USING COMPUTATIONAL TOOLS TO ENHANCE PROBLEM SOLVING

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Abstract

Many engineering curriculum around the country are re-evaluating their introductory computer programming requirement. At our university, several departments have introduced new computer-based modeling courses that integrate critical thinking and problem solving with computational thinking and programming as a replacement of the traditional first computer programming course. The skills learned in such freshman level courses are being iterated and expanded on in subsequent courses in these curricula in order to create a 'computational thinking thread'. One unforeseen consequence of the computer based modeling course was an increase in the student's problem solving ability. This study explores the role that computing has on student's problem solving abilities and tries to quantify its impact. Students in several freshman and senior level engineering courses across different disciplines were asked to solve a common problem solving task as well as reflect on the process they used to solve the problem. The student's solutions were scored using a protocol based on Wolcott's 'Steps for better thinking rubric' The paper will outline the problem used; report on the scoring procedures and methodology; and present the results from the study. The results demonstrated that students who utilized computing generated better solutions and are better problem solvers than those who did not use a computer.

Introduction

This work is part of an ongoing project that stems from assessing the impact of new introductory computer-based modeling courses that were created in two engineering departments at our university. These freshman level courses aim to educate students to model problems relevant to their specific engineering discipline, solve these problems using modeling tools (including a range of software platforms, such as Excel and VBA), and then to analyze the solutions through decision support systems (i.e., to become "power users" not programmers). Emphasis is placed on the analysis of data in order to make more efficient and effective decisions. The courses employ a series of "in-class labs", integrating the traditional lab and lecture sessions into one, and all in-class activities are done on student-owned laptops[1, 2]. The labs are crafted to capture the student's attention the entire time owing to the large distraction of having a computer. Many of the homework assignments and case studies come from industrial sponsored data and represent real world situations. Course content as well as teaching methodologies employed and developed have been described in earlier research[1,2]. Even though this course is offered in two different departments, they follow the same curriculum (i.e., labs, homework, projects, and tests) throughout the semester.

One of the main reasons for creating these new courses was to enhance the students' ability to think critically, develop algorithmic solutions to problems (flow chart out a basic solution to a problem), and develop general problem solving skills. However, in order to teach these modeling techniques to solve a series of case studies, the faculty had to break up the larger problem into smaller steps (i.e., they applied their experience in solving these problems) to make them solvable in a regular class period by students. A secondary outcome of these labs was that students were seeing how to approach and solve a wide variety of different problems. For example, one engineering problem solving method the students see is the 'divide and conquer technique' (i.e., breaking up the problem into its smallest elements and solving each of the elements (which typically is easier) and then reassembling the elements to solve the original problem) [2]. In order for students to enhance, rather than lose, these new found computational and problem solving skills in the freshman year, computational modeling and problem solving has to be utilized through their academic career by integrating these tools into upper division courses. A 'computational thinking thread' [3] is beginning to be woven throughout the curriculum in several of our engineering departments [2]. The intention is that when particular skills sets are iterated throughout the curriculum, students come to see them as being valuable in different problem solving contexts.

In the introductory courses, students are explicitly and implicitly taught some basic problem solving and critical thinking skills, namely identifying relevant information, dealing with uncertainty, articulating assumptions, interpreting and organizing information. These correspond to the 'identify' and 'explore' stages of problem solving as outlined in the Wolcott 'Steps for Better Thinking' model [4]. Students in upper division courses are not explicitly taught according to this model, although some steps may be implicitly taught.

In this paper, we report specifically on the impact that the use of technology has on a student's problem solving capabilities. Earlier we addressed the impact of the course as well as addressed the effectiveness of student learning with the innovative teaching pedagogies [1, 2].

Research Methodology

A secondary result of the introductory course was the perceived improvement in the student's ability to approach, analyze, and ultimately solve problems. To test whether or not this was reality or just perception, a fairly generic problem solving task was developed for students to solve. The task was designed to ascertain the student's ability to decipher information and a scientific equation, utilize this information and equation to analyze the problem, and then ultimately make a decision based on their analysis. This task was given to the students near the end of the semester in the two freshman introductory classes (100-level), and in selected upper division (400-level) classes. Students were required to complete the task individually and independently outside of class over a one week period, and then to turn in all their work, including a solution to the problem. Bonus points were given to students who participated in the study. In most cases over 80 percent of the class participated in the study.

For the first iteration in the fall of 2007, students were not explicitly told to use technology, but obviously this option was available to them as they saw fit, and we noted which students used a computer to solve the problem during the analysis. On the day they turned in their work, they completed a set of reflective questions in-class about their problem solving process they used to come to a decision. The reflective questions were framed to reflect the different problem solving stages implicit in the developmental problem solving model developed by Wolcott [4]. For the upper division courses, students were also asked if they had taken the introductory course during their curriculum, so that performance could be analyzed by this variable as well.

The early results showed that technology used seemed to enhance their problem solving ability but only a few of the students chose to use technology to arrive at a solution, so we needed to increase the sample size. Therefore, in the second iteration of this study in the fall of 2008, we directly compared similar groups of students who used technology with those who did not use technology to solve the problem. For one class, a requirement was stipulated that they had to use technology and needed to submit their Excel spreadsheet or other computation answer while the other group was given the same instructions as previous years (that is, it was up to them to decide how to proceed).

Task description

The problem solving task had to be sufficiently general to be applicable to different disciplines as well as different levels of students in their college career. The task involved asking students to make a decision about taking a new job offer. We asked them to decide whether or not they would keep their current job that pays \$5,000 per month or accept a new position as a manager of an equipment rental business. In the new position, their base salary would be \$3,000 per month plus they would receive 2% commission of gross margin. Students were given the equation for gross margin (Gross Margin = Total Revenue – Total Costs) along with other data about the equipment rental business. They were given information about the prices of the monthly rentals, the fixed and variable costs typically incurred, as well as estimations of the percentages of units that are leased out at any given time (i.e., 85% of the 100 units are typically rented). Ranges for the various variables were given (e.g., the problem explained that fixed costs ranged from \$10,000 to \$16,000 per month but were most often \$15,500 per month). Students were asked to assess the new job and determine whether or not they would accept the offer. The task was designed to introduce uncertainty, risk, variable information, etc. and to test their ability to decipher and apply engineering problem solving and critical thinking to the problem.

The problem is open ended with no right or wrong answer.

Scoring the problem solving task and written reflections

The reflective questions students answered after solving the problem were matched to Wolcott's levels of problem solving ability, so that there was one question for each level. Thereafter, the student's work turned in and their reflective submissions were analyzed using Wolcott's 'Steps for better thinking rubric' (see Appendix A) [4].

A scoring record sheet was developed to score the student's problem solution as well as their associated responses to the set of online reflective questions about the problem solving process Each student received a score out of 28, and this was then translated into one of Wolcott's [4] problem solving performance patterns of (a) confused fact finder (CFF) (score 0 – 4), (b) biased jumper (BJ) (score 5 – 10), (c) perpetual analyzer (PA) (score 11-17), (d) pragmatic performer (PF) (score 18 – 24), and (e) strategic revisioner (SRV) (score 25 – 28).

To ensure inter-rater reliability, two of the authors scored a batch of the student samples together to develop the scoring protocol. Thereafter, each of them separately scored an additional set of tasks and again compared ratings. Inter-rater reliability was 88.6%. There were four items on two work samples that were scored differently by the two raters, with a difference of only one point in each instance. After discussion, agreement was reached on all the items initially scored differently. Once this was done, one of the authors scored all of the student work reported in this paper, with the second randomly checking for consistency.

Scoring of task solution

We also scored the overall approach to solving the problem using the following classification. Each student solution to the task was giving a score of 0, 1, 2, or 3 based on how the student solved the problem using the levels described below.

Level 0:

The student cannot ascertain relevant information from the problem statement and cannot formulate the correct equations to model the problem and ultimately cannot make a reasonable recommendation.

Level 1:

The student is able to figure out some of the information and model the problem using the equation. They typically would calculate a point estimate around the most likely case (they may consider this the "average" case) and make a recommendation without regard to the range values of the variables. Two sub-classifications of level 1 were create: (a) 1 minus was given when the student incorrectly calculated the point estimate around the most likely case in making their recommendation (arithmetic errors), and (b) 1 plus if they were able to correctly calculate a point estimate when making their recommendation. See Table 1 for an example of a level 1 solution which could then used be used to make their decision to accept the new job offer. As one can see the, the most likely case is less than current guaranteed job.

Table 1: An Example of
Level 1 Task Solution.

Commission %	2%
Current Salary	$5,000
Base Salary	$3,000
BreakEven (LSL)	$2,000

	Most Likely Case
Revenue	
Rental Fee per Unit	$2,100
Units under Lease	85
Total Monthly Revenue	$178,500
Costs	
Variable Cost per Unit	$800
Total Variable Cost	$68,000
Fixed Cost	$15,500
Total Monthly Cost	$83,500
Gross Margin	$95,000
Monthly Commission	$1,900
Take Home	$4,900

Level 2:

Like a level one student, a level two student is able to discern the pertinent information as well as use the engineering equation. However, they also recognize that you may not always have the typical case owing to the other information given (i.e., range of values for the various input variables). Therefore, this level student may calculate the best and worst case scenarios along with the most likely case (See Table 2 for an example). Like level one, there were two similar sub-classifications in level 2: (a) 2 minus would indicate the student incorrectly calculated the best and worst case scenarios along with the most likely case and (b) 2 plus would specify a correct calculation of the best and worst case scenarios along with the most likely case. In their recommendation, they may discuss risk and uncertainty associated with the solution. If they feel they are a motivated hard worker, they may choose the new job because they could potentially make $1600 more than the current job. However, the risk adverse individuals may conclude that the worst and most likely cases are below their current salary and decide to accept the new offer.

Level 3:

A level two student ascertained that the range on the various inputs may have an impact on the solution and looked at three typical scenarios (best, most likely, and worst case) in making their decision. A level three student may recognize that it is highly unlikely to ever get the worst or best case scenarios (i.e., the probability to achieve the highest revenue by renting the maximum number at the maximum rental feel while at the same time having all the costs at their absolute e minimum level is very low). This level of student may examine a wide variety of different scenarios (i.e., more than five scenarios) to compare. Other students may recognize that more scenarios than that are needed and will perform a simulation to generate for example 1,000 random scenarios. Now the student is able to quantify the risk in terms of a probability or likelihood that they will make more money in this new job (i.e., more than the $5000 per month). Again two further sub-classifications were used in scoring: (a) 3 minus meant they attempted to incorporate probability by performing a simulation (examining various scenarios) to determine how often the new job will pay greater than $5000 per month and then base their recommendation accordingly but made mistakes in their analysis or approach while (b) 3 plus meant they correctly determined a probability of making more money by analyzing multiple scenarios and utilized this information in making a recommendation accordingly. An example of a level three solution is given in Table 3.

Results from Fall 2007

After analyzing the results, most of the students scored in the 2- and 2+ range which meant that the students typically calculated the best and worst case scenarios along with the most likely case. In their recommendation, they may have discussed risk and

Table 2: Example of level 2 task solution.

Commission %	2%		
Current Salary	$5,000		
Base Salary	$3,000		
BreakEven (LSL)	$2,000		
	Most Likely Case	**Best Case**	**Worst Case**
Revenue			
Rental Fee per Unit	$2,100	$2,500	$2,000
Units under Lease	85	100	70
Total Monthly Revenue	$178,500	$250,000	$140,000
Costs			
Variable Cost per Unit	$800	$600	$900
Total Variable Cost	$68,000	$60,000	$63,000
Fixed Cost	$15,500	$10,000	$16,000
Total Monthly Cost	$83,500	$70,000	$79,000
Gross Margin	$95,000	$180,000	$61,000
Monthly Commission	$1,900	$3,600	$1,220
Take Home	$4,900	$6,600	$4,220

Table 3: Example of a Level Three Solution.

	Most Likely Case	Best Case	Worst Case	Simulated Case	Correlated Case	
Revenue						
Rental Fee per Unit	$2,100	$2,500	$2,000	$2,222	$2,227	
Units under Lease	85	100	70	$98	$87	
Total Monthly Revenue	$178,500	$250,000	$140,000	$217,756	$193,216	
Costs						
Variable Cost per Unit	$800	$600	$900	$868	$756	
Total Variable Cost	$68,000	$60,000	$63,000	$85,064	$65,556	
Fixed Cost	$15,500	$10,000	$16,000	$11,478	$13,064	
Total Monthly Cost	$83,500	$70,000	$79,000	$96,542	$78,620	
Gross Margin	$95,000	$180,000	$61,000	$121,214	$114,596	
Monthly Commission	$1,900	$3,600	$1,220	$2,424	$2,292	
Take Home	$4,900	$6,600	$4,220	$5,424	$5,292	
$2,424	Uniform Case			$2,292	Triangular Case	
1	3134.46	Probability >= 2000		1	1918.641942	Probability >= 2000
2	2832.92	74.8%		2	2181.510307	72.2%
3	2242.54			3	1999.680284	
4	2470.12			4	2232.661069	
5	2361.24			5	1857.277255	
6	1660.3			6	1633.395594	
7	2503.96			7	2351.220234	
8	2401.38			8	1872.515142	
9	1991.32			9	2112.716432	
10	1759.76			10	1952.851566	

uncertainty. The majority of the students completing the problem solving task fell into the "Biased Jumper" (proceeds as if goal is to stack up evidence and information to support own conclusion) and "Perpetual Analyzer" (proceeds as if goal is to establish an unbiased, balanced view of evidence and information from different points of view) categories, with very few students in the upper levels of the Wolcott problem solving scale (see Appendix A).

In addition, results from the 2007-2008 academic year suggested that students who used technology to solve the problem were more successful in providing an advanced solution, incorporating probability, performing a simulation, and examining various scenarios in order to generate a solution and make an informed recommendation. Also, among the students who used technology, a higher percentage of those students scored in the upper problem solving levels on the Wolcott scale (see Appendix A).

Table 4 compares the scores of students who used technology to solve the problem versus those who did not. As can be seen, a greater percentage of students who used technology scored higher on the task score and fell into the upper categories of the problem solving spectrum. Thus, the initial results indicated that the use of technology had helped students generate a more sophisticated solution and problem solving process.

Results from Fall 2008

In the fall of 2008, the study was replicated to examine in more depth the impact that technology had on the task solutions and problem solving processes. A quasi-experimental design was adopted to compare students who used technology to solve the problem with those who did not use technology. A comparison was done with freshman level courses (100 level) and upper classman courses (400 –level). At the 100 level, two separate classes were selected that were using the same curriculum (labs, notes, homework, etc.) but taught by different instructors and required one section of students to complete the task using a computer and turn in an Excel spreadsheet, while in the other section it was left up to the students to decide how to tackle the problem.

Table 4: Task performance based on student use of technology.

	Used Technology N=28	Didn't Use Technology N=119
Problem solving score		
CFF = Confused Fact Finder	7.14	8.40
BJ = Biased Jumper	50.00	54.62
PA = Perpetual Analyzer	25.00	32.77
PP = Pragmatic Performer	14.29	4.20
SRV = Strategic Re-Visioner	3.57	0.00
Task score		
0	0.00	3.36
1-	3.57	10.92
1+	7.14	22.69
2-	53.57	34.45
2+	17.86	26.89
3-	10.71	1.68
3+	7.14	0.00

At the 400-level, three comparable courses were selected and two sections were required to turn in their computer model (i.e., mostly Excel spreadsheets) used to generate their decision while the third section was left open for the students to decide how to complete the task. Despite the explicit instructions given, in all 400-level sections there were technology users and non-technology users. Therefore, the data was aggregated for all 400-level sections by technology versus non-technology users.

100-level classes Results

The data was analyzed using the same procedures already described. Figure 1 shows the scores from the 100-level students and indicates that the highest Wolcott level achieved by either group was that of "Perpetual Analyzer". However, there was a greater proportion of technology using students (40.0%) falling into the "Perpetual Analyzer" category as compared to the non-technology users (14.3%). The figure also shows that there were more non-technology users that fell into the lower levels on the Wolcott scale (i.e., "Biased Jumper").

A similar pattern emerged when looking at the task completion scores of the two groups as seen in Figure 2. As seen in the figure, a greater proportion of technology using students scored a 2- or 2+ (73%) as compared to only 43% of the non-technology users.

There were no 100-level students scoring at the upper ends of the Wolcott problem solving framework, or scoring a task completion score of 3. This is not surprising given that these students are mostly freshmen, with a few sophomores, and have very little discipline specific knowledge.

400-level classes

The same analysis for this freshman level course was used on the upper level courses. Figure 3 shows the problem solving scores for 400-level students. From the figure, only students who used technology were placed in Wolcott's highest problem solving category of "Strategic Revisioner" (10.5%), while none of the non-computer users reached this level of problem solving ability. There were also a higher proportion of technology users falling into the "Pragmatic Performer" category (31.6%), as compared with non-computer users (14.3%). Overall, 42% of technology users achieved a level 4 or 5 on Wolcott's scale, as compared to 10.5% of those who did not use computers to generate a solution. The majority of the non-computer users fell into Wolcott's third level of "Perpetual Analyzer" (62%). This demonstrates that as seniors these students are better able to critical think and analyze problems than were the students in the 100 level courses.

A similar pattern emerged when task completion scores of the two groups were compared. As can be seen, there is a slight shift towards a higher score since a greater proportion of technology using students scored a 3- (53%) as compared to zero percent of their non-technology counterparts. The highest task completion score for those not using a computer to solve the problem was a 2+ (48%).

We further analyzed the 400-level results by those who took the 100-level computer-based modeling course versus those who did not. This was done to identify whether the course had any long term impact on student's solutions and problem solving ability. Figure 5 shows that a greater percentage of the students who took the 100 course performed at the upper levels on the Wolcott problem solving

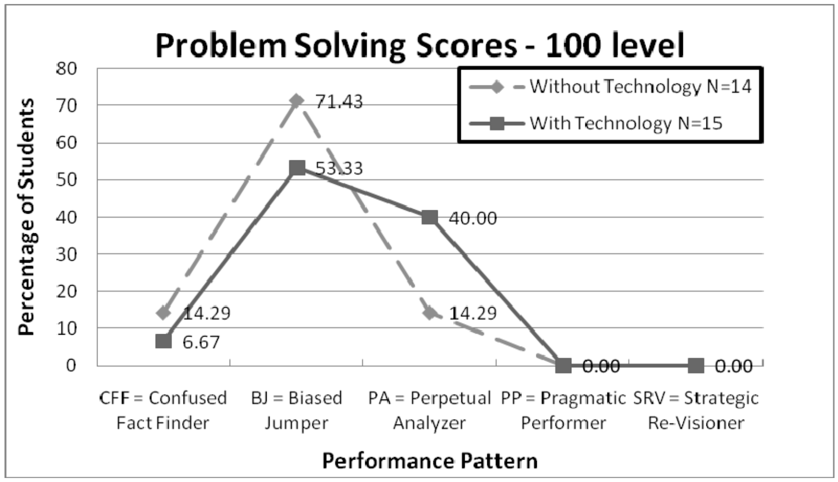

Figure 1: Problem solving scores for students in the 100 level courses, comparing students using technology to those who did not use technology.

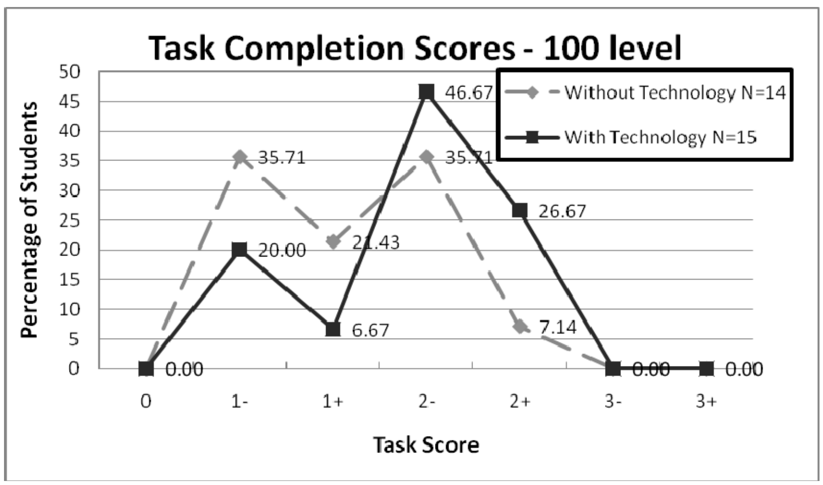

Figure 2: Task completion scores for students in the 100 level courses, comparing students using technology to those who did not use technology.

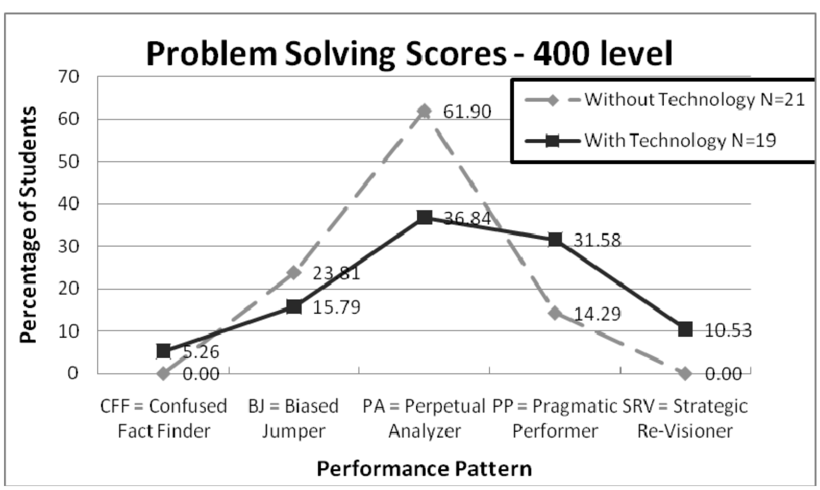

Figure 3: Problem solving scores for students in the 400 level courses, comparing students using technology to those who did not use technology.

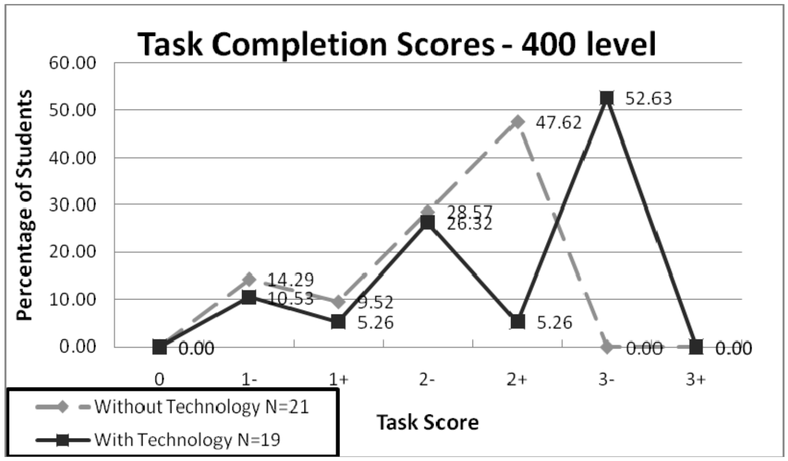

Figure 4: Task completion scores for students in the 400 level courses, comparing students using technology to those who did not use technology.

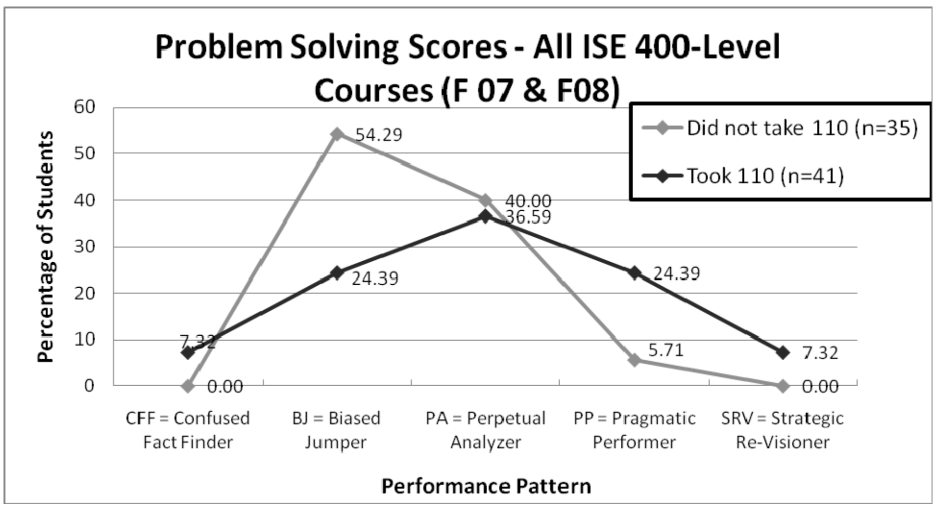

Figure 5: Problem solving scores for students in the 400 level courses, comparing students who took the 110 course to those who did not.

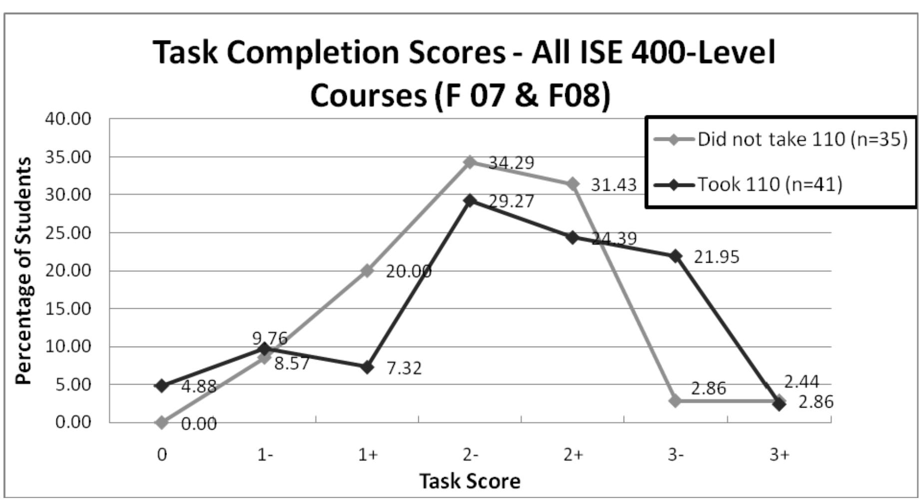

Figure 6: Task completion scores for students in the 400 level courses, comparing students using technology to those who did not use technology.

scale (24.4% Pragmatic Performers and 7.3% Strategic Revisioners) as opposed to students who had not taken the 100 course (5.7% Pragmatic Performers and 0% Strategic Revisioners).

Figure 6 shows a comparable result for the task completion score, where a greater percentage of students who had completed the 100-level course obtained a 3- or 3+ score (24.4%) as compared to those who did not take the 100-level course (5.7%).

Discussion

Our journey to this point has been quite exhilarating. It started four years ago in developing a more appropriate first computing course that utilized discipline specific problems as well as innovative teaching methods utilizing student owned computing to intertwine critical thinking and problem solving in with computational thinking thread.

Our conjecture is that technology, in this case computing, acts as enabler to assist students in problem solving. This enabler is different at the two different course levels. From Figure 1 and Figure 2, technology has certainly helped those students in the freshman level course generate a better solution as well as reach a higher level of problem solving based on the Wolcott model. The technology at this level enables or forces the students to gain a deeper understanding of the problem. Before they are able to model the problem using the computer, they need to obtain a greater understanding of what the problem is about, in order to tell a computer how to solve it. As an analogy, think about how you would tell your grandmother where the bathroom is located outside your office. You might say, 'go out the door and around the corner', which is a very surface description and understanding of the problem. To get a computer to generate the solution, one would need to be much more explicit and detailed. For example, you would need to tell your grandmother to 'first stand up, turn to the right and take five steps, then turn to the right again and go another ten steps, open the door, take three steps through the door, etc'. So, prior to entering anything into the computer, they need to comprehend what they are being asked to do, break the problem apart, analyze the problem at different levels, and then use the computer to rebuilding it and generate a solution. It should also be pointed out that the technology did not just give them a better solution, but also allowed them to be reach a higher level of problem solving ability.

At the upper class, Figure 3 and Figure 4 also demonstrated that the technology enabled the students to reach better solutions as well as higher levels of problem solving. However, at this level, the technology enabled the students to perform 'what if' scenarios, simulations, and number crunching (i.e., more scenarios) in reaching their conclusion. The technology made it easier to perform more sophisticated analyses, once the base case was setup.

Furthermore, the benefit accrued in the 100-level course appears to carry over to the upper division courses (see Figures 5 & 6). Students who had taken the lower division course tended to perform better on generating a viable problem and in their problem solving abilities than did those who had not taken the 100-level course. As part of our ongoing work in this area, we are planning to monitor this trend throughout the computational thinking thread we are developing across the curriculum [2]. It is also our intention to develop a problem solving and critical thinking thread using Wolcott's model [4] that runs parallel to the computational thread throughout the curriculum.

When looking at the results, it is interesting to note that if students were on the left side of problem solving scores (i.e., "Confused Fact Finder" for the100-level and "Confused Fact Finder and "Biased Jumper" for the 400-level), technology did not seem to help those students. It is not clear why this is the case. One conjecture may be that the students did not understand the software well enough to be able to gain the benefits of generating the model. But it does seem interesting that these lower thinking students gained no benefit from the technology and being able to figure out why will be very important in trying to enhance student learning outcomes.

The same problem solving task was used in all the classes described in this paper. The goal for the next round is to create another problem solving task to implement in similar classes at our university in the fall and spring of 2009, as an attempt to replicate the results using a different problem context. Another plan is to implement the original task at other universities that have the same engineering disciplines to see if the new course is making an impact on the student's problem solving ability. The team is currently in conversation with a few peer institutions. The goal will be conducting a comparable study at other locations and assisting them in developing a similar course.

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Biographical Information

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Appendix A:
Steps for Better Thinking Rubric

* Shaded cells most closely related to "stair step" model. Performance descriptions to the left of a shaded cell characterize skill weaknesses. Performance descriptions to the right of a shaded cell characterize skill strengths.

Steps for Better Thinking SKILLS	←Less Complex Performance Patterns				More Complex Performance Patterns→
	"Confused Fact Finder" Performance Pattern 0—How performance might appear when Step 1, 2, 3, and 4 skills are weak	"Biased Jumper" Performance Pattern 1—How performance might appear when Step 1 skills are adequate, but Step 2, 3, and 4 skills are weak	"Perpetual Analyzer" Performance Pattern 2—How performance might appear when Step 1 and 2 skills are adequate, but Step 3 and 4 skills are weak	"Pragmatic Performer" Performance Pattern 3—How performance might appear when Step 1, 2, and 3 skills are adequate, but Step 4 skills are weak	"Strategic Re-Visioner" Performance Pattern 4—How performance might appear when one has strong Step 1, 2, 3, and 4 skills
Step 1: IDENTIFY A—Identify and use relevant information B—Articulate uncertainties	A0—Uses very limited information; primarily "facts," definitions, or expert opinions B0—Either denies uncertainty OR attributes uncertainty to temporary lack of information or to own lack of knowledge	A1—Uses limited information, primarily evidence and information supporting own conclusion* B1—Identifies at least one reason for significant and enduring uncertainty*	A2—Uses a range of carefully evaluated, relevant information B2—Articulates complexities related to uncertainties and the relationships among different sources of uncertainty	A3—Uses a range of carefully evaluated, relevant information, including alternative criteria for judging among solutions B3—Exhibits complex awareness of relative importance of different sources of uncertainties	A4—Same as A3 PLUS includes viable strategies for GENERATING new information to address limitations B4—Exhibits complex awareness of ways to minimize uncertainties in coherent, on-going process of inquiry
Step 2: EXPLORE C—Integrate multiple perspectives and clarify assumptions D—Qualitatively interpret information and create a meaningful organization	C0—Portrays perspectives and information dichotomously, e.g., right/wrong, good/bad, smart/stupid D0—Does not acknowledge interpretation of information; uses contradictory or illogical arguments; lacks organization	C1—Acknowledges more than one potential solution, approach, or viewpoint; does not acknowledge own assumptions or biases D1—Interprets information superficially as either supporting or not supporting a point of view; ignores relevant information that disagrees with own position; fails to sufficiently break down the problem	C2—Interprets information from multiple viewpoints; identifies and evaluates assumptions; attempts to control own biases* D2—Objectively analyzes quality of information; Organizes information and concepts into viable framework for exploring realistic complexities of the problem*	C3—Evaluates information using general principles that allow comparisons across viewpoints; adequately justifies assumptions D3—Focuses analyses on the most important information based on reasonable assumptions about relative importance; organizes information using criteria that apply across different viewpoints and allow for qualitative comparisons	C4—Same as C3 PLUS argues convincingly using a complex, coherent discussion of own perspective, including strengths and limitations D4—Same as D3 PLUS systematically reinterprets evidence as new information is generated over time OR describes process that could be used to systematically reinterpret evidence

Step 3: PRIORITIZE E—Use guidelines or principles to judge objectively across the various options F—Implement and communicate conclusions for the setting and audience	E0—Fails to reason logically from evidence to conclusions; relies primary on unexamined prior beliefs, clichés, or an expert opinion F0—Creates illogical implementation plan; uses poor or inconsistent communication; does not appear to recognize existence of an audience	E1—Provides little evaluation of alternatives; offers partially reasoned conclusions; uses superficially understood evidence and information in support of beliefs F1—Fails to adequately address alternative viewpoints in implementation plans and communications; provides insufficient information or motivation for audience to adequately understand alternatives and complexity	E2—Uses evidence to reason logically within a given perspective, but unable to establish criteria that apply across alternatives to reach a well-founded conclusion OR unable to reach a conclusion in light of reasonable alternatives and/or uncertainties F2—Establishes overly complicated Implementation plans OR delays implementation process in search of additional information; provides audience with too much information (unable to adequately prioritize)	E3—Uses well-founded, overarching guidelines or principles to objectively compare and choose among alternative solutions; provides reasonable and substantive justification for assumptions and choices in light of other options* F3—Focuses on pragmatic issues in implementation plans; provides appropriate information and motivation, prioritized for the setting and audience*	E4—Articulates how a systematic process of critical inquiry was used to build solution; identifies how analysis and criteria can be refined, leading to better solutions or greater confidence over time F4—Implementation plans address current as well as long-term issues; provides appropriate information and motivation, prioritized for the setting and audience, to engage others over time
Step 4: ENVISION G—Acknowledge and monitor solution limitations through next steps H—Overall approach to the problem	G0—Does not acknowledge significant limitations beyond temporary uncertainty; next steps articulated as finding the “right” answer (often by experts) H0—Proceeds as if goal is to find the single, "correct" answer	G1—Acknowledges at least one limitation or reason for significant and enduring uncertainty; if prompted, next steps generally address gathering more information H1—Proceeds as if goal is to stack up evidence and information to support own conclusion	G2—Articulates connections among underlying contributors to limitations; articulates next steps as gathering more information and looking at problem more complexly and/or thoroughly H2—Proceeds as if goal is to establish an unbiased, balanced view of evidence and information from different points of view	G3—Adequately describes relative importance of solution limitations when compared to other viable options; next steps pragmatic with focus on efficiently GATHERING more information to address significant limitations over time H3—Proceeds as if goal is to come to a well-founded conclusion based on objective consideration of priorities across viable alternatives	G4—Identifies limitations as in G3; as next steps, suggests viable processes for strategically GENERATING new information to aid in addressing significant limitations over time* H4—Proceeds as if goal is to strategically construct knowledge, to move toward better conclusions or greater confidence in conclusions as the problem is addressed over time*