Applying Theory of Constraints to Solicit Feedback and Structure Improvements to a Capstone Design Experience

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Abstract

A transitional step in engineering education is the capstone design experience, which ideally emphasizes all phases of product realization as well as positive team dynamics. This paper describes an assessment and planning exercise used by capstone design instructors at the University of Idaho for the last five years. The exercise is based on Goldratt's theory of constraints and serves as a barometer of student preparation and team development in our year-long capstone design course. Results are presented in a graphical "prerequisites tree" that guides course sequencing. Prerequisite Trees were found to be quite similar from year to year. Items at the bottom of the tree, requiring initial attention, are not technical and are not generally project-dependent. These items tend to be personal and inter-personal issues, including self-learning skills, well-founded self-confidence, appreciation for diverse skill sets, and strong oral/written communication. The process of developing a classwide Prerequisites Tree during the first week of class underscores the importance of these non-technical issues and motivates proactive behavior in project teams. The Prerequisites Tree also provides a tool for monitoring individual and team development, suggesting timely interventions appropriate for any large engineering project.

I. Program Context

The capstone design experience is expected to unify a broad spectrum of design, teamwork, and communication competencies. These skill sets are diverse and multi-tiered. The Boeing Company, for example, lists some of these skill sets as desired attributes in engineers shown in Figure 1. These are mirrored in the Engineering Criteria 2000 recently implemented by the Accreditation Board for Engineering and Technology (ABET)[1]. Furthermore, each program is expected to monitor the performance capabilities of its graduates and pursue appropriate improvement activities. This expectation places even higher expectations on engineering capstone courses. The assessment and project planning process described in this paper offers a thoughtful response to these challenges. It has been implemented in our Mechanical Engineering capstone design course for the last five years.

Our capstone design course is a two-semester sequence that begins with customer interviews each September and results in a hardware prototype displayed at the Idaho Design Exposition each May. Undergraduate students are introduced to their graduate student mentors from the Idaho Engineering Works[2] in a shop familiarization project. This year they made a key-

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ring tool. Throughout the year student teams regularly interact with their graduate student mentors on technical and team issues. This is facilitated by the layout of our new capstone design suite that includes a CNC equipped machine shop, assembly area, CAD laboratory, conference/study area, and graduate student offices. The team-focus and technical excellence promoted by our program is illustrated in the video clip located at *http://niatt.uidaho.edu/education/skunkworks.ram* and in the IEWorks web page, *http://niatt.uidaho.edu/education/IEWorks.htm*. The diversity and scope of the projects our seniors have undertaken can be observed by visiting the archive located at *www.uidaho.edu/engr/ME/sr_des*.

- A good understanding of engineering science fundamentals, including mathematics, statistics, physical science, life science, and information technology.
- A good understanding of design and manufacturing processes.
- A multi-disciplinary, systems perspective.
- A basic understanding of the context in which engineering is practiced, including business practices, the environment, customer requirements, and societal needs.
- Good communication skills, including written reports, oral presentations, engineering drawings, and listening.
- High ethical standards.
- An ability to think both critically and creatively – independently and cooperatively.
- Curiosity and desire to learn for life.
- A profound understanding of the importance of teamwork.

Figure 1, Desired attributes of an engineer by the Boeing Company[3]

II. Method Selection

The design and management literature is filled with techniques for project planning. Any number of these are quite effective in situations were goals are well-defined, task sequencing is clear, and seasoned work groups already exist for implementing the plan. Unfortunately this is not the case in capstone design courses, especially those that use industry sponsored projects. Problem statements are initially quite vague, potential actions are abundant and ill-sequenced, and project teams are homogeneous without a leadership structure based on previous experience. In this circumstance, it is all too easy for students to find any number of planning tools to be sterile and irrelevant.

We were initially attracted to the work of Eliyahu Goldratt through two of his novels, The Goal[4] and It's Not Luck[5]. Both books describe ill-defined problems in an interesting engineering context that result from personality differences as well as organizational deficiencies. Underlying both plots is rational, but human-centered, planning process known as the theory of constraints. Our decision to experiment with Goldratt's thinking tools in the capstone design course was reinforced by several alumni who had read his books. All agreed that their capstone project work would have benefited from his approach.

Goldratt introduced the Prerequisite Tree in It's Not Luck as a tool for achieving aggressive goals. The tool capitalizes on the innate human ability to identify perceived obstacles to achieving the goals. These obstacles can include tangible as well as intangible constraints such as insufficient funding and personality conflicts. The process of articulating the obstacles requires inter-personal communication that promotes trust-building among potential teammates. Once the obstacles are identified, a set of intermediate objectives is generated that would remove each obstacle. For instance, if insufficient funding is an obstacle, an intermediate objective may be to give the customer design alternatives at several different budget levels. Intermediate objectives, therefore, are milestones to be achieved during the course of the project.[6]

Finally, the intermediate objectives are sequenced based on the number of obstacles that must be overcome before each objective can be successfully achieved. Some of the intermediate objectives may be achieved in parallel while others must be tackled sequentially. The sequencing is determined by discerning what other objectives must be accomplished before work can begin on each intermediate objective. Typically this process will generate two or more independent series of objectives. These series may be performed in parallel. The entire set of intermediate objectives is best displayed graphically in a Prerequisite Tree with the ultimate goal is written at the top of the page. Intermediate objectives that must be completed prior to the accomplishment of this goal are listed at progressively lower levels. Intermediate objectives that teams should accomplish first thus appear at the bottom of the Prerequisite Tree.

III. Preassessment

On the first day of class the students are informed that they will work in teams of three on a year-long, industry-sponsored project. During the first semester they will be expected to interact with an external customer to develop a problem statement, explore alternative solution concepts, and obtain approval to move one of these concepts into the detail design phase. During the second semester they will be expected to produce a working prototype that will be demonstrated at the annual Idaho Engineering Design Exposition. They are encouraged to review the archive of previous projects located on the Internet at *www.uidaho.edu/engr/ME/sr_des*. They are also encouraged to browse through a library of final reports and personal logbooks maintained by the instructor. The gravity and quantity of work required is sobering.

On the second day of class students are immersed in the planning exercise that is the subject of this paper. This begins with a discussion of the unique opportunities and challenges associated with the capstone design course. The role of big hairy audacious goals (BHAG)[7] as an engine for both personal and organizational development is discussed. An excellent senior design project and experience is established as the ultimate goal of the capstone sequence. We have found that students are attracted to the idea of achieving a quality product through a quality process. They are assured that the instructor(s) value their personal development as much as meeting customer needs.

The planning begins with a brainstorming session facilitated by the instructor. Students are asked to share all obstacles they can envision getting in the way of the senior design BHAG. Every suggestion is numbered and written on the board with plenty of adjacent space for a corresponding intermediate objective that will be generated in a later step. Effort is made to suspend judgement as a tool for revealing all of the students' concerns about the capstone course. Multiple, but similar, obstacles pose no difficulty to the theory of constraints and will end up getting lumped together at a later step. Listening carefully provides clues about the readiness of individual students to tackle a complex team-based design problem. Off-the-wall items should be gracefully and humorously accepted. Some of these might be followed-up with an example how this unlikely constraint posed a serious problem to a previous design team. Other items can be elaborated in ways that might otherwise remain unspoken, but can have a major bearing on design team performance. An example is 'lack of desire' or 'lack of motivation'. These might convey concern about the serious time commitment required for team success. Such concerns may result from a military obligation after graduation, contemplation of law school or business school, or the need to return home to run the family farm. These individuals may have done very well in other engineering classes. Yet, in forming design teams, it is important not to count on individuals who won't be pursuing an engineering career as a primary source of team leadership. At the conclusion of the brainstorming session, the instructor should introduce a few obstacles that have gone unidentified, but that are likely to plague a number of teams later in the design process. Examples might include an unresponsive customer or an uncooperative vendor. A list of obstacles from one of our brainstorming sessions is shown in the left column of Figure 2.

Next, an intermediate objective is formulated to remove each obstacle. It is important that these carry the same number as the related obstacle. Each objective should be discussed enough so that there is class consensus that the objective is sufficient to remove the obstacle. Some amount of real-time editing may be required. Care should be taken to phrase these objectives in terms of actions that students are able and willing to do. It is helpful to use action verbs. Broad-based acceptance of each objective can be used to advantage later in the year when a design team has failed to address a major element in the Prerequisite Tree. The list of intermediate objectives that we proposed remove the obstacles is given in the middle column of Figure 2.

On the third day of class, the obstacles that must be removed before each objective can be implemented are carefully annotated. It is best to illustrate this for several intermediate objectives and then allow cooperative learning groups to complete the remainder of list, periodically comparing their results. This activity also assesses students' analytical and communication skills. Notes can be taken on decision-making and communication behaviors exhibited by different groups that are worthy of consideration when designing project teams later in the semester. At this stage it is useful to remind students that annotating obstacles is a somewhat tedious process because all obstacles must be compared with each objective. At the same time it is a good idea to assure them that they will find patterns that tend to reoccur for multiple objectives. By asking student teams to compare and defend their results, key questions about sequencing and patterning are likely to get raised and the level of critical thinking is elevated. The right column in Figure 2 annotates the obstacles that must be overcome before tackling each of the intermediate objectives in the middle column.

Cooperative learning groups are then asked to report their BHAG plan in the form of a poster-size flowchart. This assignment assesses students' inductive reasoning and computer drafting skills. They are encouraged to group obstacles that tend to occur together, collapsing these under a common heading. Obstacles that occur repeatedly correspond to entry level intermediate objectives that appear at the bottom of the Prerequisite Tree. Obstacles that occur infrequently correspond to tertiary objectives that are situated higher in the Prerequisite Tree. The planning exercise concludes with a peer reviewed poster session. Group members take turns explaining their posters while the remaining members circulate and comment on the work by other teams. Students and teaching staff are given yellow sticky notes and asked to leave notes stating what they liked about each poster and what could be clarified. Figure 3 gives a synthesized Prerequisite Tree prepared by one of our graduate student mentors.

Obstacles	Intermediate Objectives	Prerequisites
1. lack of desire	1. change your attitude	4,8,16,26
2. not enough time	2. organize time	1,8,16,26,17
3. not enough money	3. get a budget	9
4. not smart enough	4. study/apply yourself	1,8,26
5. not enough experience	5. prototype early and often	1,2,4,6,8,15,16,26,28
6. poor instruction	6. provide feedback in journal/portfolio entries	1,3,7,8,15,16,17,28
7. bad communication	7. learn to communicate	1,2,4,8,16
8. lack of motivation	8. get motivated	1,4,16
9. need a project	9. get a project	12
10. poor teamwork skills	10. develop teamwork skills	1,4,7,8
11. impossible project	11. properly size project	9,12
12. difficult customer	12. learn to work with customer	1,4,7
13. personality conflicts	13. resolve conflicts	1,4,5,7,8,10,16,21
14. bad start	14. good start	1,4,5,7,8,9,13,15,16,17
15. too many other commitments	15. prioritize commitments	1,8,16,26
16. close-minded	16. open-minded	1,4,8,26
17. poor time management	17. prioritize commitments	1,8,16,26
18. lack of resources	18. get adewuate resources	9
19. other members “pull a vacuum”	19. motivate members to take responsibility	1,4,7,8,20
20. inactive graduate student mentor	20. include mentor in team meetings	1,2,4,8,16
21. group member disagreements	21. learn conflict resolution skills	1,4,5,7,8,10,16,21
22. lack of machining skills	22. get shop training	1,2,4
23. lack of space	23. find/share space	9
24. location of shop	24. set aside shop time	9
25. share machine time	25. effectively use time available	1,8,16,26
26. lack of self confidence	26. become self confident	1,8,16
27. natural causes	27. plan for them	1
28. not a high priority	28. get motivated	1,4,8,16,26
29. lack of direction	29. consult with other teams	1,4,8,16,26
30. lack of creativity	30. seek opportunities to practice creativity	

Figure 2, Obstacles, Intermediate Objectives, and the Prerequisites to the Intermediate Objectives necessary to achieve an excellent senior design experience.

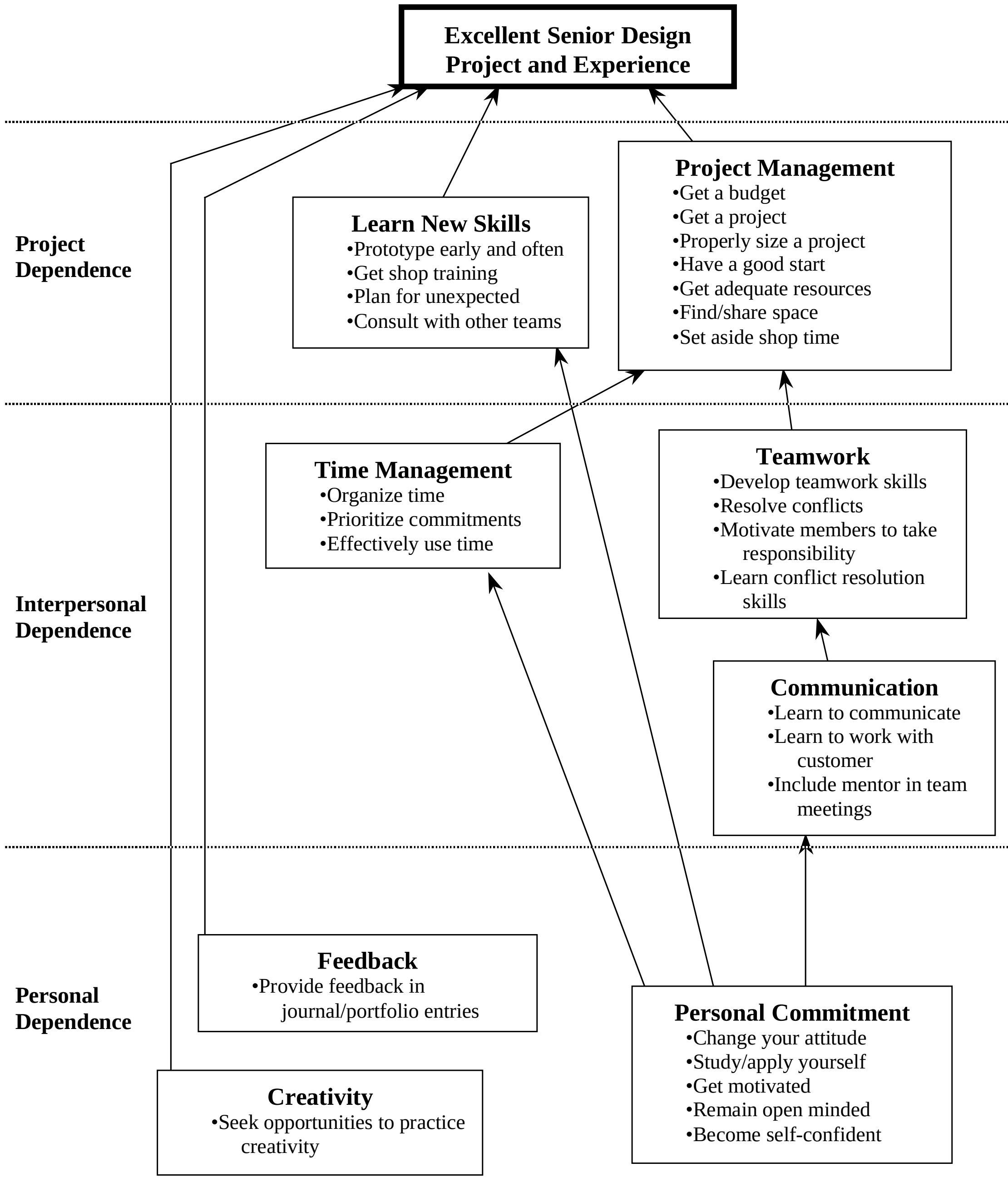

Figure 3, Prerequisite Tree showing steps leading to an excellent senior design project and experience (defined by students during first week of class).

Three distinct sets of skills continue to show up in our Prerequisite Trees. Personal issues occur at the bottom, interpersonal issues occur in the middle, and project issues occur at the top. In many capstone classes personal and interpersonal issues are given scant attention and students are plunged almost immediately into project work. This is in contradiction to findings in the personal development literature that private victories must precede public victories[8,9,10]. Our Prerequisite Trees support the concept that excellence in project work begins with personal initiative and accountability. Using feedback received from this planning exercise, we have structured a three-week orientation process to communicate course expectations, to gather data on student preparedness, and to provide opportunities to polish "human" rather than "technical" skills. We have found that it is advantageous to do this in a period when students are not infatuated with the details and possibilities of a newly assigned project. The data we collect is used to form design teams that distribute the ability present in the class while maximizing the potential to meet customer needs. Design team assignments are made at the start of the fourth week of class.

Personal commitment is addressed in a two-page proposal in which students express and then justify preferences for their top four industry projects. Proposals include a brief discussion of career plans, previous experience related to the project preferences, and goals for the capstone design experience. This is supplemented by ½ hour instructor-student interviews that are conducted in the same fashion as on-campus job interviews. Individual feedback and creativity are not regular elements in our Prerequisite Trees but these are supported through the usage of logbooks, web pages, and peer reviewed presentations. Each individual is expected to make 3-5 pages of entries each week in a personal logbook. To reinforce this habit, students are given 2-3 weeks of reading assignments and discussion questions related to a text that examines a world-class design project. For the last two years we have used <u>Visions of a Flying Machine</u>[11]. This book thoroughly analyzes the design process of the Wright brothers and thoughtfully documents the personal, interpersonal, and technical sources of their success.

Interpersonal skills are stressed in design team exercises during the month following project assignments. These include creating a team name and web page, participating in dialogue sessions with guest speakers from industry, conducting an on-site customer interview, developing a Gantt charts on Microsoft Project, making a key ring tool in the machine shop, and communicating problem statements and preliminary research in a mid-October poster session.

For the remainder of the first semester, class periods are replaced by bi-weekly instructor/mentor/team meetings in which design teams are expected to communicate technical progress as well as to discuss potential storm clouds. The first semester concludes with a formal design review presentation. Design teams are expected to explore a variety of solution concepts and to demonstrate that their selected concept is viable and within budget. A significant amount of design analysis, computer graphics, and preliminary prototyping is commonly included in these presentations. Graduate student mentorship in the machine shop and CAD lab as well as regular email correspondence with the industry customer help to facilitate this outcome.

IV. Mid-year Assessment

At the end of the first semester, the planning exercise is performed again to determine obstacles and objectives that need to be addressed during the second semester. The same process used in the initial assessment is employed. Year by year we again find the results to be similar. A typical mid-year Prerequisites Tree is shown in Figure 4. The most obvious difference between this Prerequisites Tree and the initial Prerequisites Tree is that personal issues are absent. We believe that our actions during the first semester have helped to resolve these issues. Students deem the remaining issues unimportant in comparison to the prototype implementation issues facing the design teams. In general, we have found that the off-the-wall obstacles provided in the initial assessment are gone. Also notable is that the students have self-discovered the issue of communication and time management. This is not surprising in light of industry feedback about entry-level engineers. The fact that students have independently discovered this and have decided to take action of their own accord is noteworthy.

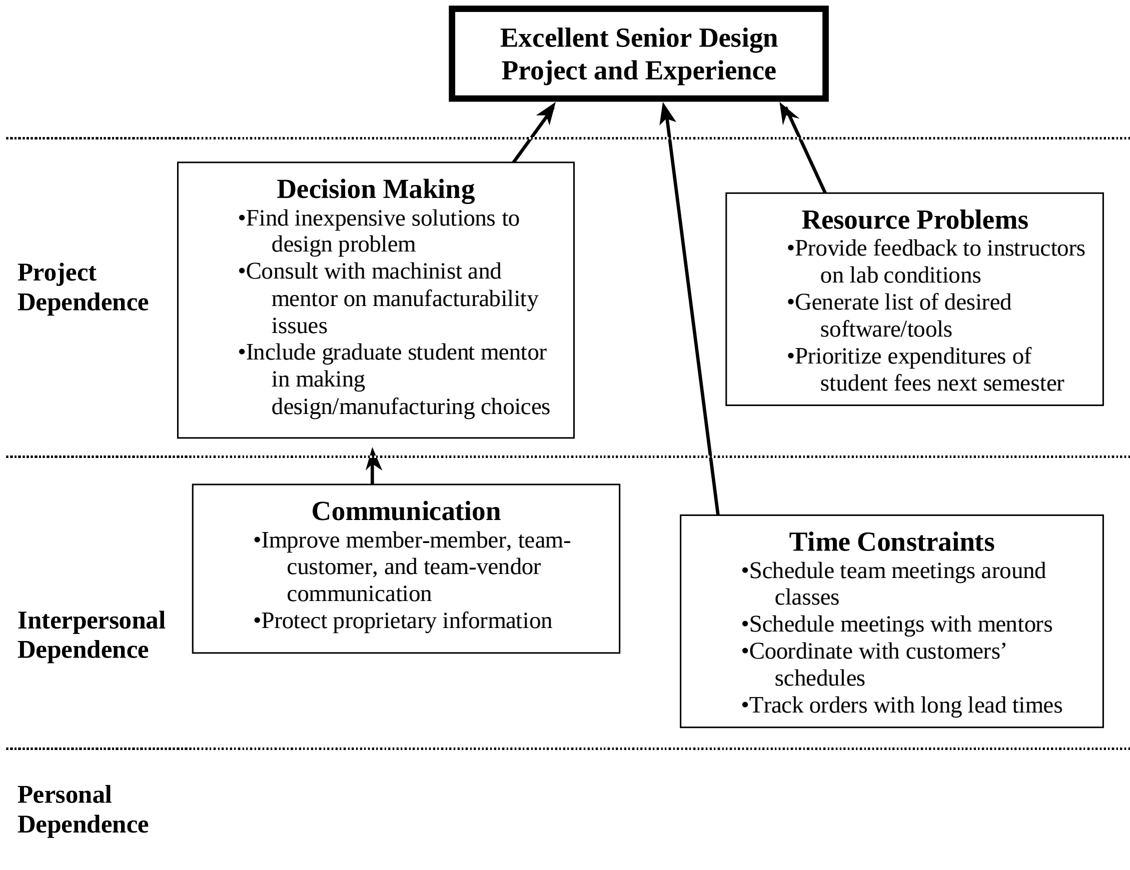

Figure 4, Prerequisite Tree showing steps leading to an excellent senior design project and experience (defined by students at the end of the first semester).

In terms of interpersonal communication, students are aware that this poses different problems depending on the audience. Many students display a sensitivity regarding proprietary information received from their customer and are concerned about how much they should share with their peers, on their web page, and in vendor inquiries. Other students express frustration in not being taken seriously by vendors. The problem of time management has been parsed, indicating awareness that time is not a monolithic problem to be solved with one action but is dependent on their schedules, other's schedules, and component lead times. Difficulty in making decisions has also been underscored. This presents an opening for implementing design heuristics as a tool for selecting between alternatives. Finally, resource shortages are identified as a critical issue. What were adequate hardware and software resources in previous courses because instructors appropriately "sized" assignments, has become an obstacle to completing open-ended design tasks. Students are not used to considering resources during decision making. Often times the problem is not using resources at hand. This can manifest itself as unwillingness to spend project funds and conduct experiments on a candidate component.

V. Conclusions

Goldratt's theory of constraints constitutes a powerful tool for discerning student preparedness for the capstone design experience and for monitoring class-wide design team development. Prerequisite Trees produced by different populations of students are essentially the same over the five year period we have used this technique. The preponderance of personal and interpersonal issues was at first a surprise, but we have used this to motivate a variety of professional development and team-building activities at the start of our year-long course. Leaving these issues to chance when undertaking any large-scale design project is probably a serious oversight. Repeated construction of Prerequisite Trees in the capstone course can provide valuable data on program outcomes. With strategic implementation, these can assess growth in highly desired technical and non-technical competencies.

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Dr. Steven Beyerlein is a leader in the design implementation of process-oriented engineering curricula that stresses cooperative learning, computer technology, and mini-projects. Since joining the UI fourteen years ago, he has regularly taught introductory courses to freshmen and sophomores, has shaped the senior laboratory course, has collaboratively taught senior design for the last five years. Implementation of Process Education techniques throughout the curriculum has significantly improved student preparation for the ME capstone design experience. Over the last four years, he has led interactive faculty workshops on Process Education at the University of Idaho, Washington State University, Boise State University, and Ricks College. He was recognized for his faculty development and outreach activities by a university teaching award in 2001.