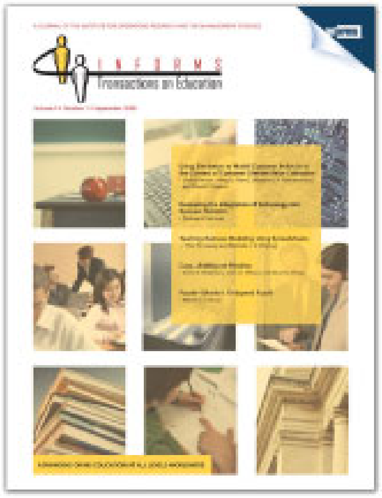

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An Effective Approach to Integrated Learning in Capstone Design

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The H. Milton Stewart School of Industrial and Systems Engineering (ISyE) at Georgia Tech has developed an integrated approach to its capstone Senior Design course in which students form teams and identify, scope, and execute projects for real-world clients. Historically, the course has focused mainly on the engineering challenges of industry projects, but the skill set required of new industrial engineering and operations research practitioners is much broader. The new course structure creatively integrates internal and external resources for teaching business skills, soft skills, professionalism, and legal issues in an interdisciplinary, on-demand team-teaching format. Assessments show that student preparation has increased, especially in nontechnical areas. In addition, project quality has dramatically improved and is much more consistent. Both an external review board and the most recent ABET review cited the new Senior Design course as one of ISyE's strengths.

Key words: capstone design; industry project; nontechnical skills; soft skills; professionalism
History: Received: May 2011; accepted: July 2012.

1. Background

At Georgia Tech's H. Milton Stewart School of Industrial and Systems Engineering (ISyE), every undergraduate is required to participate in a student project with industry when they take the mandatory capstone "Senior Design" course in their final year. Each team of students in the course works on a different real-world application of industrial engineering,[1] advised in the process by a faculty member. Approximately 300 students participate in Senior Design each year, of which about 35%–40% are women and 15%–20% are African-American or Hispanic.

ISyE's ideal is for Senior Design to be a comprehensive experience that helps students make the transition from academic life to professional life. There are a number of specific, important goals that ISyE has for student learning in Senior Design:

- Develop skills in real industrial engineering practice–solving actual, important problems in industry by integrating basic theory and knowledge, engineering principles, creative problem solving, and continuous learning.
- Develop "soft" skills like teamwork, leadership, project management, professionalism, and written and oral communication.
- Learn business-related skills like defining and scoping a problem, proposing work, valuing work, and doing detailed cost/benefit analyses.
- Learn about legal issues including confidentiality, nondisclosure agreements, intellectual property, and technology licensing.

Prior to fall 2005, the Senior Design process was as follows. Students would form teams of five–six people, and each team would find a project client, before the semester started. Teams would then register for a section of Senior Design; each section was taught by different faculty members (advisors) who would allocate the teams in their section among themselves. Each advisor then had complete control and oversight of his or her teams. For the first few weeks of the semester, the faculty member, client, and team would work to define a project for the team to work on (though in practice, it was usually the faculty member and client who did most of the project definition, and the students would learn by watching). In the remainder of the semester the team would do its work, advised by its faculty advisor. The faculty advisor would oversee the entire process for his or her teams, and then assign the team members' grades at the end of the semester. Advisors were assigned 20–30

[1] At Georgia Tech, ISyE is the primary academic department for industrial and systems engineering, operations research, and engineering statistics. For brevity, we simply refer to "industrial engineering," and our students as "industrial engineers," because our undergraduate degree for all those fields is a BS in industrial engineering.

students each, so there were as many as 12 independent faculty advisors involved each year.

In the remainder of this paper, we describe our motivations for improving Senior Design and the resource challenges we faced (§2), the design and implementation of our new Senior Design course (§3), the quantitative and qualitative indicators of improvement (§4), and the unexpected issues that arose that required us to add new pieces to our Senior Design course (§5). In §6, we discuss the potential for the implementation of our Senior Design approach at other institutions.

2. Motivations for Improvement and Resource Constraints

There were several motivations for enhancing Senior Design, stemming from feedback received from the course's major stakeholders: industry sponsors, employers, alumni, students, and faculty. There were two main types of concerns. First, the Senior Design program was insufficient in preparing all ISyE graduates for the changing and expanded needs and roles in the workplace, especially with regard to nontechnical skills. Second, there was no mechanism to ensure uniform execution of the advising and grading system, which led to high variability in project quality and student experience.

2.1. Lack of Nontechnical Training

Because about 1 in 10 ISyE graduates eventually rises to a top (C-level or equivalent) executive position within their organization, the skills and experiences targeted in Senior Design are obviously important to our students in the long run. Alumni, employers, and Senior Design client companies also made it clear that communications, teamwork, project management, leadership, and basic business competence are skills that current graduates now need to display immediately upon entering the workforce.

However, learning these skills was not structurally engineered into the Senior Design process.

Specifically, surveys revealed that students were not receiving sufficient training in how to do the following:

- Identify and recognize the value of potential projects, and use that analysis to persuade a boss or potential client that the project is worth spending money on.
- Communicate progress and results using written reports and formal and informal oral presentations directed to both technical and nontechnical audiences.
- Display leadership and teamwork skills in small work groups, and manage group projects effectively.
- Learn new industrial engineering material when needed throughout their professional career.
- Understand the legal and ethical issues involved with confidentiality and intellectual property.
- Participate effectively within an organization.
- Exhibit professional behavior in all facets of work.

These issues were not unique to ISyE or Georgia Tech; they have been discussed in the academic literature (see Lang et al. 1999, Bucciarelli et al. 2000, Shuman et al. 2005, etc.) as well as the popular literature. Informal conversations with colleagues in other departments and other institutions indicate that similar challenges are faced in the industrial engineering discipline and in other engineering disciplines, not just at Georgia Tech but across the country.

2.2. Variability of Training

Surveys of ISyE alumni between three and six years out of school show that Senior Design was rated as much more important to their success than any other ISyE course, and gave them better preparation. Table 1 summarizes the results of the surveys; each question was answered on a five-point Likert scale.

The surveys were administered in 2004 and 2007, so all alumni surveyed had taken the "old," pre-2005 version of the course. However, despite the apparently good survey results, it was clear to us that there was significant room for improvement. Table 2 gives more detail than Table 1 about the alumni survey responses on the amount learned in Senior Design that students later applied professionally; as shown in Table 2, the high variation was a cause for concern.

One reason for the high variation in Table 2 was that there was no mechanism to ensure uniformity of learning and performance expectations across the 10–12 faculty advisors who taught the course each

Table 1 Results of Alumni Survey on the Importance of Senior Design and the Amount They Learned in Senior Design That Could Be Applied Professionally

		Importance of senior design to alumni professional success		Amount learned in senior design that alumni applied professionally	
	n	Responses ≥ 3 (%)	Mean	Responses ≥ 3 (%)	Mean
2004	198	68.5	3.3	89.4	3.7
2007	230	64.4	3.1	88.7	3.6

Table 2 Details of Alumni Survey Responses to the Question "How Much Were You Able to Understand and Apply What You Learned in Senior Design Professionally?"

				Percent of alumni giving each answer				
Year	*n*	Mean	Variance	5	4	3	2	1
2004	198	3.7	1.1	27.8	33.3	28.3	6.6	4.0
2007	230	3.6	1.0	20.0	34.4	34.4	7.8	3.5

year, which led to high variability in project quality and student experience.

2.3. Incentive Mismatches and Resource Constraints

Part of the reason for the high variability and lower quality was that as a result of the design of the course before 2005, the incentives for students, faculty, and clients were misaligned. All three were incented toward low-quality projects that involved less effort and less learning than desired. Institutional resource constraints also inadvertently incented a reduction in Senior Design quality.

2.3.1. Student Incentives. Despite the variability in content, grades were uniformly high (see Table 3): the average GPA was 3.7, and more than 2/3 of the students received As. (For other courses in ISyE the average is approximately 3.0.) So students began to expect an A regardless of project quality, leading them both to put less effort into the course and to resent faculty advisors who tried to push them to do more, and many advisors felt pressure to assign higher grades than they wanted to when they saw other teams receive high grades for doing less than their own teams. Students, especially those who worked the hardest and accomplished the most, found the system to be very unfair, and the effort they put into learning and execution in Senior Design decreased.

2.3.2. Faculty Incentives. Because of the low expectations of students in Senior Design, being assigned to teach Senior Design was considered a "perk" by some faculty—because expectations for projects and for learning were not high, some advisors did not put in as much time and effort as they would if teaching a regular course. In addition, because the standard questions asked in teaching evaluations are mostly not applicable to Senior Design, identifying and rewarding the best advisors was difficult; there was significant variability as students struggled to give meaningful answers to questions like "were exams and quizzes of appropriate difficulty?"

Table 3 Senior Design Grade Comparison Before and After Implementation of the New Senior Design System

	Mean	Var	A (%)	B (%)	C (%)	D (%)	F (%)
Old Senior Design grades, $n = 2{,}068$	3.7	0.4	73	22	4	1	0.1
New Senior Design grades, $n = 1{,}991$	3.0	1.1	40	26	24	8	2

Notes. Note that from 1999–2004 Senior Design was a two-semester course, so the number of students taking the course each semester was approximately double.

2.3.3. Client Incentives. Clients, too, had difficulties with incentive mismatch. Because the expectations of students were not uniformly high, client companies often used Senior Design solely as a way of getting their name in front of potential employees and/or as an "extended interview" after which they might offer a job to one or two team members. So, instead of putting in the effort to define a meaningful project and assign company resources to support the students' work, many clients would create make-work tasks that they cared very little about. In addition to these projects being unsatisfactory for the course goals, there was an important secondary effect: students "learned" the false lesson that industrial engineering work in practice has little impact and that industrial engineers do little of value in the real world. (Note that we use the term "companies" generically; it includes governmental agencies, nongovernmental organizations, international agencies, civic organizations, etc. as well.)

2.4. Institutional Resource Constraints

Because of institutional resource constraints, students entering Senior Design have less nontechnical preparation than they used to. Courses formerly required by ISyE such as public speaking and technical writing were no longer offered at Georgia Tech, meaning that students came into Senior Design without those key professional skills. Student enrollment has been increasing over the last 10 years while faculty resources have not increased, leading to larger class sizes where students have less opportunity to do significant project work prior to Senior Design; therefore, the loosely defined, large-scale projects inherent in Senior Design can naturally come as a shock to students.

3. The New Senior Design System

To address the shortcomings in ISyE's old Senior Design curriculum, we developed a new structure for our Senior Design course (Hackman et al. 2010). The most important changes from the old system are the following:

- The creative use of resources to foster an interdisciplinary, on-demand team-teaching approach for nontechnical skills outside of normal faculty expertise.
- The creation of a senior design coordinator position (held by a faculty member) to oversee the entire course and impose uniform and high standards.
- An expanded schedule to give students time to learn-by-doing how to identify, scope, and value projects, and how to propose their work in writing.
- The definition of clear requirements for technical and nontechnical aspects of Senior Design projects.
- The decoupling of advising and grading.

3.1. New Resources for Students

As in the past, students have a faculty advisor and a primary contact at their client company. The faculty advisor is still the students' primary source of guidance in the technical areas of the project, management of the project, and communication about the project. The client contact is the students' primary source of guidance regarding the client's needs and wants, getting data and access when needed, etc. These resources have not changed.

In addition, students now have access to the following new resources:

- *Senior Design coordinator* (*faculty*). Provides guidance to all students in team formation, client selection, professionalism and professional communication etiquette, defining and scoping a project that will have value and importance to the client, and proposing and valuing work.
- *ISyE Communication Lab* (*ISyE resource*). Full-time in-house workplace communication expert focusing on developing Senior Design students' oral presentation abilities.
- *GT Communication Center* (*Georgia Tech resource*). Provides guidance to students in writing engineering reports.
- *Teamwork office* (*volunteer*). Available for confidential consultation as a "coach" for teamwork, leadership, and project management.
- *Professionalism advisors* (*volunteer*). Consultants who advise students on issues of professional communication, behavior, dress, etc.
- *Professional mentors/advisors* (*volunteer*). Executives who provide guidance to students in resume writing, interview preparation, and development of professional mentorship relationships.
- *Georgia Tech Office of Legal Affairs*, *Georgia Tech Office of Technology Licensing* (*Georgia Tech resources*). Handle negotiation of nondisclosure and intellectual property agreements and advise students on legal and intellectual property (IP) issues.
- *Executive panel* (*volunteer*). Executives who speak to students about engineering roles and the demands on engineers in the workplace, with focus on soft skills.

Except for the executive panel, resources are available to students on demand, rather than in a lecture-based approach. The on-demand format is designed to increase student learning by allowing students to utilize the resources exactly when they are most relevant, rather than mismatching the time of delivery and the time of need. This approach also allows learning to be active rather than passive, when students bring their immediate question/problem to the appropriate resource. In addition to students being able to voluntarily get help from the course resources, the senior design coordinator and/or the faculty advisors can suggest (or require) that a team visit one or more of these experts.

There is a significant difference between this resource-based approach and a lecture-based approach that would cover the same topics. The on-demand format allows students to learn and get help when they need it, as they will need to do in their professional lives, utilizing each resource's expertise when that resource is most relevant to them. Student learning will be active rather than passive: when students bring their immediate question/problem to the appropriate resource, they can learn by doing, addressing their specific issue, so that the lessons they learn are more likely to stick with them. Finally, because the expert resources are outside the formal grading loop (see below), students are more willing to admit difficulties and ask for help than they would from someone who is also involved in the grading process.

3.2. New Senior Design Structure

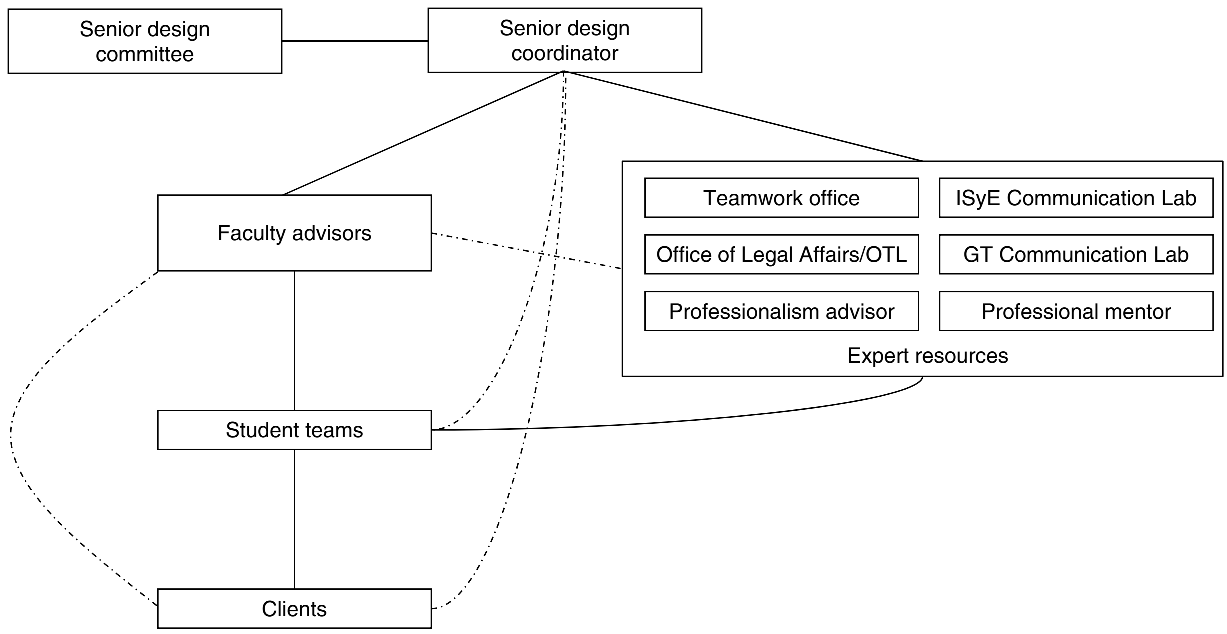
The new Senior Design structure mimics a corporate environment. The coordinator acts as an executive of a consulting company. The advisors act as project managers or coaches. The expert resources (communication labs, teamwork office, professional mentor, professionalism advisor, office of legal affairs, and other faculty-at-large) act as internal resources. The Senior Design committee, made up of the associate chair for undergraduate programs and one or more past senior design coordinators, plays the role of a "board," providing oversight of the course. Figure 1 shows the Senior Design structure.

3.3. New Senior Design Timeline

With project expectations increased, a single semester for students to find teams and then find, scope, and execute a project was not enough time. Expanding to two semesters was not an option, because our previous experience showed that an eight- or nine-month timeline was too long—clients generally were not willing to wait that long to get results to important projects. So, we modified the Senior Design timeline so that team formation and project identification and scoping, and proposal/justification, all take place over a two-month "pre-semester" period before the Senior Design semester. In that pre-semester, the senior design coordinator gives every team instruction, advice, and feedback; and is responsible for ensuring that every team's proposed project will satisfy the expectations and requirements of the course. Figure 2 shows the new Senior Design timeline (not to scale). As Figure 2 implies, students are responsible for finding teams and projects; this will be discussed in §5.

The pre-semester has turned out to be a beneficial change for both students and clients. The

Figure 1 **New Senior Design Structure**



Note. Solid lines indicate more commonly used avenues of communication than dashed lines.

only difficulty is that dozens of our students do internships, co-ops, or study-abroad semesters just before Senior Design. As a consequence, during the pre-semester teams have to learn to work together remotely using technology. Although this can be an annoyance for teams, students report that it actually is a beneficial skill to learn.

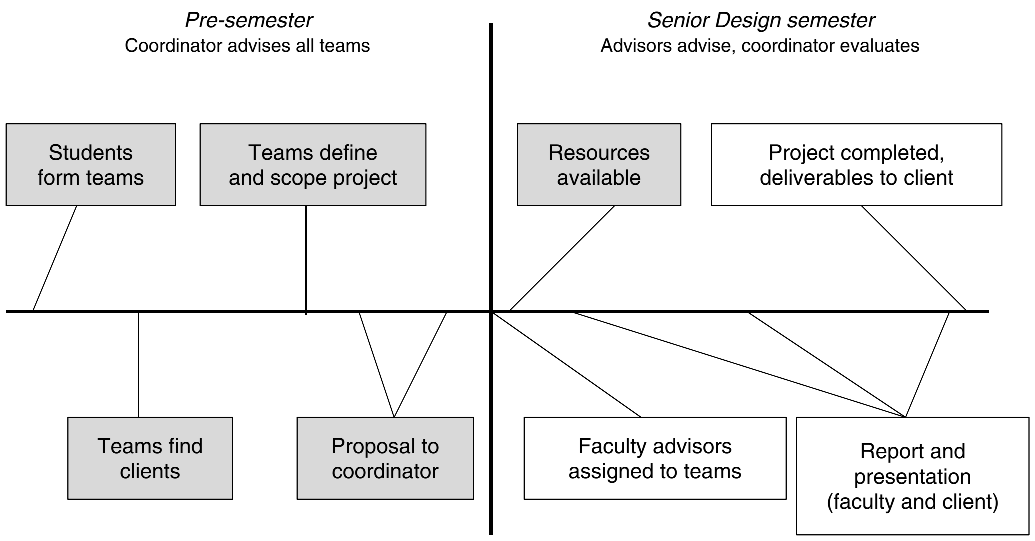
3.4. Senior Design Coordinator

Because the senior design coordinator has a unique and integral position in the course, we describe the coordinator's responsibilities in more detail.

During the pre-semester, the coordinator advises all students and all teams. The primary responsibilities of the coordinator in this time period are the following:

- Provide guidance to all students in team formation, client selection, and project identification and scoping; and give instruction on professionalism and professional communication etiquette.
- Guide students in their early communications with clients regarding resource issues (what sort of resources the company will need to devote to the project) and legal issues.

Figure 2 **New Senior Design Timeline**



Note. All shaded steps are new.

• Work with each team before the semester starts to help them define and scope a project that will meet the requirements of the course without being overly broad or too difficult.

Once each team has successfully proposed a suitable project, the coordinator assigns each team to a faculty advisor, matching project topics and methodological needs with faculty expertise. (However, because projects often require knowledge and/or methodology from several different areas, there is a well-defined process where students can approach other faculty if needed.) At that point, the senior design coordinator steps back into an administrative/grading role and the faculty advisors and resources take over the primary instruction of the students for the Senior Design semester.

During the Senior Design semester, the coordinator's primary responsibilities are the following:

• Coordinate all of the internal and external resources that ISyE now provides for Senior Design students.

• Act as the administrative point of contact for current and potential future clients, for legal issues, etc.

• Give periodic feedback to each team regarding their progress.

• Assign course grades for all students.

Rather than having each faculty advisor be fully responsible for his or her own section of Senior Design, the coordinator oversees the entire course and assigns course grades to all students. This helps ensure consistency of expectations. The senior design coordinator takes input and advice from faculty advisors and other experts, but the coordinator's judgment is final.

An additional benefit of having the coordinator as the single grader is that, because the advisor does not have responsibility for grading students, he or she is more able to act as a mentor and coach, and students are more willing to admit their struggles and shortcomings and receive guidance.

3.5. Grading and Feedback

Senior Design uses a carefully developed nonlinear grading formula that has significant components in professionalism, teamwork, and written and oral communications on top of the project's technical and strategic merit (see Appendix A). The grading criteria correspond to ABET program outcomes, ISyE's program outcomes, and ISyE's desired outcomes for its capstone engineering design course. Missing deadlines, unprofessional behavior, and sloppiness carry significant penalties. These nontechnical components of the course grade teach students that workplace professionalism and communication are very important. At the orientation class at the beginning of the semester, the senior design coordinator shows the students exactly how the grading formula works, and gives various examples. Students are then encouraged to experiment to get an even better feel for the system.

Teams receive feedback several times throughout the Senior Design process:

• During the pre-semester, students meet with the senior design coordinator to receive verbal feedback.

• In the second week of the semester, each team presents a project proposal to the coordinator and a panel of faculty and receives immediate verbal feedback (usually in the form of suggestions on how the project could be improved or extended).

• In the eighth week of the semester, each team makes an interim presentation to the coordinator and faculty panel and delivers an interim report to the coordinator. They receive verbal feedback about their project at the presentation, and detailed written feedback on their work product, written report, oral presentation, and professionalism a few days later. They also receive a grade calculated according to the grading rubric.

• At the end of the semester, each student receives a final grade for the course and is encouraged to get verbal feedback on their team's performance on the grading rubric and any personal grade adjustments they earned.

Individuals also receive feedback during the semester if their advisor and peers believe the individual's contributions are subpar.

Almost all of the feedback the team receives before the final grade is informational, to help them improve their work before the end of the semester, because all aspects of the grading except for professionalism are noncumulative. This allows students to learn from their mistakes in the technical engineering components of the project as well as written and oral communication without hurting their grade, as long as they fix the problems by the end of the semester.

Ideally, every student on a team will receive the same grade. However, in reality approximately 15% of students receive a different course grade than their team's overall project grade. Of those 15%, slightly more than half receive a slightly higher grade for contributions above and beyond expectations, and slightly less than half receive lower grades either for poor professionalism or for lack of contribution. Grade adjustments upward and downward for lack of contribution are determined based on a series of peer evaluations submitted by each student evaluating each of his or her team members, and on the opinion of the faculty advisor. Adjustments are made only if there is a reasonable consensus, so that personal opinions of one or two students will not affect course grades. In no case does an increase or decrease in a student's course grade affect the grades of that student's teammates; grading within a team is not zero-sum, to ensure that there is no incentive to falsely downgrade a teammate and no disincentive for acknowledging a teammate's extra contributions.

We have observed that after working with teams for a whole semester, faculty advisors often become biased in their teams' favor in terms of grading (on average, by about 1/2 of a letter grade), so it is not uncommon for the impartial coordinator to assign lower grades than advisors would like for their own teams. Table 3 shows the comparison of Senior Design grades during the last two years before the change in Senior Design, and the grades after the transition was completed. The new grades are more appropriate considering the students' preparation and the challenging nature of the design project and are more in line with other ISyE courses. The mean grade went from 3.7 to 3.0 and the variance increased from 0.4 to 1.1. The mode grade has remained an A.

3.6. Incentives for Learning

The new Senior Design structure has much better incentives for faculty, students, and clients.

3.6.1. Project Quality. In addition to grades and learning, our students seem to be motivated by competition. Beginning in fall 2005, we instituted an end-of-semester showcase of the top Senior Design projects. The three or four best projects (usually out of about 20–25) are designated as senior design finalists. The finalist teams give a well-publicized presentation to which current and prospective Senior design students, family, friends, alumni, faculty, staff, project clients, and corporate sponsors of Senior Design are all invited to attend. Posters of the finalists are displayed prominently in the hallways, and the names of team members, the client, and the faculty advisor, are engraved in a plaque displayed outside the academic office. The best of the finalists is designated the semester's best senior design project, and is highlighted in a press release. The recognition involved, especially after so many hours of hard work, gives strong incentive for both students and advisors to perform. We have even seen alumni several years out return with parents, siblings, and even new spouses to point out and pose for pictures next to the plaque listing their name. Clients too are incented to help increase project quality, as they get free publicity from the press release and other external recognition earned by the students.

3.6.2. Professionalism and Understanding Professional Obligations. Academic and professional environments can be very different, especially the difference between how a senior student and a newly hired employee are expected to (or allowed to) behave. In addition to bringing in volunteer consultants to help students learn about professional behavior and communication, Senior Design's grading policy enforces professionalism requirements more similar to the workplace than to academia. Reliability, ethics, attitude, etc. are all explicitly part of the grading rubric, and students learn what will be expected of them upon graduation. The Senior Design system also helps students learn their professional obligations to coworkers; for example, students who are worried about their grade, or are not getting along with their teammates, are not allowed to drop out as would be allowed in any other course, because their teammates are counting on their contributions.

3.6.3. Faculty Incentives. Because the senior design coordinator and other supporting resources assist the students in nontechnical areas, faculty advisors can focus on technical issues and engineering design, which are generally more interesting to them. In addition, the ability to advise without grading has made the advisor role more like that of a coach who wants his or her team to do well under the coordinator's evaluation, leading advisors to be more diligent. The competition, too, incents advisors to do a good job, because their names appear on the posters and plaques. However, the workload on senior design faculty advisors has increased significantly, to the point where it is clearly more than teaching a regular course. To balance that disincentive, ISyE's associate chair for undergraduate programs and director of development secured some funding from corporate and alumni sponsors to give a small amount of professional-development funds to senior design advisors to use for travel, equipment, etc. This helps make senior design advising a win–win situation, and most advisors request to teach Senior Design again, and/or volunteer to advise teams even without getting teaching credit.

4. Indicators of Success

Our new senior design structure focuses on expanding the skill sets of our industrial engineering graduates to meet the current and future needs of the profession. Every year, approximately 300 students go through our senior design experience and graduate with knowledge and skills gained from our course's experts in both technical and nontechnical areas. To gauge the success of our new senior design structure, we have surveyed clients, faculty, and students regarding the senior design students' abilities after completing the course. We also have observed the increased globalization and diversity of clients and projects, the increased importance and value of the work our students do in Senior Design, the recognition our students win in international competitions, and the opinions of external evaluators.

Table 4 Results of Student and Faculty Surveys of ISyE Program Outcomes

	Clients		Students		Faculty	
Program outcome	Mean	Acceptable (%)	Mean	Acceptable (%)	Mean	Acceptable (%)
Work in teams	4.4	94	3.9	95	3.7	83
Describe a problem, recognize its difficulty, develop and evaluate potential solutions	4.2	94	4.2	96	3.3	72
Understand professional and ethical responsibilities	4.0	89	3.8	90	3.6	82
Present proposals and results effectively (written)	4.2	100	3.7	88	3.5	80
Present proposals and results effectively (oral)			3.9	93		
Continue to develop in the field	4.6	100	3.9	92	3.4	74
Participate effectively within an organization	4.2	94	3.9	92	3.7	84
Apply IE methods to design of constrained systems	4.6	94	4.1	97	3.3	74
Apply mathematics, science, and engineering to the IE domain (client and faculty question)	4.7	100	n/a	n/a	3.6	84
Overall learning (student question)	n/a	n/a	4.3	96	n/a	n/a

4.1. Student Preparation and Learning

As we hoped, the ratings for the skills ISyE graduates need beyond the traditional technical content have risen to almost as high a level as the ratings for the technical abilities themselves. Project clients, faculty, and students were surveyed on a five-point Likert scale regarding the students' abilities in the new senior design system (see Table 4). The metrics were high (faculty were the harshest critics, and clients gave very high scores in most categories), and the coefficient of variation dropped from 0.32–0.38 to 0.10–0.25.[2] In addition, employers have given indirect feedback by hiring our graduates; employment of graduating seniors remained high even through the bad economy.

We also surveyed senior design students on how much the new course has improved their abilities (see Table 5). Because more than half of ISyE students do some form of co-op or internship while in school, we expected that the scores would be lower than those in Table 4; as many students noted in the free-response section of the survey, they had already learned some of these skills in professional environments. However, the numbers are still high, and contribute to the decrease in variability observed in the Table 4 questions.

Qualitative feedback from project clients supports the quantitative evidence in Tables 4 and 5. Of the feedback we receive, especially at the executive levels, about half of the compliments they give our students are for their nontechnical skills.

4.2. Project Quality and Consistency

Faculty agree that project quality (engineering content, value, and nontechnical output) has significantly improved, and clients are much more likely to acknowledge six- and seven-figure benefits from projects, and to begin implementation even before the Senior Design semester has ended. As a result, we have noticed a number of positive outcomes related to the client base, the diversity and importance of projects, and external evaluations of project quality in national and international competitions.

Table 5 Results of Improvement Surveys

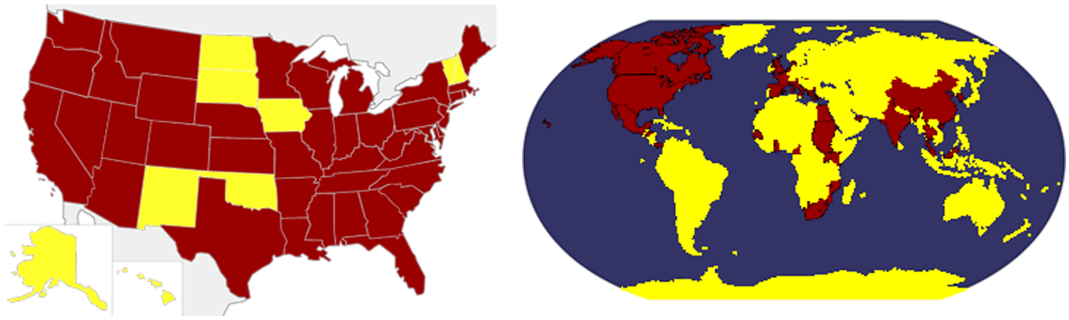
To what degree has senior design improved your skills/abilities?	
Work in teams	3.7
Professional/ethical understanding	3.7
Define and scope a problem	4.1
Technical writing	3.5
Presentation and oral communication	4.0
Apply industrial engineering methods and tools	4.0
Continue developing after graduation	3.7

4.2.1. Globalization and Diversity of Clients. Our new Senior Design course has helped our students experience the diverse, global nature of industrial engineering. Since the implementation of our new Senior Design course, the client base for Senior Design has grown tremendously. Senior design projects have been based not only in the Atlanta area, but have had key components in 41 states and the District of Columbia, and in 29 countries on four continents (North America, Europe, Asia, and Africa), as shown by the red-shaded states and countries in Figure 3.

Our list of senior design clients now includes not just the "usual suspects" (large Atlanta-based companies that want to create and maintain a connection to Georgia Tech) but also a wide range of other organizations, including branches of government, international manufacturers and distributors, and global aid organizations. The companies range in size from startups with fewer than five employees to the top company in the Fortune rankings. Appendix B lists the senior design clients we have attracted since changing to our new senior design system.

[2] The surveys taken before implementation of the new senior design system asked different questions, so the means are not comparable. However, the large decrease in coefficient of variation suggests that the student experience has become much more uniform than before.

Figure 3 **The Red-Shaded States and Countries are Places in Which at Least One ISyE Senior Design Project has had a Major Component Since Fall 2005**



Note. The figures were generated by World Map Maker 2012.

4.2.2. Importance and Diversity of Projects. In addition to the increased client base, the range of projects that our students take on has increased. Of course, we still have a core set of traditional warehousing, manufacturing, and logistics applications, but in the past several semesters students have also used industrial engineering methodology in other creative ways. A few examples include the following:

- Using advanced statistical techniques to help an automobile manufacturer structure its new leasing and warranty program to optimize profits.
- Delivering large-scale optimization-based operational planning tools to help an airline significantly cut its maintenance costs.
- Designing balanced manufacturing lines and creating work schedules to allow a relatively small machine shop to compete for a significant defense contract.
- Assisting in planning the manufacture and distribution of sterile mosquitoes to eradicate malaria in a hard-hit region of Sudan.
- Planning wholesale network redesign and routings for several corporations in diverse industries.
- Providing a manufacturer with Brownian-motion models that gave the company strategic intuition for cost-effective distribution of its ultra-low-cost PC chip line.
- Developing pricing and capacity-management strategies for exhibits at a major art museum.
- Designing combinatorial auction mechanisms (and providing software solutions for implementation) to help a major carrier increase profitability and improve carrier satisfaction.
- Improving visitor flow at a major new aquarium.
- Creating a real-time simulation tool to help a hospital give more accurate wait times to arrivals at its emergency department.
- Recommending an inventory prepositioning planning policy for an international aid organization to increase their speed and efficiency in delivering aid to populations in need.

The scope and importance of the projects has increased to the point where we regularly expect senior design teams to develop solutions with at least a six-figure annual benefit to their clients, and a number even pass the million-dollar-per-year level. We believe that, as potential client companies hear about the increased quality (and decreased variability) of senior design projects, they give our students more challenging and more important problems to solve. Supporting evidence includes the following:

- Students increasingly need access to confidential data, and nondisclosure agreements (NDAs) and IP clauses have become much more common. This is actually what led us to begin including legal and intellectual property resources in the course curriculum; when we first piloted the new course these resources were not included.
- Companies (and individuals who move from company to company) return with new projects semester after semester.
- Companies are more willing to support Senior Design monetarily.
- ISyE Senior Design has been used as a selling point in recruiting companies to move to Georgia.
- Anecdotally, students often report that discussing their senior design project in interviews is the primary reason they were offered a job.
- Anecdotally, our students report that the work they do in Senior Design is a source of pride, and gives industrial engineering students increased respect around campus.

4.2.3. External Competition. Since 2009, we have begun to encourage our students to submit the results of their senior design projects to international award competitions. In the past three years, papers based on ISyE senior design projects have won awards and achieved recognition in international competitions such as the IIE Undergraduate Student Technical Paper Competition, the INFORMS Undergraduate Operations Research Prize, and the INFORMS Doing Good with Good OR student competition. The last competition is of special note, because it was open to students at all levels, and of all the finalists the only one that was not a Ph.D. student was the entry from ISyE senior design.

The list of student awards since 2009 includes the following:

• 2009–IIE Undergraduate Student Technical Paper Competition (1st in region, 2nd international)

• 2010–INFORMS Undergraduate Operations Research Prize (shared second place)
INFORMS Doing Good with Good OR (Finalist)

• 2011–INFORMS Undergraduate Operations Research Prize (second place)
INFORMS Doing Good with Good OR (Finalist)

• 2012–IIE Undergraduate Student Technical Paper Competition (won first place in region, but had to give up their place when none of the students were able to attend the international competition)

4.3. External Reviews

External evaluations by ISyE's peers and accreditors have also noted the success of our new Senior Design course. In 2007, the dean of Georgia Tech's College of Engineering appointed an external review committee to review ISyE. The committee's report include the comment that "ISyE has also made impressive improvements in the senior design project ... in addition, grading by independent judges has added to the value of the course." In ISyE's 2008 ABET review, the reviewer pointed out that "The Senior Design course is a recognized asset of the undergraduate program. The rigor of the projects, the assessment, and the external constituent involvement are particularly noted."

5. Unexpected Issues and Responses

As we learned (and continue to learn) from our experiences implementing this new Senior Design course, we have identified some unexpected issues that have required us to modify or augment our course design and materials. In this section, we discuss several such issues and corresponding improvements.

5.1. Legal Issues

As the importance of senior design projects to our clients has risen, more and more companies (sometimes up to 1/2 of all projects in a semester) are requesting that students and faculty sign NDAs and IP releases. Faculty NDAs must be negotiated and/or approved by Georgia Tech's Office of Legal Affairs. In addition to NDAs, some companies have begun to ask for IP releases, because normally, IP for student projects is owned by the students. Georgia Tech's Office of Legal Affairs and Office of Technology Licensing have been very helpful as resources for both students and faculty in this regard; their advice has specifically saved a number of student teams from signing unfavorable documents prepared by client company lawyers unfamiliar with the workings of student capstone projects.

5.2. Team Building

With 300 graduating seniors per year, ISyE classes are large and most students do not know enough classmates well enough to trust that they will be good teammates. Almost half the senior design students knew two or fewer of their teammates before the start of the course, and 98% of students were unable to find a complete team on their own. (Most teams are formed as chains; for example, A and B decide to be on a team together, A brings in friends C and D, B brings in friend E, and E brings in friend F.)

In the old senior design system, because more than 2/3 of teams and students received a grade of "A," team composition was not very important. When we increased expectations, the importance of team composition increased significantly. Students needed teammates whose work they could trust, whose goals and work ethics were compatible, and who collectively covered a wide range of skills and knowledge, from technical skills taught in various ISyE elective courses to soft skills like speaking and writing to assorted software and programming skills. The lack of students' ability to find such teammates led to unfortunately high levels of team discord. In the first few semesters of the new senior design system, 35% of teams self-reported significant discord because of mismatches in the students' desired level of effort. As many as 10% of students per semester were unable to find a team altogether, resulting in the coordinator having to group these students into teams; such teams' senior design grades average 1.1 GPA points lower than other teams in the course.

To aid students in finding compatible and complementary teammates, we created the ISyE TeamBuilder, a modification of open-source online dating software (Sokol 2012). Students now post their own information and then search for teammates based on schedule availability, work styles, course goals, project preferences, technical and nontechnical knowledge and skills, languages spoken, work and study abroad experiences, etc. Since we introduced TeamBuilder, only 1%–2% of students have been unable to find a team (down from 10%), and the incidence of "assigned" teams has decreased from three–four per year to just one every two–three years. The number of teams self-reporting significant discord has been cut in half. Thanks to the quantifiable improvements, TeamBuilder won a significant Georgia Tech award for innovative use of technology in education and was recognized by inclusion in the National Academy of Engineering Foundations of Engineering Education Symposium.

5.3. Students Withdrawing from the Course

Another issue that arose when expectations increased is that students began to worry about their grades when teams were struggling with projects. Georgia Tech allows students to withdraw from courses through the midpoint of the semester, and senior design students—especially those taking the course the semester before graduation—would sometimes drop the course halfway through. There were even extreme cases in which all but one or two team members dropped out, leaving the remaining team member(s) in an untenable position—it was impossible for them to complete a satisfactory project alone. Therefore, the ISyE faculty voted unanimously to not allow students to drop from Senior Design once they have committed to a team. Of course, in cases of serious illness, personal issues, etc., the associate chair for undergraduate studies allows them to withdraw. However, students who are not happy with the progress their team has made, are worried about their grade, or are not getting along with their teammates are not allowed to withdraw from the course; their teammates are counting on their contributions, and it would be unfair to all of those teammates to allow the student to quit. In addition to eliminating unfairness, this rule has (anecdotally) really helped emphasize the issue of professional responsibility to one's co-workers.

5.4. Team Size

A few years after we implemented the changes to Senior Design, the increasing student population coupled with a temporary decrease in faculty forced us to raise the team size from five–six to six–eight. Based on Griffin et al. (2004), we were worried that teams as large as eight would be unwieldy, making organization and task delegation difficult, and teams' achievement would decrease. We also were concerned that with eight team members, it would be easier for students to slip through the cracks and either intentionally or unintentionally contribute less than expected to the project.

The data we have collected over the past few semesters surprised us. The average team grades have not been significantly different between teams of sizes five–eight. However, we did notice significant differences in variability. The fraction of teams earning an A is lower among eight-person teams (36%) than among six–seven person teams (43% and 44%), suggesting that eight-person teams do in fact have a harder time excelling. On the other hand, the fraction of C and D teams is lower for seven and eight person teams (24% and 27%) than for six-person teams (36%), suggesting that having seven or eight people allows students to fill in the gaps and fix the little errors that smaller teams might run out of time to work on. (There were not enough teams of size five to make meaningful comparisons.)

It is hard to generalize these results, because expectations and student abilities will vary from school to school. It is also possible that our data overstate the magnitude of the differences, because the "best" teams might realize the wisdom of limiting their size. However, our experience is that the ideal team size might be larger than expected.

5.5. Project-Finding and Project Funding

Because of our large student population, we have needed anywhere from 17 to 27 projects each semester, with an average well above 20. In the old senior design system, projects were not vetted, and companies were often willing to do a favor for students in need by giving them something small and inconsequential to work on. In the new version, where projects must meet strict minimum requirements, finding enough quality projects can be challenging.

We did not want to change the idea that students should find their own projects, because project identification, definition, and scoping are important skills we want students to learn. On the other hand, their sources of co-op/internship connections, family/friend networks, and cold calling were barely able to keep up with the demand, while at the same time, companies began contacting us with potential projects asking for students who would be willing to work on defining and executing them. So, we created an online system where companies can post projects and students can find one that satisfies the requirements and matches their interests. There are still usually not enough projects on that website to go around, but it has relieved a lot of the pressure; many teams prefer to use their own connections or cold call companies they are interested in working for, so that lack of projects has not been an issue.

On the other hand, charging project clients a mandatory fee like many other schools do is still not possible for us. With a need for so many projects (40–50 per year), the ratio of companies in the Georgia Tech area to student population is not in our favor like it is for much smaller departments. Instead, we rely on voluntary industry support. A number of companies both support senior design financially and sponsor projects, and others find the program valuable and give financial support even in semesters where they are not sponsoring a project. Many other companies in the Atlanta area already provide support to other ISyE initiatives, centers, chairs, etc., and thus understand that they indirectly support senior design as well. Still, one of our longer-term goals is to increase the fraction of client companies who do financially support senior design, especially given the value of our students' work to them.

6. Potential for Widespread Adoption

As successful as our new implementation of senior design has been, we believe other institutions will benefit from adopting similar structure. On the surface, finding all the necessary resources sounds like a significant challenge to implementation, but our experience has been positive.

6.1. External Resources

Finding external expert resources for such a wide range of skills and knowledge has been much easier than it sounds. We found potential resources to be very open to volunteering their time to help our students. Alumni and area professionals are especially helpful sources of professional mentoring and professionalism help, and our experience has been that they are very willing to volunteer. Our professionalism advisors, professional mentors/advisors, and executive panel all are volunteers from the local alumni and professional communities. Our Teamwork Office has been staffed by an expert faculty member, but local alumni and professionals have also volunteered to help in that area as well. So, finding external resources has not been a problem.

6.2. Institutional Resources

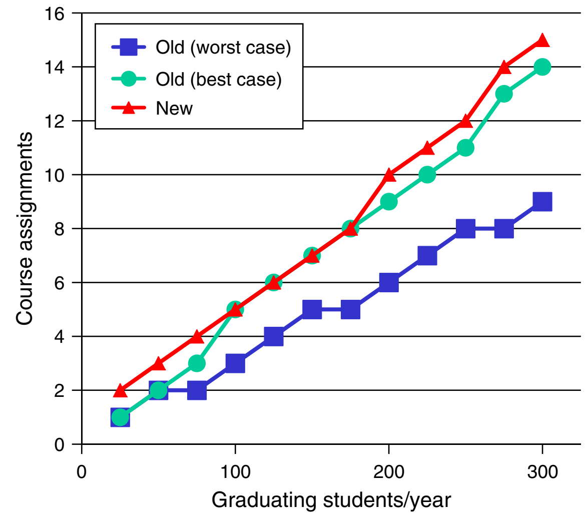
Institutional resources for communication already exist at most universities. The Georgia Tech Communication Center has been our students' resource for technical writing, and would have been the primary resource for presentations as well, except that ISyE is fortunate to have its own internal lab to help students with oral communication. Our experience was that both resources were not just happy to help our students, but were enthusiastic about the prospect (possibly because increased student usage helps justify higher institutional funding for the resources).

We have had similar experience with institutional legal resources. The Georgia Tech Office of Legal Affairs and Office of Technology Licensing have been proactive in finding ways they can help our students, even as the load our course puts on them has increased. In fact, even if they were not so enthusiastic about helping senior design students, there is a strong institutional incentive for them to participate: more-educated students are less likely to put Georgia Tech at risk with their actions.

6.3. Faculty Resources

Because external and institutional resources are available at no cost, the only significant increase in resources required by the new senior design structure is faculty. For 300 students per year, senior design now requires about 15 faculty-course assignments, compared to about 11–12 that were required in the past. Coming up with enough faculty to teach the course is

Figure 4 Faculty-Course Assignments Required by Department Size



sometimes difficult, so we have had to rely on qualified visiting faculty, adjuncts, and instructors to fill the gap. However, we have become more successful raising more money from satisfied project clients, so that we can financially incent the best faculty to prefer teaching senior design even to graduate courses. This helps make senior design advising a win–win situation, and many advisors want to teach senior design again and again because they find it rewarding from an intellectual and mentoring standpoint.

We expect that other institutions might more easily find the faculty resources necessary to adopt our system, however, because our size is much larger than most in industrial engineering. In our old system, the ideal was to require one faculty-course assignment per 20–24 students, but some faculty taught 30–36 students for the same amount of credit. In the new system, we now require one faculty-course assignment per 24–32 students for advising, plus one faculty-course assignment per 65–85 students for the coordinator. As Figure 4 shows, at these rates the worst-case difference between the old and new structures is only one–two faculty course assignments for departments even as large as 150 graduates per year, and best-case (starting from 20–24 students per faculty-course assignment) the new structure requires at most one more faculty-course assignment regardless of department size.

7. Summary

In fall 2005, we piloted the first offering of the new senior design structure. Half of the senior design students were assigned to our section—much to the displeasure of some of them when we told them they were in an experimental section with much higher expectations and workload than their peers in the other sections. By the end of the semester, though, their pride in their accomplishments outweighed the annoyance of all the extra work for most of our students. At the inaugural senior design finalist presentations that semester, it was clear that not only were the finalists from our section far superior to the other sections' finalists, but at least half of the projects in our section were better than any of the projects in the other sections. We repeated the pilot in spring 2006 (1/4 of students were in our section), and again the best project was from the new section. Beginning in fall 2006, all ISyE students have been in the new version of senior design.

Since the changeover, it is clear that the new senior design structure has changed the culture for both students and faculty. Students are now required to work hard and smart on a real project, and to maintain strict professional standards. Consistent, fair, and rigorous standards are now applied, and more resources are now made available to support students.

All of our stakeholders have given positive feedback. Students have a real appreciation for what they learn, and campus pride in industrial engineering has increased along with the quality and importance of their projects. For clients, the importance, value, and implementation of projects have increased. Faculty find advising to be more rewarding, if more demanding, and they enjoy being able to advise students without the burden of grading. Alumni have appreciated the new structure as well, and have volunteered to return as resources for current senior design teams. Employers appreciate the improvements in students' nontechnical skills and knowledge. Although the number of required resources seems large, most of them are available at no cost as volunteers or already-existing institutional entities. Overall, the implementation appears to be a success, and we encourage other institutions to copy our senior design structure.

Acknowledgments

ISyE's new Senior Design course could not have been successfully implemented without the support of our school's administrators and the dedication and hard work of all faculty and staff who have contributed to its development and/or served as advisors over the past six years, nor could it have succeeded without the participation of our many client companies. We would also like to thank the alumni and companies who have financially supported our Senior Design program.

Appendix A. New Senior Design Grading Formula

Under the new senior design system, teams are graded in 12 categories. The work product is graded on its scope/challenge, methodology (including appropriateness, correctness, and completeness), and value to the client (including the ability of the client to implement the solution—some companies can easily extract value from models and ideas, and others, usually ones without industrial engineering employees of their own, might require the students to deliver basic working software); the final written report is graded on its content, style, and mechanics; the final oral presentation is graded on its content, speakers, and visuals; and the professionalism throughout the semester is graded on attitude, reliability, and honesty. Each category includes a number of specific subcomponents, as well as general judgments. In each of these 12 categories, a team receives a rating on a five-point scale based on their performance (5 = outstanding, worthy of a senior design finalist; 4 = very good; 3 = satisfactory; 2 = unsatisfactory; 1 = unacceptable). For each category, ratings are worth a certain number of points, as shown in Table A.1. The points are then added, and Table A.2 shows the overall grading scale. For reference, senior design finalists almost always score above 200.

Table A.1 **Points Awarded for Achieving Each Rating in Each Grading Category**

	Points awarded for each rating				
Grading category	5 = Outstanding	4 = Very good	3 = Satisfactory	2 = Unsatisfactory	1 = Unacceptable
Work product					
Scope/challenge	24	20	14	0	−60
Methodology	24	20	14	0	−60
Value	24	20	14	0	−60
Written report					
Content	12	10	7	0	−30
Style	12	10	7	0	−30
Mechanics	12	10	7	0	−30
Oral presentation					
Content	12	10	7	0	−30
Speakers	12	10	7	0	−30
Visuals	12	10	7	0	−30
Professionalism					
Attitude	22	17	14	0	−60
Organization	22	17	14	0	−60
Integrity	22	17	14	0	−60

Note. The point values were carefully calibrated to match our beliefs about what combinations of ratings should earn what overall letter grade.

Table A.2 Senior Design Grading Scale

Points	Grade	Points	Grade	Points	Grade	Points	Grade	Points	Grade
200+	A+	170–179	B+	130–149	C+	75–89	D+	≤39	F
190–199	A	160–169	B	110–129	C	60–74	D		
180–189	A−	150–159	B−	90–109	C−	40–59	D−		

Note. The maximum score is 210.

As is clear from Table A.1, the grading scale is such that below-satisfactory ratings hurt a grade more than above-satisfactory ratings help. This is especially true for ratings of "unacceptable." We want to ensure in senior design that all of our graduates understand and have been held to at least minimum professional standards in all of the major aspects of the engineering workplace, and the severe penalties for unacceptable work in any category makes it clear to the students that maintaining such professional standards is of real importance.

Appendix B. Senior Design Clients

Table B.1 shows the list of senior design clients our students have done projects for since the changeover to our new system, including the two pilot sections in fall 2005 and spring 2006. Underlined clients have sponsored at least two

Table B.1 ISyE Senior Design Clients Since Fall 2005

FOR-PROFIT

- *ADEX Machining*
- AGL Resources
- *AirTran*
- American CyberSystems
- Anheuser-Busch
- AT&T
- Atlanta Brewing Company
- Atlanta Gas Light
- *Atlanta Journal-Constitution*
- Avery Dennison
- Bella Cucina
- BellSouth
- *BlueLinx*
- *Burger King*
- CAB
- Canvas Systems
- Carrier Europe
- Carter's
- *Caterpillar*
- Cbeyond
- Chick-fil-A
- Cisco Systems
- Coca-Cola
- Coca-Cola Enterprises
- Coca-Cola North America
- Coca-Cola Refreshments
- *Comcast*
- *Cooper Industries*
- CR Bard
- Craft-Art
- CYI Gifts
- Delta
- DHL
- Dick's Sporting Goods
- e^2M
- EarthLink
- EGO North America
- Elesys
- *Enraf*
- Exel
- Express
- F&P Georgia Manufacturing
- *GE Energy*
- *General Mills*
- *Georgia Power*
- Goody Products
- Grenzebach
- Gypsum Management & Supply
- H.C. Brill
- Home Depot
- *Honda*
- Honeywell
- House of Cheatham
- IKEA
- iKobo
- *Intel*
- InterContinental Hotels Group
- Kimberly Clark
- Kubota Tractor
- Legacy Property Group
- Lockheed Martin
- Macy's
- *Manheim Auto Auctions*
- Marmi Natural Stone
- *Mars*
- Matador Distributing
- *McKesson*
- MedShare International
- Michelin
- Midtown Consulting Group
- *Newell Rubbermaid*
- *Next Wave*
- *Norfolk Southern*
- *Office Depot*
- PACCAR Parts
- Panasonic
- *Platt Electric Supply*
- *Porsche*
- Pratt & Whitney
- Predictix
- RaceTrac
- *Radiant*
- Rainmaker
- Reliance Electric
- Remington Medical Supply
- *RMI*
- Rock-Tenn
- Rockwell Collins
- Roswell Recycling
- Ryder
- *Saia*
- Sandoz
- Sandvik Mining & Construction
- Scientific Atlanta
- Shaw Industries
- Siemens
- *Southern Company*
- Starline Associates
- Summit Industries
- SunTrust
- SynQ Solutions
- TriVantage
- Tyco Healthcare
- Tyco Safety Products
- United Distributors
- *UPS*
- USG
- UTi
- Vertical Brands
- VF
- Waffle House
- Wal-Mart
- *Whirlpool*
- WIKA
- *Windstream*
- ZF Industries

HUMANITARIAN

- *Atlanta Community Food Bank*
- CARE
- *Centers for Disease Control*
- Flu-Free Schools
- UNICEF
- United Nations High Commissioner for Refugees
- *United Nations World Food Programme*
- *World Health Organization*

MEDICAL

- Atlanta Gastroenterology Associates
- Cardiovascular Associates
- Children's Healthcare of Atlanta
- DeKalb Medical Center
- *Emory Crawford Long Hospital*
- Emory University Healthcare
- Emory University Hospital
- Northside Hospital
- Piedmont Fayette Hospital
- Piedmont Heart Institute
- Piedmont Hospital
- Piedmont Newnan Hospital
- WellStar Kennestone Hospital

GOVERNMENT

- Atlanta Fulton County Emergency Management Association
- Atlanta Regional Commission
- City of Atlanta
- DeKalb County
- DeKalb County Police Department
- Fulton County
- Georgia Poison Control
- *Gwinnett County Public Schools*
- Metro Atlanta Regional Transportation Authority

NON-PROFIT

- *Buckhead Baseball*
- Dunwoody Baseball
- *Georgia Aquarium*
- Georgia Tech Athletic Association
- *Georgia Tech Campus Recreation Center*
- Georgia Tech Capacity Planning and Space Management
- Georgia Tech Office of Undergraduate Admissions
- High Museum of Art
- Project Open Hand
- Salvation Army
- Second Harvest
- The Children's School

Notes. Clients shown in italics have sponsored at least one project whose team was selected as a Senior Design Finalist. Underlined clients have sponsored more than one project.

projects each, and italicized clients have sponsored at least one project whose team has been recognized as a senior design finalist. The list is through the writing of this paper in spring 2012.

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