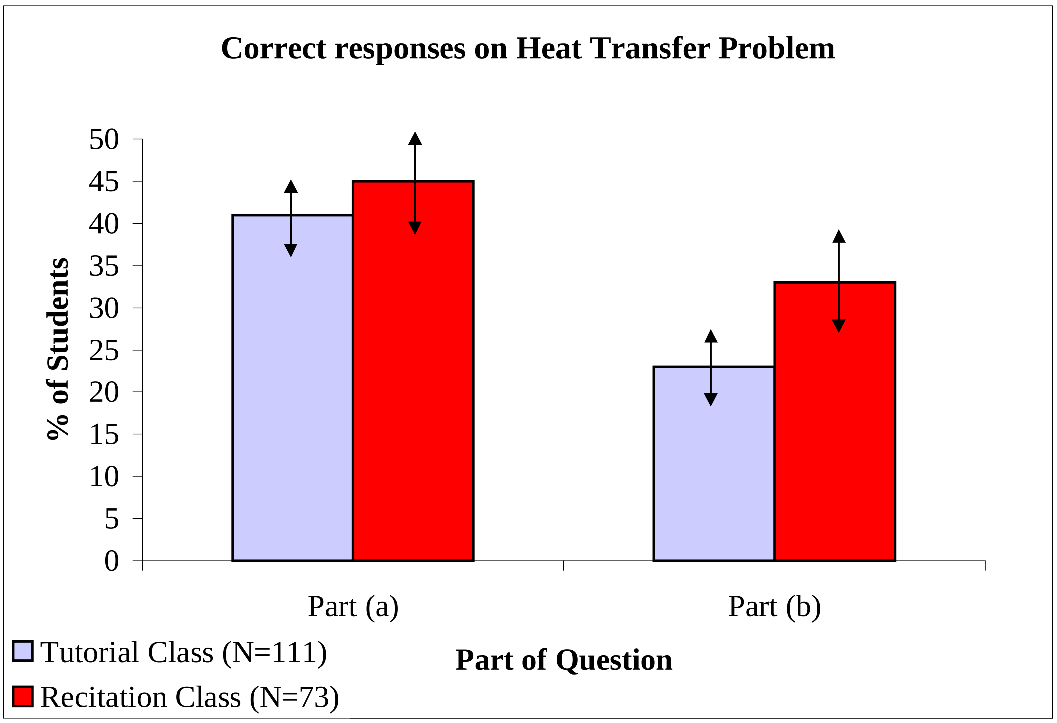


Figure 8 - 4

Performance on the heat transfer exam problem in the tutorial and recitation classes.

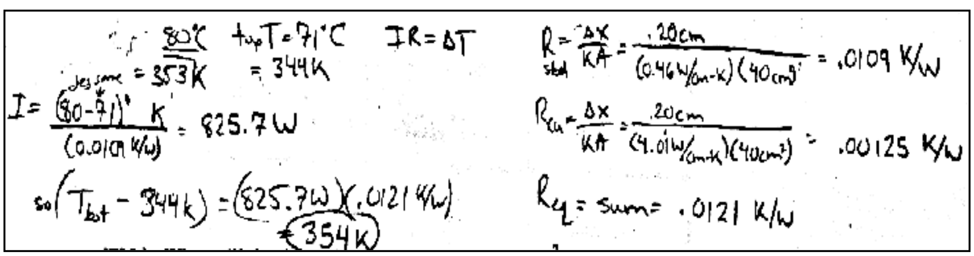
The two-step solution requires a qualitative understanding of the subject and also requires a conceptual understanding of current. Work that has been done concerning student understanding of electric current shows that students often lack a deep understanding of current, even after traditional instruction. Two examples of difficulties with current are that (1) students believe that current gets used up in a circuit after going through a light bulb or resistor, and that (2) a battery is a constant supply of current (independent of the circuit).[6] Without a good conceptual understanding of electric current it is reasonable that students will not posses a good conceptual understanding of thermal current though there is no evidence that the same or even similar misconceptions will appear.

The four-step solution indicates more of a pattern-matching approach to the exam problem. By applying each of the four steps correctly students will obtain the correct answer. Some instructors may feel that this is enough for students but one of our goals in physics education research is to give students an understanding of the materials that will allow them to think critically about a problem and allow them to transfer knowledge from one situation to another situation.

In order to compare how the students in the two classes solved the problem we classified each students' response into one of the two categories. Figure 8 - 5 shows two correct student responses.

The graph shown in Figure 8 - 6 shows the percentage of students in the tutorial section and recitation section that attempted to solve the problem by using the equivalent resistance. Note that the percentages shown are not necessarily students who answered the problem correctly. The graph indicates that although the solution using R_{eq} is more indirect, many students attempted to apply that method to solve the problem. One possible explanation for this is that students are applying a pattern matching approach to solve the problem. The graph also indicates that students in the tutorial section were less likely to apply this approach. These results may indicate that students in the recitation class are more likely to apply patterns of solution that they recall using on similar problems instead of applying the underlying concepts to the problem.

4-step solution (using R_{eq})



2-step solution (using $I_{Cu}=I_{Al}$)

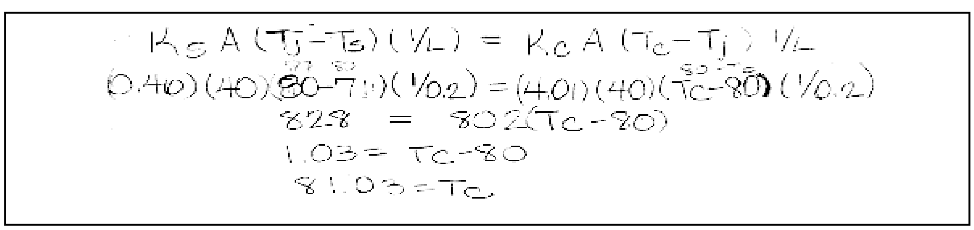


Figure 8 - 5

Two sample student responses on the exam problem. The first method of solution is more indirect and follows the same steps as the homework problem.

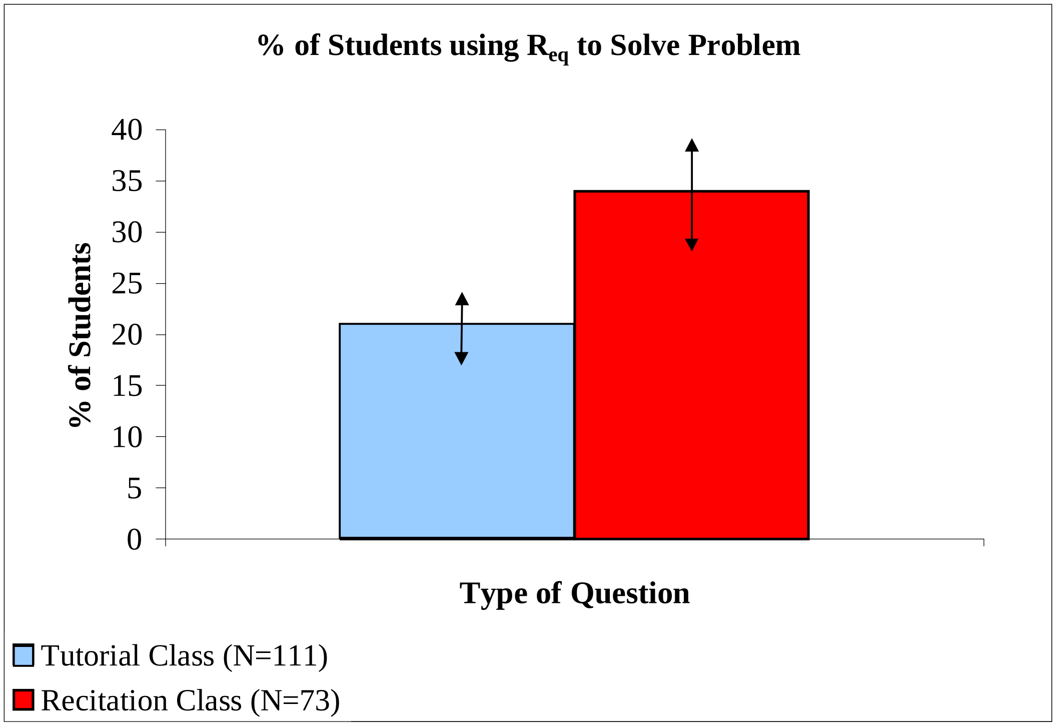


Figure 8 - 6

Graph showing how the students solved the problem in the two classes.

Physical Optics Problem

In our second study we presented the students with a problem in physical optics. In this study both the tutorial class and the recitation class had preparation on the material. The work was conducted by the PEG at the University of Washington and the PERG at the University of Maryland and has since been published.[7]

The UW-PEG has done an in-depth study of student understanding in optics, including the topics of geometric and physical optics. The physical optics paper cited above reports on a study conducted at the University of Maryland where a comparison between a tutorial class and a recitation class was done. A double-slit interference problem was posed on an exam in both classes. The first part of the problem was very similar to a traditional textbook type problem. We will focus on the student responses to that part of the problem.

The question was asked in the Physics 263 class at UMd. Physics 263 is the third semester of a three-semester sequence for engineering students. Students were given the problem shown in Figure 8 - 7 on an exam in both the class with traditional recitations and the class with tutorials.

Light with λ = 500 nm is incident on two narrow slits separated by d = 30μm. An interference pattern is observed on a screen a distance L away from the slits. The first dark fringe is found to be 1.5 cm from the central maximum. Calculate the distance, L, to the screen. Show all work.

Figure 8 - 7

Physical optics exam problem asked in a tutorial and a recitation class.

Students in the tutorial section performed significantly better than the students in the recitation class on this problem. Figure 8 - 8 shows the comparison between the two classes on this problem. The most common error made by the students in the recitation class seemed to be in applying remembered formulas in a haphazard manner. Many of the students in the recitation class used the condition for a maximum instead of a minimum, therefore obtaining an answer of 0.9 m. The students in the tutorial tended to attach more conceptual meaning to the formula for the path difference. Almost none of the students answering the question correctly in

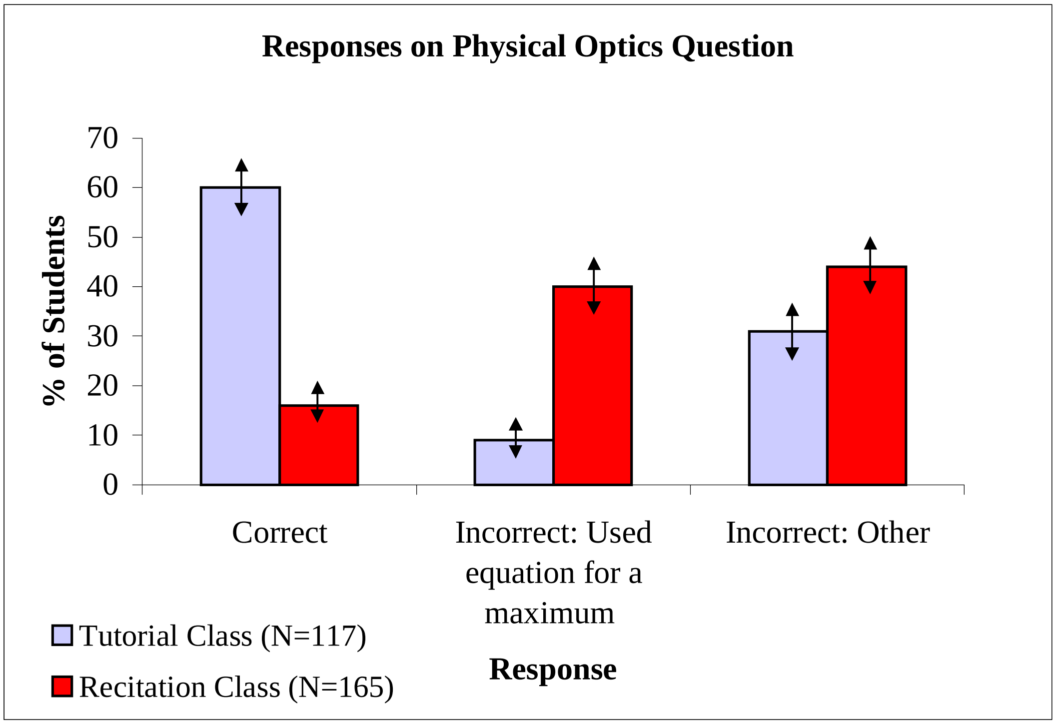


Figure 8 - 8

Performance of students on the physical optics question in the two instructional modes. Students in the tutorial class performed significantly better on this quantitative problem.

the tutorial section started with the derived formula, $L = {yd}/{n\lambda}$. Instead they began with the more fundamental equation $\left({1}/{2}\right)\lambda = d\sin\theta$ using the fact that $\Delta D = ½\lambda$. This shows that there was most likely some level of qualitative reasoning in the application of the equation for the tutorial students who answered correctly. The difference in performance for the two groups indicates that increased conceptual understanding can improve quantitative problem-solving in certain contexts. For this to be the case, qualitative knowledge and quantitative knowledge must be linked.

Curricula that address problem-solving

We have shown in this chapter that tutorials can help student problem-solving. But recall that in the previous chapter there was little improvement in the quantitative performance despite a large number of tutorials on the subject of dynamics. But the emphasis of the tutorial curriculum is on conceptual understanding and not on problem-solving.

Others have focused specifically on improving student problem-solving ability. Issues related to problem-solving have been addressed by a number of physics education researchers, and are discussed in chapter 2. Innovative curricula have been implemented at a number of colleges and universities based on that research. In the rest of this chapter we will discuss some of the curricula that are currently being used to address problem-solving. The curricula we discuss are:

- Cooperative group problem-solving (UMinn)
- Qualitative strategies for problem-solving (UMass)
- Overview case study physics (OSU)
- Bridging problems and problem-solving tutorials (UMd)
- Lecture homework worksheets (UW)

A number of approaches designed to help students become better problem solvers include a set of problem-solving steps. Polya presents a general framework for solving problems in his 1945 book *How to Solve It*.[8] This framework consists of four steps, which include understanding the problem, devising a plan, carrying out a plan, and looking back. Since then, others have developed similar frameworks that range from general, like Polya's, to more specific. Reif, Larkin, and Brackett used a similar four-step process that included description, planning, implementation, and checking.[9] Reif describes a revised version of the four step process in his 1994 Milikan Lecture.[10] A schematic from the written version of the lecture has been reproduced and is shown in Figure 8 - 9. Heller, Keith and Anderson[11] and Heller and Hollabaugh[12] used a five-step approach to problem-solving in their cooperative group problem-solving.

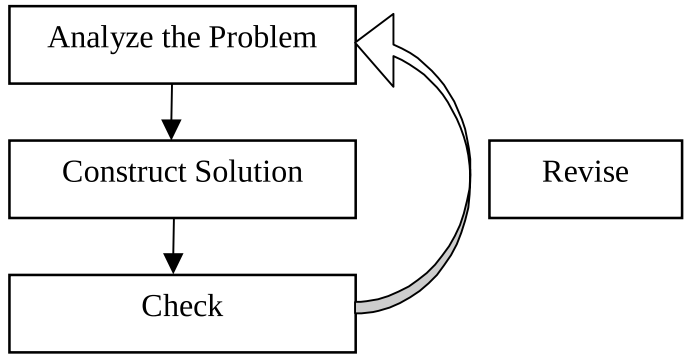


Figure 8 - 9

Problem-solving steps from Reif's Milikan lecture.

Cooperative Group Problem-solving (UMinn)

The Physics Education Research and Development Group at the University of Minnesota has implemented cooperative group problem-solving (CGPS) sessions in their introductory courses. The introductory course consists of lectures, TA-led recitations, and TA-led laboratories. The recitations and laboratories are designed to address student problem-solving. The two specific goals of the Minnesota curriculum are "(1) learn the fundamental principles and (2) learn general qualitative and quantitative problem-solving skills that they can apply to new situations."[13] Their curriculum is therefore designed not only to teach students how to solve problems but to teach students physics concepts through problem-solving. In order to achieve these goals the group at Minnesota relies on cooperative groups, problem-solving steps, guided questioning by TA's, and context rich problems.

The structure of the cooperative groups at Minnesota is similar to the structure of the groups we have discussed earlier when describing the tutorial curriculum. The group at Minnesota has investigated how to structure groups so that they function well. They found that groups of three or four students worked best. Groups of two tended to focus on only one approach to a problem solution and often had one member who would dominate the group.[14] Their study investigated the number of contributions each member of the group made, for groups of three and four students. They found that in the group of four there was usually one member of the group who did not participate as much as the others. In addition they found that the gender and the difference in the ability of the students strongly affect how a group will function. One method that is used to help a group function well is the assignment of roles. Each role has specific duties that are outlined for the students. For groups of three they used the roles of manager, skeptic, and checker/recorder. Students are asked to rotate the roles throughout the semester so each member would have an opportunity to take on each role. Students are also given 5 minutes at the end of the class to discuss how well their group functioned.[15]

The problem-solving instructional approach begins with a problem-solving strategy. This strategy is similar to the strategy described by Reif and Heller[16] and earlier by Polya.[17] The five steps used by Minnesota are (1) visualize the problem, (2) construct a physics description, (3) plan a solution, (4) execute the plan, and (5) check and evaluate. Students are first asked to translate the problem statement into a visual and verbal understanding. This often includes a sketch, identification of the relevant information, and identification of the general approach they would apply to the situation. The physics description takes the visualization and represents it in physics terms. For instance a sketch of the situation may turn into a free body diagram. This step is similar to the step experts take in going from the naïve representation to the physical representation in the work of Larkin (described in chapter 2).[18] Once this is done students begin to plan a solution, where the physical representation is turned into a mathematical representation. At this stage students make sure they have enough information to solve the problem. Once all the information is available and the mathematical description is completed, students obtain an answer and check to see whether their answer is reasonable.

An important feature of this approach is the type of problems students will solve in the sessions. If a problem is too easy or simply requires manipulating formulas it will not foster group interaction and the general steps discussed earlier will not be important to solve the problem. For this reason the Minnesota Group has developed problems that are more challenging for the students. These *context-rich* problems have a number of characteristics that separate them from the traditional problems usually found in textbooks. (1) The problem statement will not always identify the unknown variable; (2) the problem may include information that is not important to the solution; (3) the problem may require the student to make estimations; and (4) the problem may require the student to make reasonable assumptions. These characteristics tend to make the context-rich problems too difficult for an individual student to solve, but appropriate for the three or four member groups.[19]

Graded questions provided the students with motivation for participating and working earnestly in the groups. Students are evaluated by group performance as well as individual performance. During each class test, each group submits one solution and each member of the group receives the same grade for that solution. A group is given credit for using the problem-solving steps as well as for the correctness of the solution. The individual component insures that students can not simply sit back and allow the rest of their group to do all the work. It also aids the instructor in identifying students that need additional help with the material. One way individuals were held accountable is that students are selected at random to present their group's solutions to various problems.

Heller et al. performed three types of studies to evaluate the CGPS.[20] The first study looked at whether the cooperative group's solutions were better than the individual solutions of the top scoring students. In the second study they looked at the dynamics of student problem-solving performance to see whether individual problem-solving performance improved over time. In the third study they compared the performance of students in the CGPS sections to students in a traditional section on standard problems.

They based their evaluation of problem solutions on six criteria: evidence of conceptual understanding, usefulness of description, match of equations with description, reasonable plan, logical progression, and appropriate mathematics. This scoring criteria was checked for reliability and validity.

To compare the solutions of the group to the solutions of the top individuals Heller et al. used matched problems. Students first solved a context rich problem in a group. Individual students were then given a similar problem that was less difficult than the group problem. Group solutions were then compared to the solutions of the individuals from each group who scored the highest on the individual exams and the final exam problems. Scores on the group solutions and the individual solutions showed that the performance of the group surpassed the performance of the individuals, despite the fact that the individual problem was easier than the group problem and the fact that the group problem was completed first. This result led Heller et al. to conclude that the group work is not simply the work of the best problem solvers in the class.[21]

Heller et al. also looked at the quality of solutions on the least difficult individual problems throughout the course. The class was divided into the top third, middle third, and bottom third, based on total individual grades on the tests and final exams. They found that all students benefited from the CGPS on all six criteria except conceptual understanding, where there was no appreciable gain.[22] Saul has reported that performance on the FCI in the CGPS class was comparable to performance in a tutorial class but better than performance in a traditional recitation.[23]

The final investigation compared performance of students in the CGPS class with performance of students in a traditional class on standard problems. (Instructors in the standard class judged the context rich problems to be too difficult for their students.)[24] Students in the CGPS class scored significantly better on the criteria outlined by Heller et al. The biggest different was in the qualitative analysis of the problem. All CGPS students drew free-body diagrams compared to 57% in the traditional class. Heller et al. therefore conclude that students in the CGPS curriculum exhibit more expert-like characteristics in their problem solutions.[25]

Qualitative Strategies for Problem-solving (UMass)

The Physics Education Research Group at the University of Massachusetts, Amherst has developed curricula which encourage the application of qualitative analysis to quantitative problems. In 1991, Dufresne, Gerace, Hardiman, and Mestre presented questions to students using a computer-based environment called the Hierarchical Analysis Tool, or HAT. HAT begins by asking the student to select a principle that could be applied to a problem. HAT then proceeds to ask additional questions that are more specific, therefore employing a top down approach to problem-solving. After HAT completes an analysis, based on the user's input, it provides a set of equations that are consistent with the user's input. These equations may therefore be inappropriate for solving the particular problem. HAT's analysis is independent of the content of problem. It merely asks a series of general questions which aid the user in adopting a top-down approach to problem-solving.

Evaluation of HAT was done using forty-two undergraduate students. Each student took part in eight problem-solving interview sessions. The forty-two students were divided into three groups each having different instruction. The first group used HAT for a qualitative analysis before solving the problems, the second group was given a textbook they could use to solve the problems and the third group used an Equation Sorting Tool (EST) which contained a database of 178 equations that could be searched. Students who used the HAT material tended to categorize problems by principles more often than the other groups. Dufresne et al. also concluded that HAT was more effective in improving student problem-solving than traditional methods.[26]

Based on earlier research, Leonard, Dufresne, and Mestre discussed a problem-solving curriculum that could be implemented on a large scale.[27] Their work describes how qualitative strategies could be used to highlight the role of conceptual knowledge in solving problems. They describe a strategy that can be employed in large introductory physics classes without making large changes to the course. In solving problems, they stress the use of identifying the concept or principle, justifying why the principle is appropriate, and describing the procedure by which the principle or concept could be used. Although the authors claim that a large restructuring of the course is not required, they do make some significant revisions in the course. In particular, one sample problem is worked out during each lecture. Students were also encouraged to apply strategies in every problem they attempt in the course.

Leonard et al. performed two types of studies to evaluate the effectiveness of the modified instruction. They looked at categorization tasks and students' recall of important ideas.

In the categorization tasks they administered five multiple-choice questions on a final exam. Students were given a problem and asked to select the major principles (from five choices) that should be used to solve the problem. Their results show that the students in the modified curriculum were less inclined to choose principles based on the surface features of the problem.[28] These results were true for all students in the modified curriculum.

The recall task occurred six months after students in the traditional class had completed the course and 11 months after students in the modified class had completed the course. The students were "asked to name the most important physics ideas and principles used to solve problems in mechanics."[29] Both populations of students were found to identify Newton's three laws with about the same frequency but the students in the modified curriculum cited the remaining four principles (conservation of energy, work-energy theorem, linear momentum conservation, and angular momentum conservation) at a consistently higher frequency than the other students. The authors caution that this data does not mean that the students who went through modified curriculum knew more than the students in the traditional class. But the data does suggest that focusing attention on the principles does help students retain the major ideas.

The researchers found that the modified curriculum they presented did help students improve their explanations. In addition, the grading of strategies helped the instructors become aware of how well students understood the ideas in the course.[30,31]

Overview, Case Study Physics

Alan Van Heuvelen at the Ohio State University is the project director of the Overview Case Study (OCS) curriculum. The OCS curriculum is designed to help students develop coherent knowledge by dividing the physics course into conceptual blocks. Students first qualitatively construct the basic ideas of a particular block.[32]

They then learn to build mathematical representations and then they apply their knowledge to complex case study problems. OCS tries to first lay the foundation and frame and then incorporate the details.[33] In addition, students are active participants in constructing this knowledge.

The frame and foundation are the overview, where the students are qualitatively constructing the concepts in a particular block. The details start getting filled in during the exposition, where the student translates the concepts into mathematical form. At this stage students are also investigating different representations for the problems, such as pictorial or physical representations. The next stage is the case study, where students integrate a number of concepts that were introduced earlier, in order to solve problems.[34] A case study can last between several days and several weeks. At the end of the semester a week-long review is conducted in which students are shown a hierarchical chart of the different blocks of knowledge. Throughout the semester students utilize a set of Active Learning Problem Sheets (ALPS). ALPS are designed to make the lecture parts of the course more interactive. The students complete an activity and then talk to their neighbors about their reasoning.

We will discuss two examples of the type of evaluation done on the OCS curriculum at New Mexico State University.[35] In the first study they compared the performance of students who went through the OCS curriculum to students who went through the conventionally taught curriculum. Students in the OCS curriculum used only one overview lasting about two weeks that covered material on NII and work-energy concepts. Students were evaluated on responses to quantitative problems. In the second study they compared the same types of populations (different students) on qualitative questions. Students in the OCS curriculum used the first edition of the OCS study guide and a standard calculus text. They compared student responses on questions involving NII (24 questions) given as a pretest and a posttest.

Analysis of the quantitative problems asked on the final exam showed that OCS students performed better than the students in the conventionally taught class. 51% of the OCS students answered correctly while only 13% of the conventionally taught students answered correctly on the dynamics problem. In addition 94% of the students in the OCS class included a free-body diagram in their solutions compared to only 9% including the diagram for the conventionally taught population. Van Heuvelen states that the conventionally taught students tried to solve the problems by applying special memorized equations rather than applying the fundamental concept to the problem.[36]

On the qualitative questions about NII both populations scored about the same on the pretest. The conventionally taught students took the posttest at the end of the semester, while the OCS students took the posttest after NII had been covered. Conventionally taught students had a posttest score of 53% while OCS students had a posttest score of 73%. On an additional posttest given at the end of the semester to the OCS students, which included slightly more difficult questions, the OCS students had a score of 86%.[37]

Research results show that the OCS curriculum does help students develop better qualitative skills and quantitative skills.[38] The integration of qualitative representations into quantitative problem-solving was shown to improve performance on qualitative questions. As we saw in the work done by the group at Minnesota, curricula that have a strong problem-solving component can be used to improve qualitative understanding as well as quantitative problem-solving.

Bridging Problems and Problem-Solving Tutorials (UMd)

Our results show that concept-based curricula like the UW Tutorials can sometimes improve students' quantitative problem-solving. The results also indicate that this improvement depends on the context and the topic. Although this chapter provided results showing that tutorials did play a role in improving student problem-solving the last chapter showed that the tutorials had little effect on problem-solving ability. In addition we have observed that when asked qualitative questions prior to a quantitative question students sometimes performed worse. The results point out some limitations in the tutorial curriculum.

The nature of the tutorial curriculum makes it difficult for the students to see the connection between the concepts they are developing and the quantitative questions they are given on textbook homework assignments and exams. To aid the students in making the link between their qualitative knowledge and their quantitative knowledge, the PERG at the University of Maryland has been developing materials to try to address some of these transfer issues. Two methods we have developed are *bridging problems* that supplement the tutorial homework assignments and *problem-solving (PS) tutorials*.

Bridging problems are problems that contain both qualitative and quantitative parts. The bridging problems are discussed briefly in chapters 3 and 5 of this dissertation. Students are asked to answer a series of qualitative questions before a final quantitative question. Success on the quantitative part of the problem requires a deep conceptual understanding of the material. By asking qualitative questions along with the quantitative question, we are attempting to foster the acquisition of links between students' qualitative and quantitative schema. Bridging problems are given as supplements to the tutorial homework each week. They involve ideas and concepts that were covered in the tutorial for that week. Students are provided with solutions to the problems after they are due. The bridging problems I have been involved in constructing are included in Appendix A.

Problem-solving (PS) tutorials were designed by the PERG at the University of Maryland to meet goals similar to the goals of the bridging problems. Problem-solving tutorials are implemented in the same way the University of Washington-style tutorials are implemented.[39] Students work in groups of three or four on the PS-tutorials with two facilitators in the room asking the students guided questions. The PS-tutorials do not concentrate on a particular subject. Instead, they include problems based on the material in preceding tutorials. Three or four problems are constructed that require a deep qualitative understanding of the material. The problems are similar to the bridging problems in that the students are asked qualitative questions before they are asked to answer the quantitative part of the problem. Although most of the problems on the PS-tutorials were designed by the PERG at UMd, some were adopted from other sources.[40] The PS-solving tutorials I have been involved in constructing are included in Appendix B.

These curricula are small perturbations to the course, therefore their evaluation is difficult. Only one or two of the thirteen tutorials in a given semester are problem-solving tutorials. In addition, only one of the problems out of about nine problems the students solve on homework assignments each week are bridging problems. In order to have an effect on creating links between qualitative knowledge and quantitative problem-solving we expect that bridging problems and problem-solving tutorials must be implemented on a much larger scale. Unfortunately, due to time constraints and logistic constraints, a larger scale implementation was impossible at the University of Maryland.

Lecture Homework Worksheets (UW)

Steve Kanim and the University of Washington Physics Education Group (PEG) have been developing *lecture homework worksheets* to supplement the textbook homework. These worksheets are designed to address the difficulties students had in applying conceptual models to standard problems.[41] The worksheets attempt to accomplish goals that are similar to the goals of the bridging problems[42] designed by the PERG at Maryland. The homework worksheets are assigned weekly, consist of about four pages, and include both qualitative and quantitative questions. Because of this supplemental homework, instructors in the course decrease the amount of textbook homework assigned.

Kanim has seen gains in performance on quantitative circuits problems for students in the upper half of the class. On paired qualitative and quantitative questions, his research shows that the performance on the qualitative questions remains about the same yet the performance on the quantitative question improves for these students.

The performance on quantitative problems in electrostatics and Gauss's Law did not improve with the homework worksheets. Research into why students were not performing better on quantitative problems in electrostatics indicated that students had conceptual difficulties that had not previously been addressed.

Common Elements

There are a number of elements that these curricula have in common that separate them from the traditional physics curriculum. Students in these instructional settings are actively participating in constructing their own knowledge. In the traditional course students often sit passively watching instructors solve problems for them. Even when instructors attempt to make the class interactive by asking questions, only a small number of students participate in the discussion. In addition, the students that participate are usually the students that already know the material. These research-based curricula described above also rely on the students solving problems that require them to use concepts and principles and not simply facts and formulas.

As stated by Dufesne et al. traditional textbook problems often foster the use of

> memory taxing strategies . . . to solve problems. Such strategies use much of the novice's available working memory to attend to the details of executing a problem's solution . . . there is little working memory left to extract from a solution generalizable principles and procedures.[43]

Ward and Sweller, [44] as cited by Maloney,[45] suggest that standard end of the chapter textbook problems can actually be counterproductive. Our results, presented in this chapter, suggest that a traditional problem-solving recitation where students watch an instructor solve problems at the board may actually encourage students to apply a pattern matching approach. Students sometimes think less about the underlying physics and more about how similar a problem is to problems they have already solved. My own experience in graduate school suggests that many physics graduate students engage in similar activities. For instance, many students perform well on the physics qualifier by solving many older problems, and being able to recognize similarities between different questions. Although this may be a good method to perform well on a test it is not necessarily the best way to learn physics.

Summary

In this chapter we compared responses given by students in two instructional modes. The analyses of the responses to the two exam problems presented in this chapter suggest some tentative conclusions. We have seen that the traditional problem-solving recitation that is common at most large universities did not help students on the problems presented in this chapter. An identical heat transfer question was given, on an exam, to students in a physics 262 class with tutorials and a class with traditional recitations. Even though students had additional instruction on heat transfer in the recitation class, and solved a similar problem in the recitation section, they performed no better than the tutorial class, which received no additional instruction on heat transfer.

The recitation section seems to help the students apply pattern-matching approaches to problems. This encourages students to simply look at the surface features of a problem and not the underlying principles and concepts. The data from the heat transfer problem also shows that simply using tutorials to develop conceptual understanding does not mean students will develop more expert-like characteristics; i.e. think qualitatively about quantitative problems.

When students have explicit instruction on a particular topic in the tutorial class it is possible that they will perform better on quantitative problems than students who go through a traditional recitation class. This was true in the physical optics question. Students in the tutorial class performed much better than students in the recitation class. It seemed as though students in the tutorial class were applying the concepts more often than the students in the recitation class. Unfortunately, this improvement for tutorial students, in applying the concepts, does not happen in topics throughout the introductory sequence (as we saw in chapter 7.) It therefore depends on the type of question.

The tutorial curriculum is not designed to address student problem-solving. The PERG at the University of Maryland has supplemented the tutorial curriculum with bridging problems and problem-solving tutorials to help students develop coherence in their qualitative and quantitative content knowledge. Because these supplements were implemented on such a small scale it was difficult to evaluate their effectiveness.

Other curricula have been developed, using PER as a guideline, which place a much greater emphasis on student problem-solving. Three well-established curricula which teach problem-solving and use problem-solving to teach concepts are discussed in some detail in this chapter. Each curriculum shares a number of common elements including a strong research base, students actively participating in constructing their knowledge, and the use of problems which require and encourage the use of conceptual understanding. Research on the effectiveness of these curricula show that they can be effective in helping students improve their problem-solving ability.

[1] The tutorial curriculum is discussed in chapter 3.

[2] See L.C. McDermott, and the Physics Education Group, A perspective on physics education research as a guide to the improvement of instruction, unpublished collection, (1998) and E.F. Redish, J.M. Saul, and R.N. Steinberg, "On the effectiveness of active-engagement microcomputer-based laboratories," Am. J. Phys. **66** (3) 212-224 (1998).

[3] S. Kanim, "An investigation of Student difficulties in qualitative and quantitative problem solving: Examples from electric circuits and electrostatics," Ph.D. dissertation, Department of Physics, University of Washington, (1999); B. Thacker, E. Kim, K. Trefz, S. Lea, "Comparing problem-solving performance of physics students in inquiry-based and traditional introductory physics courses," American Journal of Physics 62 (7), 627-633 (1991); and B. A. Ambrose, P. S. Shaffer, R. N. Steinberg, L. C. McDermott, "An investigation of Student Understanding of Single Slit Diffraction and Double Slit Interference," Am. J. Phys., **67** (2) 146-155 (1999).

[4] There was a single TA for the recitation class.

[5] P. Tipler, Physics for Scientists and Engineers, 4th edition, (W. H. Freeman and Co., NY, 1999).

[6] For more detail see L.C. McDermott and P.S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity, Part I: Investigation of student understanding." Am. J. Phys. **60** (11), 994-1002 (1992); Erratum to Part I, Am. J. Phys. **61** (1), 81 (1993).

[7] B. A. Ambrose, P. S. Shaffer, R. N. Steinberg, L. C. McDermott, "An investigation of Student Understanding of Single Slit Diffraction and Double Slit Interference," Am. J. Phys., **67** (2) 146-155 (1999).

[8] G. Polya, *How to solve it*, (Doubleday, NY, 1945).

[9] F. Reif, J.H. Larkin, and G.C. Brackett, "Teaching general learning and problem-solving skills," Am. J. Phys. **44** (3) 212-217 (1976).

[10] F. Reif, "Millikan Lecture 1994: Understanding and teaching important scientific thought processes," Am. J. Phys. **63**, 17-32 (1995).

[11] P. Heller, R. Keith, and S. Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," Am. J. Phys. **60** (7), 627-636 (1992).

[12] P. Heller and M. Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," Am. J. Phys. **60** (7), 637-644 (1992).

[13] from their web site; see http://www.physics.umn.edu/groups/physed/Research/MNModel/MMt.html

[14] See ref. 11. (Heller, Keith, and Anderson)

[15] See ref. 12. (Heller and Hollabaugh)

[16] See F. Reif and J. I. Heller, "Knowledge structures and problem solving in physics," Educational Psychologist, **17** (2), 102-127 (1982)

[17] G. Polya, *How to solve it*, (Doubleday, NY, 1945).

[18] J.H. Larkin, "The role of problem representation in physics." In D. Gentner and A. L. Stevens (Eds.), *Mental models*, (Lawrence Erlbaum, NJ, 1983), pp. 75-98

[19] See Ref. 12.
[20] See Ref. 11.
[21] See Ref. 11.
[22] See Ref. 11.
[23] J. M. Saul, "Beyond Problem Solving: Evaluating introductory physics courses through the hidden curriculum," Ph.D. dissertation, Department of Physics, University of Maryland, College Park, (1998).
[24] See Ref. 11.
[25] See Ref. 11.
[26] R. J. Dufresne, W. J. Gerace, P. T., Hardiman, and J. P. Mestre, "Constraining novices to perform expert-like problem analyses: Effects on schema acquisition," Journal of the leaning Sciences, **2** (3) 307-331 (1992).
[27] W. J. Leonard, R. J. Dufresne, and J. P. Mestre, "Using Qualitative Problem-Solving Strategies to Highlight the role of conceptual knowledge in solving problems," Am. J. Phys., **64** (12), 1495-1503 (1996).
[28] See Ref. 27.
[29] See Ref. 27.
[30] See Ref. 27.
[31] For more information see the group's web site at http://www-perg.phast.umass.edu/. They have developed a course at the high school level which ties together many of these ideas called *Minds on Physics*. Kendall/Hunt publishes the curriculum.
[32] A. Van Heuvelen, "Overview, Case Study Physics," Am. J. Phys. **59** (10), 898-907 (1991)
[33] See ref. 32 in which Van Heuvelen makes a reference to a statement made by Steve Kanim. The statement compare physics instruction to building a house room by room versus foundation and frame first - then the details.
[34] See Ref. 32.
[35] See Ref. 32.
[36] See Ref. 32.
[37] See Ref. 32.
[38] See Ref. 32.
[39] Implementation of tutorials is discussed in detail in chapter 3 and in P. S. Shaffer, "Research as a guide for improving instruction in introductory physics," Ph.D. dissertation, Department of Physics, University of Washington, (1993).
[40] A. B. Arons, *Teaching introductory physics* (Wiley, New York, 1997).
[41] S. Kanim, "An investigation of student difficulties in qualitative and quantitative problem solving: Examples from electric circuits and electrostatics," Ph.D. dissertation, Department of Physics, University of Washington, (1999).
[42] Bridging Problems are discussed in chapter 3
[43] See Ref. 26.
[44] D. S. Ward, and J. Sweller, "Structuring effective worked examples," Cognition and Instruction. **7,** 1-39 (1990).
[45] D. P. Maloney, "Rule-governed approaches to physics: Newton's Third Law," Phys. Educ. **19**, 37-42 (1984).