

A Conceptual Framework for Progressively Developing Students' Team and Problem Solving Skills Across the Curriculum

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Abstract

Project Catalyst is an NSF-funded initiative to promote systemic change in engineering education by utilizing proven instructional design techniques, transforming the classroom into an active learning environment, and incorporating the use of information technology in the teaching/learning process. In the first two years of Project Catalyst, a core group of faculty from all five engineering departments at Bucknell University has begun implementing this focused shift by systematically incorporating collaborative and problem-based learning into their courses. This emphasis has required a coordinated effort to introduce significant elements of team building and problem solving into the undergraduate curriculum.

This paper discusses a conceptual framework for progressively developing students' problem solving and team skills across the curriculum. The framework is modeled after the university's writing program and identifies introductory, intermediate and advanced problem solving and team building courses that are staged through the undergraduate engineering programs. This staged framework provides a structure to guide faculty in selecting teaming and problem solving activities to be emphasized in a given course.

To assist faculty in introducing appropriate teaming and problem solving activities, Project Catalyst has also developed instructional modules for faculty that focus on team building and problem solving at each level. These modules are course and curriculum independent and can be used in any course at other institutions. This paper will also describe preliminary assessment results of the curriculum structure. It concludes with the future work for the remaining year of this 3-year NSF-funded project.

Introduction

Bucknell's College of Engineering is implementing Project Catalyst, a three-year effort to develop a general-purpose model for the nationally recognized need of systemic engineering education reform. The plan is to integrate instructional design techniques, transform the

classroom into a cooperative learning environment, and incorporate efficiently and effectively the use of information technology in the teaching/learning process.

This NSF-sponsored project focuses on the four-year undergraduate curricula in all five engineering disciplines (chemical, civil and environmental, electrical, mechanical and computer science) at Bucknell University. Specifically, Catalyst provides an environment in which to promote change and encourage faculty members, students, and administrators to re-envision their roles in the engineering learning process.

Prior to the 1999-2000 academic year eight faculty and fifteen students studied team building and developed course materials and activities for cooperative learning. These materials were introduced in six courses ranging from an introduction to engineering to electrical and chemical engineering and computer science. The activities were quick in-class exercises such as turn-to-your-partner; laboratory work on open-ended problems and design; teamwork with peer and team evaluations; and using an electronic course management system such as BlackBoard[1]. Several interesting lessons were learned from these initial trials at implementing cooperative learning. First, working in teams does not come easily for faculty or students. It was found that faculty teams are harder to form than student teams but are essential since individual faculty efforts are not capable of producing systemic change. From the student point of view, team structure seemed to prevent the weaker students from falling too far behind their peers. Second, effective teaming requires time and well-structured exercises in team development. Third, overcoming resistance to teamwork is difficult and requires instruction in teamwork and problem solving skills in order to gain the maximum benefit from cooperative learning. Finally, to develop the desired levels of proficiency in the problem solving and team skills of students, it is necessary to have consistent repeated teaming exercises throughout the curriculum. To address this conclusion, the Catalyst group has developed a conceptual framework for developing a structured sequence of modules that will lead students from basic to advanced levels of problem solving and teamwork.

This framework draws on the structure of Bucknell's writing program[2]. This program defines two types of writing courses, W1 and W2, which emphasize different writing skills at each level with W2 courses building on skills developed in W1 courses. From the onset the implementation of Project Catalyst has focused on three aspects of the curriculum: introductory courses, core technical courses and capstone design courses. Combining these three levels with a Writing-Program-like structure produced the conceptual framework described in the remainder of this paper. A series of Supplementary Skills Modules (SSM)[3] that address the learning outcomes in each contained in frameworks are also under development at Bucknell. While these modules can be used at any point in the curriculum, Level 1 modules will be targeted at introductory courses, Level 2 modules at core technical courses and Level 3 modules at capstone design courses.

Developing Problem Solving Skills

The curricular structure to promote problem-solving skills consists of core courses phased throughout the curriculum that emphasize problem solving at distinct levels. The courses are broken down into introduction problem solving courses (P1), intermediate problem solving

courses (P2) and advanced problem solving courses (P3). The type of problems utilized in each course differentiates the courses. As a result of the distinct problem types used, the courses develop different problem solving abilities. Since these courses are staged throughout the 4-year curriculum, students gradually receive practice and instruction in a broad range of problem solving skills. As a result, students are gradually weaned away from textbook problems and develop more practical problem solving abilities.

Table 1 provides an overview of the types of problems encountered at each level of problem solving in the curriculum. The table also identifies where courses tend to fall in the four-year curriculum and maps learning outcomes associated with each course to Bloom's taxonomy. One can see that there is a steady progression in the range of problem solving skills required and in the level of Bloom's taxonomy [4] as students move through the staged problem-solving courses in the undergraduate curriculum. While there is not a complete separation of problem type used by course designation, a designated course will *emphasize* problems of a certain level. Therefore, while an intermediate problem solving course may contain some P1 and P3 type problems, the major emphasis will be on vaguely defined problems requiring significant problem definition on the part of the student. A more detailed description of each level of problem solving is described below.

Table 1.
Staged Levels of Problem Solving

Course Level	Definition	Example	Bloom's Taxonomy
<i>P1: Introductory Problem Solving</i>	Recognition and application of routine algorithms	Calculate the heat flux through a wall of known composition	Knowledge, Comprehension, and Application
<i>P2: Intermediate Problem Solving</i>	Solution of poorly-defined problems requiring students to reformulate problem into a solvable form before applying algorithms.	Determine why a room's heating system does not maintain a comfortable temperature	Analysis
<i>P3: Advanced Problem Solving</i>	Solution of open-ended, vaguely-defined problems requiring significant creativity. Comparing alternative design solutions.	Design a new heating system for a room that meets size and cost constraints.	Synthesis and Evaluation

Introductory Problem Solving Courses

Introductory problem solving or P1 courses emphasize well-defined problems having unique solutions and often unique solution methodologies. These are the types of exercises that are frequently found at the end of textbook chapters. Many of these problems rely on "problem recognition" and applying known algorithms. In introductory problem solving courses, students must develop the knowledge base to recognize the problem, choose an appropriate algorithm and execute it. For example, students in a course on heat transfer might be asked to calculate the heat flux through a wall, given the wall materials, thickness and temperatures of each surface.

This type of problem solving happens in many classes. While routine, it develops skills that are prerequisites for more advanced problems. In addition to providing the technical knowledge base necessary for engineering practice, introductory problem solving courses can be used to develop a number of general problem-solving skills. Specific learning outcomes associated with introductory problem solving courses include:

- The ability to recognize routine engineering problems and choose appropriate solution algorithms.

The most critical part of introductory problem solving courses is to accumulate the requisite background knowledge. The other major task of P1 courses is to help students recognize different kinds of problems—essentially to get students fluent in problem translation and problem identification. The task at this point is to help students sort through problems and to identify which are which.

- The ability to map out a solution plan.

Part of the ability to plan a solution is the ability to recognize when multiple solution methodologies exist and to evaluate the most efficient solution technique. Instructors are cautioned to be very tolerant of different solution paths and suggestions for alternatives. If the students think instructors are just trying to get them to all end up at the same point they may not go along on this. Here is where instructors will get the “Why don’t you just tell us what you want” statement. Even if the instructor knows that something won’t work, he or she should encourage the student to try it and let him/her come to that realization and understand why. It will be much more powerful and will also demonstrate the problem solving process.

- The ability to obtain relevant information necessary to solve the problem.

While identifying what needs to be known is part of mapping out the problem solution, the ability to obtain that information from reliable sources is a foundational skill for problem solving that can be emphasized in introductory courses.

- The ability to make and evaluate appropriate assumptions

This is a critical problem solving skill that is often under-emphasized by the heavy reliance on textbook problems where the problem is well defined and all relevant data is provided. We have found that students struggle with this aspect of problem solving and require significant practice to become comfortable with their ability to make appropriate assumptions.

- The ability to draw appropriate conclusions

Similarly, most textbook problems do not require students to draw conclusions from their calculations. Including this element of problem solving in student assignments not only develops practical problem solving skills, but also can add an element of reality and motivation for students.

Some of these skills, especially the ability to recognize a problem and plan a solution strategy, are elements of several published problem-solving methodologies. Therefore, instructors might think about introducing students to a formal problem solving methodology in introductory or subsequent courses emphasizing problem solving. We have introduced students to the well-known methodology of Donald Woods [5] because of its wide recognition and acceptance in engineering education. While it would be an oversimplification to suggest that all published methodologies are similar, a quick look at a sample of methodologies published in engineering references (Table 2) demonstrates that many of the published methodologies in engineering share several common features. The specific methodology adopted is not central to the curriculum structure proposed in this article, though Woods makes an articulate argument for his approach and provides a good overview of the literature for interested readers [9].

Table 2.
Comparison of Different Problem Solving Methodologies

<i>Woods [5]</i>	<i>Oakes et al. [6]</i>	<i>Polya [7]</i>	<i>Wankat [8]</i>
Engage: I want to and I can			I can
Define stated problem	Define the problem	Define	Define
Explore: Create internal idea of problem	Diagram and describe		Explore
Plan a solution	Apply theory and equations	Plan	Plan
	Simplify the assumptions		
Do it. Carry out your plan	Solve the necessary problems	Do it	Do it
Evaluate, check and look back.	Verify accuracy to required level	Look back	Check
			Generalize

Instructors might also give some thought to when they want to introduce students to formal problem solving methodologies. Again, Woods makes a good argument for the benefits of introducing a formal problem solving methodology at some point in the instructional process [9]. However, some instructors might consider that the introduction of a formal problem solving methodology is more appropriate in intermediate or advanced problem solving courses where students might most benefit from having a formal methodology to fall back on.

Intermediate Problem Solving Courses

Intermediate problem solving or P2 courses utilize problems that are more realistic in that they are vaguely defined. The significant difference from P1 courses is that intermediate problem solving courses emphasize problem definition in a way that is not present in introductory problem solving courses. This is accomplished by phrasing the problem in such a way that there is some ambiguity and uncertainty. A common approach used in these courses is to embed the

problem in a scenario that one might encounter if one were a consultant and just hired by an organization to correct a problem. Using the example in Table 1, students in a heat transfer course might be asked to assume the role of an engineering consultant brought in to analyze why the heating system does not maintain a comfortable room temperature. A common reason might be that the system is not adequately sized to handle the heat loss from the room, which students can determine by examining the specifications of the heating system and the relevant room characteristics. Students, however, must examine the problem and do the required analyses to determine the problem. Only then can they make a rational recommendation to address the problem.

The use of ill-defined problems develops critical problem solving skills that our students need. However, this is not necessarily design, nor does it require a great deal of creativity or synthesis. While having upped the ante, so to speak, by requiring significant and practical problem solving skills, the problems differ from those found in traditional design courses in that no significant amount of real design is necessary. However, there is a critical difference from P1 courses in that *students* must put the problem into a solvable form. Only then can students apply appropriate algorithms to complete any necessary calculations to solve the problem.

As with introductory problem solving courses, there are specific learning outcomes associated with intermediate problem solving courses that are independent of technical content. The generic learning outcomes associated with intermediate problem solving courses are:

- Those from P1 courses, which are foundational

Students still need the skills that they have learned in introductory courses to solve problems in the intermediate problem solving courses. Therefore, P2 courses can reinforce skills learned in P1 courses.

- The ability to define a problem

This is the critical distinction in intermediate problem solving courses. *Students* must first *put* the problem into the form that is solvable using an algorithm. The element of problem definition, common to almost all problem solving methodologies, must be in a different form than in P1 courses to move students along. Typically, the instructor might need to embed the problem in a scenario to distract students and to cause them to think deeply about what needs to be done. In this context, the introduction of a formal problem solving methodology that emphasizes the need to define the problem makes sense. Students might also be exposed to the literature that differentiates expert and novice problem solvers by the amount of time that they spend on problem definition and the literature that identifies problem definition as where most unsuccessful problem solvers go wrong [9].

In an intermediate problem solving course, students should also be encouraged to achieve a number of learning outcomes associated with problem definition, such as the ability to recognize that the problem as stated might not be the real problem and the ability to recognize that the problem might have several possible solutions.

- The ability to assess that the solution developed adequately addresses the given problem

This is analogous to Woods' "evaluation" stage in his formal problem solving methodology. We have found that the evaluation stage provides rich opportunities to have students reflect on both the technical solutions proposed and on the problem solving process itself.

Advanced Problem Solving Courses

Advanced problem solving or P3 courses emphasize problems that require significant elements of creativity. These might be the types of problems found in senior design courses. Here, design is described as ill-defined problems (poorly defined problem statements, goals or both) with multiple solutions and solution methodologies possible. In essence, the magnitude of the ambiguity changes from intermediate courses. The problems become one of scale and scope. The students are asked to start at the beginning and to build something rather than fix something. If the instructor is embedding the problem in the context of a consulting problem, the student as consultant might be asked to design a plant of some sort—which would be different from the type of ill-defined problem encountered in an intermediate problem-solving course. Advanced problems allow for more creativity and for more errors.

The specific learning outcomes associated with advanced problem solving courses include:

- All of the skills developed in P1 and P2 courses
- Ability to generate creative solutions to address the real problem

This skill might be developed through the use of brain storming or similar activities designed to promote creativity.

- Ability to evaluate and choose among multiple possible solutions

This relates to both the evaluation stage in Woods' methodology and to the evaluation level of Bloom's taxonomy. The evaluation of multiple solutions, together with the creativity required to generate these solution options, are the critical features of advanced problem solving courses.

Assessment of Problem Solving

Assessment of results of the curriculum structure to develop problem solving skills are preliminary at this point. We are still in the process of developing appropriate modules and instructor materials to develop problem solving skills. We are also still in the process of fully integrating the staged approach for problem solving into the curriculum. However, we have systematically surveyed both faculty and students involved in Project Catalyst [10] on the effectiveness of the courses for developing problem-solving skills. Because the Chemical Engineering program has achieved the highest level of curriculum integration at this point, the survey results are shown from chemical engineering courses in the sophomore, junior and senior years. Those results are shown in Table 3. While survey data are only one measure of the

effectiveness in achieving learning outcomes, there is some evidence to suggest that survey data correlate reasonably well with other objective measures. For example, Pike [11] found that self-reported measures of educational gains were as valid as objective measures to the extent that the self-report measures reflected the content of the learning outcomes under consideration.

The results show a high degree of consistency between students and faculty and from course to course. Both students and faculty moderately to strongly agree that the targeted courses were effective for developing a range of problem solving skills. In addition, both students and faculty moderately to strongly agree that the targeted courses were more effective for developing problem solving courses than traditional courses.

Table 3.
Student and Faculty Survey Data on Problem Solving

Questions for Spring of 2001	Student Response¹	Faculty Response
This course was effective in developing students' abilities to analyze and evaluate problems beyond the simple recall of facts.	6.61 [†]	6.33
This course satisfactorily developed students' abilities to integrate course material to solve open-ended problems.	6.45	5.67
The collaborative learning format of the course was more effective in developing problem-solving skills than a traditional lecture based approach	6.59	6.67
The collaborative learning format of the course was more effective in developing critical thinking than a traditional lecture based approach	6.44	6.67
Questions for Fall of 2001	Student Response²	Faculty Response
This course was effective in requiring students to use knowledge gained previously from other courses in the curriculum.	6.08 [†]	6.29
This course was effective in developing students' abilities to solve problems that are vaguely defined or that have more than one acceptable solution.	6.27	6.14
This course was more effective than a lecture-based format [‡] for requiring students to use knowledge gained previously from other courses in the curriculum.	5.84	6.57
This course was more effective than a lecture-based format [‡] for developing students' abilities to solve problems that are vaguely defined or that have more than one acceptable solution.	6.02	7.00
<p>1. Student data taken from 3-targeted courses in the chemical engineering curriculum. Fluid Mechanics in the sophomore year, Unit Operations laboratory in the junior year and Advanced Design in the senior year. Each course stressed elements of teamwork at different levels.</p> <p>2. Student data taken from 4-targeted courses in the chemical engineering curriculum. Chemical Engineering Principles in the sophomore year, Heat and Mass Transfer and Equilibrium Stage Processes in the junior year, and Design in the senior year. Each course stressed elements of teamwork at different levels.</p> <p>[†] All responses on a 7-point scale: 7-highly agree, 6-moderately agree, 5-slightly agree, 4-neutral, 3-slightly disagree, 2-moderately disagree, 1-highly disagree.</p> <p>[‡] For purposes of this survey, a "lecture-based" format was defined to be one where the professor sets the agenda and lectures for the majority of the time in class.</p>		

Developing Teamwork Skills

Oakes and Gunn [6] state that “Tough problems require teams.” An important characteristic of successful teams is the power of *creative collaboration*. Michael Schrage [12] defines creative collaboration as “the process of shared creation: two or more individuals with complementary skills interacting to create a shared understanding that none had previously possessed or could have come to on their own.” This is the synergy created within the team where the whole is much more than the sum of the parts. Creative collaboration is what allows teams to solve tough problems. Creative collaboration is the essence of why to use teams.

Students need to experience being on successful teams to understand and appreciate the values of good teamwork. However, many students lack appropriate team skills, such as managing effective meetings, being a good listener and being able to resolve conflicts. Also, just placing several students in a group and telling them “Be a team!” results in many dysfunctional teams. A team is not the same as a group. The term “group” implies little more than a collection of individuals. The term “team” implies much more. What are the fundamental skills that students need to learn in order to be effective in a team environment?

Based on their research work to better specify the eleven ABET program outcomes (3.a-k) defined in Engineering Criteria 2000, Besterfield-Sacre, et al. [13] provide attributes needed to achieve Program Outcome 3.d of “An Ability to Function on Multi-Disciplinary Teams.” Table 4 summarizes the 15 outcome elements needed to develop students' skills in teamwork. These outcome elements are categorized into collaboration/conflict management, team communication, team decision-making, and self-management, with each outcome element having six to eight attributes, based primarily on Bloom's cognitive/affective domain. These attributes are measurable, student learning outcomes [13], and they provide the instructor with a buffet from which to pick and choose, in order to reach a specific program outcome element. The 15 elements in Table 4 for ABET Program Outcome 3.d serve as a basis from which to develop the integration of teamwork skills across the curriculum.

The curricular structure to promote teamwork skills consists of core courses phased throughout the curriculum that emphasize teamwork at distinct levels, similar to that defined above for problem-solving skills. The courses are broken down into introductory teamwork courses (T1), intermediate teamwork courses (T2) and advanced teamwork courses (T3). Since the practice of teamwork needs a context, the T1, T2, and T3 courses are associated with the P1, P2, and P3 problem solving courses, respectively. These problem types coupled with the instructor/student control of activities in each course differentiate the courses. As a result of the distinct activities used, the courses develop different teamwork abilities. Since these courses are staged throughout the 4-year curriculum, students gradually receive practice and instruction in a broad range of team skills. As a result, students are gradually weaned away from instructor-directed activities and develop more practical teamwork abilities in student-directed activities.

Table 5 provides an overview of the types of skill elements encountered at each level of teamwork in the curriculum. The table also identifies where courses tend to fall in the four-year curriculum with respect to problem type and instructor/student control. One can see that there is a steady progression in the range of problem solving and teamwork skills as students move

Table 4.
Learning Outcome Elements for the Ability to Function on Teams [13]

Collaboration/Conflict Management	
• Team Development:	Basic principles of group development and interpersonal dynamics.
• Interpersonal Style:	Recognizing and capitalizing on differences in style and perspective.
• Conflict Management:	Principles of problem-based conflict management.
• Participation:	Understanding of and willingness to be fully involved in team efforts.
Team Communication	
• Active Listening:	Conveying understanding and using listening skills to move a conversation forward.
• Feedback:	Giving and receiving constructive criticism.
• Influencing others:	Persuading others through well-reasoned use of facts and clear conveyance of ideas.
• Sharing Information:	Providing and reviewing information in a timely manner.
Team Decision-making	
• Defining a Problem:	Identifying and articulating the problem to be solved.
• Innovation/Idea generation:	Generating creative and viable solutions.
• Judgment/Using facts:	Reaching conclusions based upon clear analysis of facts and ideas.
• Reaching Consensus:	Ensuring buy-in and commitment to decisions reached.
Self-Management	
• Establishing directions and standards:	Helping create plans and structure for the team.
• Managing meetings:	Using principles of effective team meetings
• Personal conduct:	Demonstrating personal responsibility to the team and respect for team members.

Table 5.
Staged Levels for Teamwork

Course Level	Definition	Skill Elements
<i>T1: Introductory Teamwork</i>	Recognition and application of basic team skills to solve P1-type problems; Highly-structured activities and materials provided by instructor to guide and mentor students.	Team development and interpersonal dynamics, team contract, managing meetings, and active listening with feedback.
<i>T2: Intermediate Teamwork</i>	Practice and application of T1 skills augmented with intermediate team skills to solve P2-type problems; Transition from highly-structured to loosely-structured activities giving students more control.	Conflict management, constructive criticism, and persuasion.
<i>T3: Advanced Teamwork</i>	Practice and application of T2 skills augmented with advanced team skills to solve P3-type problems, giving students full control to self-monitor; Instructor serves as a facilitator to set timelines and provide feedback.	Team decision-making involving problem definition, idea generation, judgment, and reaching consensus.

through the staged teamwork courses in the undergraduate curriculum. While there is not a complete separation of skill type used by course designation, a designated course will *emphasize* teamwork skill of a certain level. Therefore, while an intermediate teamwork course may contain some T1 and T3 type skills, the major emphasis will be on moving students from

instructor-directed to self-directed activities as a team. A more detailed description of each level of teamwork is described below.

Introductory Teamwork Courses

Introductory teamwork skills are associated with P1 courses that emphasize well-defined problems having unique solutions and often unique solution methodologies. We have found that bi-weekly team projects of assigned exercises, which are frequently found at the end of textbook chapters, work well here. Team membership of 3-4 students works best. Two is too small because there is not enough diversity of ideas and more than four leads to some team members not actively participating. In introductory teamwork courses, students must gain a knowledge base about interpersonal dynamics, create team contracts, manage meetings, and practice active listening and feedback. These activities help to develop those basic skills that are prerequisites for more advanced teamwork activities. Specific learning outcomes associated with introductory teamwork courses include:

- The ability to recognize team development phases and preferred styles of learning

Organizational behavior theory suggests that teams typically go through five stages of development: forming, storming, norming, performing and adjourning. Students should be aware of these stages so they do not become demoralized by the low productivity and personality conflicts that are typical of new teams in the earlier stages. Teams need to progress to the "performing" stage, where members understand and are committed to their individual responsibilities and to the team's overall success.

People think, learn, and approach problems differently. These varied styles give diverse teams the potential to be far more effective than individuals working alone. Unfortunately, those same distinctions can lead to friction and confusion among team members, especially those relatively new to teamwork activities. It is therefore important for students to recognize that styles other than their own exist, and that a mixture of preferred styles can ultimately be beneficial in a team setting.

Instructors should be aware of instructional strategies to help students recognize the team development process, the preferred styles of learning, and other teamwork skills. Through Project Catalyst, we are developing a practical teamwork guide that provides advice on how to develop students' team skills at the T1, T2, and T3 levels in an educational setting.

- The ability to develop and use a team contract for monitoring membership conduct

A team needs to formulate its own contract on team behavior that the members will follow for the rest of the semester. We have learned not to hand out a sample contract and to tell the students to develop their own based on it. They will take the easy route and all the resultant contracts will look very close to the sample. The instructor needs to provide resources with good ideas that the students must process to formulate their own contract. The instructor wants to foster shared ownership by the team.

A team contract needs to include rules and regulations on, at least, the following elements from Table 4: participation, sharing information, establishing directions and standards, managing meetings, and personal conduct. A contract is basically an assessment instrument that members can review periodically to evaluate how their team is performing, and instructors can use it to mentor teams when they are having difficulties.

- The ability to apply principles for effective team meetings

Team meetings are necessary to communicate progress, exchange ideas, resolve misunderstandings, and to plan future activities. Team members must describe the components of an effective team meeting, must discourage side-conversations and/or getting off track during discussions, must manage time during meetings, must assist in note taking and recording meeting minutes, must monitor meeting progress and effectiveness, and must evaluate team performance relative to their team contract.

Teams need time and space to hold their meetings. We have found it effective to devote some lecture time to allow teams to hold their meetings. The instructor can initially provide a highly-structured procedure for team meetings. Once teams obtain mastery of the process, they can be given more freedom to re-design their meeting procedures.

- The ability to do active listening with meaningful feedback

Active listening and feedback are essential for teams to be productive and to develop cooperatively the solutions to well-defined problems. Team members must convey understanding and use listening skills to move a conversation forward. Students need to restate what has been said to show understanding, to ask open-ended questions in order to encourage discussion, to summarize main points of discussions before moving on to other topics, to ask questions to clarify misunderstanding, and to convey understanding of other perspectives. Active listening and feedback skills are also important when teams do regular self-assessments on their performance relative to their team contract.

In Table 5, the teamwork skills associated with conflict management, constructive criticism, and persuasion are usually not needed in P1 courses, because student teams are working on solving well-defined problems that have unique answers. However, if these intermediate teamwork skills are needed, the instructor can introduce them on a case-by-case basis. The advanced skill of team decision-making in Table 5 is also not needed in P1 courses, because synthesis and evaluation of alternatives are not the focus in these courses. However, decision making could be applied to different solution procedures that give the same unique answer to a well-defined problem. For example, a material balance problem could be solved based on mass, moles, and atoms—giving three different solution procedures but the same answer. Comparing these procedures, student teams could select the best one based on efficiency. Furthermore, comparing the solution procedures could result in a heuristic observation. For example, "solve a well-defined problem using mass balances when most of the information is given in terms of mass quantities."

In introductory teamwork courses, students are learning fundamental skills to be able to function in teams. They are also learning how to apply a problem-solving methodology (Table 2) to solve well-defined problems. As shown in Table 6, cooperative learning provides a framework in which to practice teamwork and allow students to develop and gain confidence in their team skills. It allows instructors to design highly-structured team activities that incorporate positive interdependence, individual accountability, face-to-face promotive interaction, appropriate use of teamwork skills, and regular self-assessment of team functioning. These five tenants of cooperative learning when coupled with a problem-solving methodology are powerful strategies to foster deep learning of a specific subject matter, particularly early in students' academic studies.

For example, sophomore students in chemical engineering must learn to apply the principle of material balances to solve well-defined problems. They must distinguish between different types of systems—continuous with no chemical reaction, batch, semi-batch, and continuous with chemical reaction. Starting with the fundamental conservation law of matter, students can write material balances based on mass, moles, or atoms. An instructional strategy could be designed to explicitly practice the six steps of a problem solving methodology that results in a conceptual diagram, a mathematical model, a mathematical algorithm, a numerical solution, some heuristic observations, and formal documentation. If a four-member team is assigned a two-week project that contains four problems (P.1, P.2, P.3, P.4) to solve the material balances for four different systems, then each lecture period can be devoted to each step in the problem-solving methodology, as illustrated in the following diagram:

Project:	First Week			Second Week		
Student	Monday	Wednesda	Friday	Monday	Wednesda	Friday
Marv	Diagram.	Model, P1	Algorithm.	Solution.	Heuristics.	Document.
Mike	Diagram.	Model, P2	Algorithm.	Solution.	Heuristics.	Document.
Beth	Diagram.	Model, P3	Algorithm.	Solution.	Heuristics.	Document.
Jack	Diagram.	Model, P4	Algorithm.	Solution.	Heuristics.	Document.

At each lecture period, all students are focusing on the same step in the problem-solving methodology, but each is doing it on a different problem. Before a lecture period, a team member must develop a draft outside of class and bring it to the lecture period. These drafts are used to focus the discussions and then plan for the next period. When team members move to the next lecture period, they will all have the same focus but on a different problem. At the end of the two weeks, all team members will have worked on all four problems and interacted with each other. In the sixth period, teams can be required to spend time doing self-assessment of their team functioning. This highly-structured instructional strategy incorporates all five tenets of cooperative learning and provides guided practice in the problem-solving methodology. It also allows deep learning to occur; that is, team members learn more collectively than what an individual could learn over the same two-week period.

Intermediate Teamwork Courses

Intermediate teamwork is associated with P2 courses that utilize realistic but vaguely-defined projects. The projects are given a context or scenario and are phrased in such a way that there is

Table 6.
Five Tenets of Cooperative Learning

Project Catalyst uses the pedagogical framework of “cooperative learning” to practice teamwork and allow students to develop and gain confidence in their team skills.

“*Cooperative learning* is instruction that involves students working in teams to accomplish an assigned task and produce a final product (e.g., a problem solution, critical analysis, laboratory report, or process or product design), under conditions that include the following elements (Johnson, et al., 1998):

- *Positive interdependence.* Team members are obliged to rely on one another to achieve the goal. If any team members fail to do their part, everyone on the team suffers consequences.
- *Individual accountability.* All team members are held accountable both for doing their share of the work and for understanding everything in the final product (not just the parts for which they were primarily responsible).
- *Face-to-face promotive interaction.* Although some of the group work may be done individually, some must be done interactively, with team members providing mutual feedback and guidance, challenging one another, and working toward consensus.
- *Appropriate use of teamwork skills.* Students are encouraged and helped to develop and exercise leadership, communication, conflict management, and decision-making skills.
- *Regular self-assessment of team functioning.* Team members set goals, periodically assess how well they are working together, and identify changes they will make to function effectively in the future.”[†]

Reading the above *five tenets*, one can see that teamwork is an integral part of cooperative learning. Cooperative learning has many benefits beyond being a training ground for teamwork.

“An extensive body of [educational] research confirms the effectiveness of cooperative learning in higher education. Relative to students taught conventionally, cooperatively-taught students tend to exhibit better grades on common tests, greater persistence through graduation, better analytical, creative, and critical thinking skills, deeper understanding of learned material, greater intrinsic motivation to learn and achieve, better relationships with peers, more positive attitudes toward subject areas, lower levels of anxiety and stress, and higher self esteem (Johnson, et al., 1998; McKeachie, 1999).”[†]

In Project Catalyst, a *team* is two or more persons who work together to achieve a common purpose *and* practice the five tenets of cooperative learning. However, we do not want to imply that group work is inferior to teamwork. Group work such as having students turn to their neighbor in class to solve a problem can be valuable learning experiences. For effective learning, the educator needs to provide a variety of learning activities, e.g., lecture, group work, and teamwork.

[†] Felder, Richard M. and Rebecca Brent, “How to Improve Teaching Quality,” *Quality Management Journal*, Vol. 6, No. 2, 1999, pp. 4-5.

some ambiguity and uncertainty in the problem; however, it is not a design problem. We have found that two- to four-week projects assigned to teams of 3-4 students work well. Given that they are working on ill-defined problems, team members need to develop their abilities in conflict management, constructive criticism, and persuasion. The specific learning outcomes associated with intermediate teamwork courses include:

- The ability to apply those teamwork skills from T1 courses, which are foundational

Students still need the skills that they have learned in introductory courses, in order to practice teamwork in the intermediate courses. Therefore, T2 courses can reinforce skills learned in T1 courses.

- The ability to apply the principles of problem-based conflict management

As teams are given more control over their activities, they may experience interpersonal conflicts as they address solving ill-defined problems. By regularly using self-assessment on how the team is functioning, team members and the instructor can monitor a team's progress. When conflict is detected, the instructor can use a just-in-time strategy to help the team reflect on its conflict. The team would be encouraged to read materials on problem-based conflict management, asked to apply the conflict-resolving principles, and requested to self-assess after a period of time. Basically, the team is given a chance to exercise self-control in solving its conflicts. During this time, the instructor acts as a mentor and consultant.

- The ability to give and receive constructive criticism

The exchange of ideas and the evaluations of them contribute significantly to finding a better solution to an ill-defined problem. Students must develop the ability to give and receive constructive criticism, without it being personal. Giving specific and constructive feedback to other team members requires the ability to balance negative comments with positive ones and to avoid judgmental language or cheap shots. In addition, team members need to accurately assess their own and others' ability to give and receive constructive criticism.

- The ability to influence others through logical reasoning and clear conveyance of ideas

In a team environment, the art of persuasion can be a powerful tool to find a better solution to an ill-defined problem. Team members must understand the principles of how to influence others, must articulate ideas clearly and concisely using specific examples, must develop plans and presentations that influence others, must accurately assess their own and others' ability to influence others, and must comfortably express alternative points of view.

In Table 5, the advanced skill of team decision-making is usually not needed in P2 courses, because students are analyzing vaguely-defined problems and putting them into solvable forms. However, if this advanced teamwork skill is needed, the instructor can introduce it on a case-by-case basis. Because P2-type problems contain ambiguity and uncertainty, their solutions will require teams to apply conflict management, constructive criticism, and persuasion, particularly as the students take more control on how the team functions.

In intermediate teamwork courses, students are transitioning from highly-structured to loosely-structure activities as they function in teams to solve realistic but vaguely-defined problems. The instructor designs instructional activities to give students more control as they progress through the course. For example, initially team meetings may be highly-structured by the instructor. This requirement helps to reinforce what students have learned in T1-type courses. Later in the course, the instructor would relax the structure, giving the students more control in how they

conduct their team meetings. This transition helps to introduce students to the loosely-structured activities that they will experience in advanced teamwork courses. In addition to taking more control, students are also learning about new T2-type skills. For example, team members would need to apply constructive criticism and persuasion while addressing a vaguely-defined project on global warming, materials recycling, or energy conservation.

Advanced Teamwork Courses

Advanced teamwork is associated with P3 courses that solve complex problems using significant elements of synthesis and evaluation. Teams of students must solve ill-defined problems with multiple solutions, typically found in design courses. Advanced problems allow for more creativity, for more errors, and for more cooperation among team members. Students take more control over how the team functions, but still under the supervision of the instructor. The specific learning outcomes associated with advanced teamwork courses include:

- The ability to apply all of the teamwork skills developed in T1 and T2 courses

Students will need the teamwork skills from the introductory and intermediate courses to solve the complex problems associated with advanced problem-solving courses. These P3 courses encourage self-direction on the part of the students with respect to the T1 and T2 team skills and foster students' abilities in team decision-making.

- The ability to apply the principles of team decision-making.

Given the complexity of ill-defined problems in senior-level courses, teams must function in a cooperative manner to make decisions and find a viable solution. They need to identify and articulate the problem to be solved, generate creative and viable solutions, reach conclusions based upon clear analysis of facts and ideas, and ensure buy-in and commitment to decisions reached.

In advanced teamwork courses, P3-type problems require decision-making that involves the synthesis of alternative solutions and then the subsequent evaluation of those solutions to select the "best" one. For example, polluted water needs to be purified continuously and at a certain rate. Three competing solutions might be distillation, reverse osmosis, or membrane separation. The "best" one might be selected based on capital and operating costs. In practicing decision-making, students are given more autonomy and control as they function in teams to solve complex problems. The instructor serves as a facilitator, consultant, and/or client to set timelines and provide constructive feedback.

Assessment of Teamwork

Assessment of results of the curriculum structure to develop teamwork skills are preliminary at this point. We are still in the process of developing appropriate modules and instructor materials to develop teamwork skills. We are also still in the process of fully integrating the staged approach for teamwork into the curriculum. However, we have systematically surveyed both faculty and students involved in Project Catalyst [10] on the effectiveness of the courses for

developing teamwork skills. Because the Chemical Engineering program has achieved the highest level of curriculum integration at this point, the survey results are shown from chemical engineering courses in the sophomore, junior and senior years. Those results are shown in Table 7.

The results show a high degree of consistency between students and faculty and from course to course. Both students and faculty moderately to strongly agree that the targeted courses were effective for developing teamwork skills. In addition, both students and faculty moderately to strongly agree that the targeted courses were more effective for developing teamwork courses than traditional courses.

Faculty Teamwork

Learning to function in a team environment is hard work, but it can be a very rewarding experience for both students and instructors. Realizing the power of teamwork is the synergy it can bring to solving problems; that is, "two heads are better than one" and "the whole is much more than the sum of the parts." Project Catalyst is a good example of teamwork in action. The team is 11 faculty members from five disciplines (chemical, civil, electrical, and mechanical engineering and computer science), a project director with degrees in education, instructional technology, and electrical engineering, and an instructional technologist with degrees in mathematics and instructional technology. The faculty members have no formal training in instructional theory or information technology; however, they bring a wealth of experience in teaching ranging from two to thirty-four years. The major focus of this experience has been in instructor-directed or traditional instruction, but all faculty participants in Project Catalyst have migrated to active learning in the classroom over the past ten years.

The diverse mix of talent on the Project Catalyst team has contributed significantly to the progress made over the last two years. Most of the faculty members have had limited experience functioning in a true team environment, mainly because most of their opportunities have been in group work and not teamwork. The work of Project Catalyst is designed to foster faculty teamwork, in order to reach the major project goal of integrating active learning and information technology across the curriculum. The road was initially bumpy as the team found its way through the forming, norming, storming, and performing stages of team development. With the completion of the second year of Project Catalyst, the diverse team is progressing steadily into the performing stage.

The development of this paper on problem-solving and teamwork skills serves as a good example of the synergy needed to formulate the models for integrating these skills across the undergraduate curriculum. During this past summer, five faculty members worked on developing an initial draft of a practical guide on problem solving. At the same time, six other faculty members worked on developing a practical guide on teamwork. The purpose of these two guides is to provide practical advice on how to develop students' skills in an educational setting. The project director provided the initial idea on the P1-P3 and T1-T3 models that stage student experience through an engineering program. This staged framework, which is modeled after the university's writing program, provides a structure to guide faculty in selecting teaming and problem solving activities to be emphasized in a given course. This paper presents the

formal descriptions of both models, each authored by a faculty member who coalesced the ideas and materials produced by all members of the Project Catalyst team. The synergy present here has led to a paper that could not be developed by one faculty member, working full time at teaching, over a two-year period.

Table 7.
Student and Faculty Survey Data on Teamwork

Questions for Spring of 2001	Student Response ¹	Faculty Response
This course was effective in developing students' skills as a leader and a participant in group-based activities.	6.62 [†]	6.00
The collaborative learning format of the course was more effective in developing team skills than group activities in a traditional lecture based approach.	6.58	6.67
Questions for Fall of 2001	Student Response ²	Faculty Response
This course was effective in developing students' skills as leaders and/or participants in group-based activities.	6.26 [†]	6.29
This course was more effective than a lecture-based format [‡] for developing students' skills as leaders and/or participants in group-based activities.	6.20	7.00
<p>1. Student data taken from 3 targeted courses in the chemical engineering curriculum. Fluid Mechanics in the sophomore year, Unit Operations laboratory in the junior year and Advanced Design in the senior year. Each course stressed elements of teamwork at different levels.</p> <p>2. Student data taken from 4 targeted courses in the chemical engineering curriculum. Chemical Engineering Principles in the sophomore year, Heat and Mass Transfer and Equilibrium Stage Processes in the junior year, and Design in the senior year. Each course stressed elements of teamwork at different levels.</p> <p>[†] All responses on a 7-point scale: 7-highly agree, 6-moderately agree, 5-slightly agree, 4-neutral, 3-slightly disagree, 2-moderately disagree, 1-highly disagree.</p> <p>[‡] For purposes of this survey, a "lecture-based" format was defined to be one where the professor sets the agenda and lectures for the majority of the time in class.</p>		

Conclusions

The Project Catalyst team has developed a conceptual framework for progressively developing students' team and problem solving skills across the curriculum. Each framework consists of three distinct levels of learning outcomes. Work has begun on developing generic curriculum modules that are not course or discipline specific which faculty can use to promote student attainment of the outcomes specified in each framework. Preliminary assessment efforts indicate that both faculty and students perceive that the course sequences in which the problem solving and team skills frameworks were implemented improved students' problem solving and team skills and that courses were more effective than traditional courses in developing these skills.

Future Work

Building on the early success of this curricular structure, the Project Catalyst team will focus its efforts on four areas: 1) completing the Supplementary Skills Modules associated with the

learning outcomes contained in problem solving and team skills frameworks; 2) increasing the frameworks' integrations into Bucknell's programs; 3) developing a framework for information technology skills; and 4) conducting a series of national workshops.

The primary focus will be on completion of the Supplementary Skill Modules associated with the learning outcomes in each of the conceptual frameworks described above. Some of these modules have been completed and implemented, others are still in their infancy and work on others has yet to begin. At the conclusion of the project, the team expects to have one or more modules that address each of the learning outcomes at Level 1, Level 2 and Level 3 of the problem solving and team skills frameworks.

To date, our conceptual framework has been integrated most completely into the chemical engineering curriculum. With the initial success of the framework in that program, we will continue to work with Bucknell's other programs to promote their continued adoption of the frameworks. Based on faculty participation in Project Catalyst, we expect Bucknell's electrical and civil and environmental program's adoption of the framework to grow significantly in the next year.

When the model for the conceptual framework was initially conceived, it also contained an information technology component. Work on this aspect of the model has not begun yet. In general the information technology goals of Project Catalyst have lagged behind the other programmatic emphases. This is in part due to the interest of the faculty and in part due to a desire to not have technology drive a teaching learning reform effort. However, developing the students' ability to use technology effectively in the problem solving and team building process is still seen as an important goal of Project Catalyst's work. To that end, we expect to develop an information technology conceptual framework of depth and specificity similar to the frameworks presented here.

Finally, based on our three-year experience with Project Catalyst, Bucknell's College of Engineering will share that experience by conducting a series of national workshops during the summer of 2002. These week-long workshops will introduce the participants to the integration of problem solving and teamwork into the curriculum, and give them training with the techniques and skills needed to implement this integration. They will also be exposed to appropriate modules and instructor materials to develop problem solving and teamwork skills. During the course of the academic year, participants will also be given an opportunity to work electronically with a mentor from Bucknell who will help them implement the changes in their instructional practice and adapt the modules to fit their particular classroom activities.

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