Teaching by Disaster: The Ethical, Legal and Societal Implications of Engineering Disaster

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In a new course developed in the College of Engineering and Applied Sciences at Stony Brook University, we are exploring the use of engineering disasters as a teaching tool to enhance student learning of the ethical, legal and societal implications (ELSI) of engineering and technology. ELSI instruction often presents a difficult challenge for engineering programs, but is one that has the potential to enhance recruitment and retention of students, in particular from underrepresented groups, and create an interdisciplinary learning environment. In addition, by its nature, ELSI instruction emphasizes connections to societal issues and enhances learning through a narrative approach to teaching. We will show that coursework on engineering disasters provides an excellent forum for ELSI instruction. In particular, we present examples of various modes used in teaching about disaster, results of student feedback, and the application of teaching about engineering disasters to issues such as public and educational outreach, ABET evaluation, and learning about the impact of engineering in a global and societal context.

Introduction:

The inclusion of ethical, legal societal and other 'broader' issues in undergraduate engineering degree programs has been noted to be critical in preparing students for successful careers, not just as engineers but also as productive and valuable members of society.[1] In recent years, the emphasis for the need for engineers to develop more than just "hard engineering" skills has grown, especially in response to reports and studies showing the need for engineering education to respond to trends in globalization of the engineering enterprise, professional mobility, increasing importance of communication skills, and the need for engineers to understand the implications of their work in a broader socio-economic context.[2]

The Accreditation Board for Engineering and Technology (ABET) has emphasized the importance of these issues, including them in multiple ways in the prescribed set of Student Outcomes.[3] These are what well-educated engineering students are expected to know at the time of graduation. Of special importance to the topic of this paper are the following outcomes (c,d,f,g,h,i, and j):

"Engineering programs must demonstrate that their students attain the following outcomes:
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as *economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability*
(d) an ability to function on multidisciplinary teams
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues"[3]

As evaluation of Student Outcomes now requires direct evaluation (for example, citing and tracking student performance in a particular course which demonstrates competence in a learning objective), it is all the more important to design and evaluate learning tools (such as courses) which respond to particular outcomes in a measurable sense.

Introduction to the broader issues in comprehensive engineering education is often a daunting task, falling outside the expertise (and in many cases interests) of engineering faculty. The difficulty in meeting these "professional skills" area in engineering education has been cited as being particularly challenging and requiring new approaches (for both teaching and assessment).[4] Shuman, et al., categorize these skills as "process oriented" (communication, teamwork and ethics) and "awareness oriented" (global and societal context, knowledge of contemporary issues, life-long learning). A number of different approaches have been taken to enhance the learning of these skills in undergraduate engineering programs, including service learning courses, "clinical" or internship experiences, design contests, co-taught courses, and development of on-line or hybrid classes.

Use of texts and readings of case studies in engineering disaster or engineering failure (often in a historical context) has been suggested for use in enhancing communication skills, teaching design, and enhancing the appeal of freshman engineering courses. In our "Introduction to Engineering Science" first year course (ESG 100), engineering disasters have been used in order to introduce concepts of ethics and problem solving to first year students who have been admitted to the Engineering Science B.E. degree program. As part of a modular approach to introducing a broad range of engineering subjects, including research and design, this approach has proved very successful.[5] Going beyond the straightforward and somewhat traditional use of engineering failures and disasters as case studies to illustrate ethical, design and materials failure, we have been exploring the use of active, cooperative, and problem-based learning as they apply to teaching both the technical and broader (economic, societal, legal, psychological and government/regulatory) interdisciplinary implications of engineering failure. The course and some of our preliminary results are described below.

Course design and modes of delivery of content:

"Learning from Disaster", ESG 201, has been designed as a course with will fulfill the University's Diversified Educational Curriculum (DEC) in the area of "Category H - Implications of Science and Technology". According to the Undergraduate Bulletin, "Category H courses are designed to help students understand the social and global implications of science and technology and to examine examples of the impact of science, culture, and society on one another." The course was designed during the early Fall 2009 semester, based partly on a module the author (and course instructor) developed for the mandatory first-year introductory course to be taken by all incoming Engineering Science majors.

The published catalog description of the course reads: "The role of the engineer is to respond to a need by building or creating something along a certain set of guidelines (or specifications) which performs a given function. Just as importantly, that device, plan or creation should perform its function without fail. Everything, however, does eventually fail and, in some cases, fails with catastrophic results. Through discussion and analysis of engineering disasters from nuclear meltdowns to lost spacecraft to stock market crashes, this course will focus on how modern engineers learn from their mistakes in order to create designs that decrease the chance and severity of failure." The course is 3 credits and, while required for Engineering Science majors, is open to any student in the University who has completed at least one science or engineering course. Hence, it has been designed to have a broad range of content, and this appeal is reflected in the diverse student population who participated in the first class offering (see Table 1 below).

Texts for the course included the book "Inviting Disaster: Lessons from the Edge of Technology", by James R. Chiles (Harper Business, 2002), and the recommended text "To Engineer is Human", by Henry Petroski (Vintage Books, 1992). Additional web-based resources were made available via the author's website on learning from engineering disaster at: www.stonybrook.edu/disaster. Included on this site is a link through which students can access the ASCE report entitled "The New Orleans Hurricane protection System: What Went Wrong and Why". Additional articles and course notes are included on the Blackboard site for the class (Blackboard is the course management system used by Stony Brook University, providing tools for posting class documents, announcements, communicating with students, grading, etc.)

As one might expect, the course is organized around a number of case studies selected from different engineering disciplines. To enhance student motivation and learning, an active learning, problem-based approach is used. Students are required to complete two reports – one individual and one group report – as well as give group presentations to the class. Due to the large number of students in the course, the presentations require several weeks of class time, but this includes time for class discussion. These discussions focus on the ethical, legal and societal aspects of engineering disasters, and hence provide additional time to expand on these topics. Case studies are used to introduce specific course topics. These include: the engineering design process (including design for reliability); engineering systems; the causes of failure; the business of engineering; sustainability; risk and uncertainty; failure analysis and forensic engineering; materials science; professional societies and codes of ethics; and ethical problem solving. As a general guideline for the class, the primary causes of failure are presented as: (i) human factors (negligence, ethics, and related causes), (ii) extreme conditions or environments, (iii) design flaws, (iv) materials failures, and, moist importantly, (v) combinations of all the above. The students are introduced to the concept that it is most often combinations of causes which lead to disaster. In every case study, the ethical, legal and societal aspects are presented and discussed. Class discussions often focus on misconceptions, psychological aspects of disaster, legal issues and consequences (and who was at fault), how engineering failures/disasters are portrayed in the media, and especially how such highly educated and experienced professionals, with so much equipment, technology and often money at their disposal, can allow such seemingly obvious and predictable failures to occur.

The first report (midterm report) is an individual report focused on a historical failure (i.e. the Hindenberg, the space shuttle Challenger, collapse of the Tay Bridge) of the student's choosing. In particular, the students are to focus almost entirely on the causes of failure (creating a graph showing how much each cause contributed to the overall failure and defending their choice with citations from books, journals and reports). They are also to describe the resulting impact of the failure on business, society and engineering – including how engineers can use the knowledge they gain from examination of the failure and its causes to create better designs in the future.

The second report, and the associated presentation to the class, is a group project, and may be clearly classified as an example of "problem-based learning". Problem based learning is described by Cindy E. Hmelo-Silver[6] in the following way: "*Problem-based learning (PBL) is an instructional method in which students learn through facilitated problem solving. In PBL, student learning centers on a complex problem that does not have a single correct answer. Students work in collaborative groups to identify what they need to learn in order to solve a problem. They engage in self-directed learning (SDL) and then apply their new knowledge to the problem and reflect on what they learned and the effectiveness of the strategies employed. The teacher acts to facilitate the learning process rather than to provide knowledge.*" For this final semester project, students must research, as a team, a recent or current engineering failure or disaster. The definition of "recent or current" means that students must consider a failure which has either occurred during or in the six months previous to the course, or one which is still being actively investigated. Students are encouraged to read news sources (and are taught how to judge the likely veracity or 'pedigree' of a new story – especially one from the internet). This is an important component of the course, and in the future will most likely require participation by a guest lecturer from the University's journalism or rhetoric programs. Students do have some difficulty with this concept; for example, one student provided images from the internet of a close-up view of the "explosion" of the NASA space shuttle Columbia, supposedly taken from a secret spy satellite – not noting that these pictures come from a broadly and obviously debunked source on the internet.

Table 2 below lists the projects chosen by student groups, and provides the results of their analysis of causes of failure.

Results:

Students from a wide variety of majors participated in the first class offering in the Spring semester, 2010. The distribution of students taking the course is summarized in table 1. Note that the total number of majors exceeds the number of students who completed the course (119), as some students had double majors – and both majors are included in the totals, in that case.

Table 1: Demographics from first class offering (Spring, 2010)

College/School	**Major**	**Number of majors in course**
Engineering		
	Engineering Science	25
	Computer Engineering	4
	Information Systems	2
	Computer science	4
	Mechanical Engineering	6
	Electrical Engineering	1
	Biomedical Engineering	3
	Chemical and Molecular Engineering	1
	Technology Systems Management	1
	Applied Mathematics	4
Total:	*All majors*	*51*
Arts and Science		
	Mathematics	3
	Physics	1
	Health science	2
	Economics	6
	Political science	6
	History	1
	Studio Art	2
	Music	2
	Biology	4
	Biochemistry	1
	Chemistry	5
	Engineering chemistry	1
	Sociology	3

	Psychology	2
	Pre-nursing	1
	Undeclared	16
Total:	*All majors*	*56*
Business		
	Business Management	19
Journalism		
	Journalism	2
Marine Sciences		
	Marine Vertebrate Biology	1
	Environmental studies	1

The largest numbers of students have majors in Engineering Science (as this course is recommended for these students as part of their core program), Business Management (in the School of Business), Mechanical Engineering, Economics and Political Science. Overall, there is a fairly even split between the College of Engineering and Applied Sciences and the College of Arts and Sciences. Further, 31% of the students in the class were female (a very high percentage for any class with "engineering" in the title). The completion rate for the class was 97.5% and the pass rate was over 90%, an indication of student interest and motivation as well as course content.

Results of class projects:

Most importantly, what can we learn about the impact on student learning from the nature of evidence provided by student work?

Of the 31 final projects, focused on recent (2007-2010) engineering disasters, the breakdown of self-selected topics and the resulting breakdown of student interpretation of causes of failure are summarized in the following table. Since topics were self-selected, and to better stimulate class discussion, student groups were allowed to pick the same disaster or failure. Hence some topics (the Toyota recall, the Upper Big Branch mine disaster in West Virginia, a crane collapse in Manhattan, the I-35W bridge collapse, and the crash of the Polish Air Force Tu-154) were chosen by more than one group.

Table 2: Summary of results of student final projects

Group #/ research topic	**% cause of failure attributed to**				**Location, date, other causes, etc.**
	human factors or ethics	**extreme conditions**	**design flaws**	**materials failure**	
23/Toyota recall	50	10	20	20	2010 (United States)
27/Toyota recall	55-90		10-45		Students divided recall into failure of individual system components: analyzed

					causes of each
26/Toyota recall		20	50	30	Suggested some design flaws result of ethics failure
12/Toyota recall	75		25		
4/Toyota recall	25		30	45	
20/Toyota recall	>50				Breakdown not provided; ethical failure implied
5/Upper Big Branch mine disaster	100				April 2010; West Virginia
7/Upper Big Branch mine disaster	70	10	20		System failure cited
8/Upper Big Branch mine disaster	100				
10/Upper Big Branch mine disaster	50		50		
22/Upper Big Branch mine disaster	60	5	25	10	
1/Upper Big Branch mine disaster	55	5	40		
11/Manhattan Crane Collapse	50			50	March 2008; New York
29/ Manhattan Crane Collapse March 2008	99			1	
21/I-35W Mississippi River Bridge Collapse	10	45	35	10	August 2007; Minnesota
16/I-35W Mississippi River Bridge Collapse	75		20	5	
28/Polish Air	70	20	5	5	April 2010; Russia

Force Tu-154 Crash					
2/Polish Air Force Tu-154 Crash	70		15	15	
30/Polish Air Force Tu-154 Crash	50	40	5	5	
3/ Collapse of the Lalla Khenata Minaret	30	5		30	February 2010; Morocco; 35% for lack of proper maintenance
9/ 2010 Earthquake in Haiti	60		40		January, 2010; Haiti
19/ Imperial Sugar Factory Disaster	33		33		February 2008; Georgia 33% for lack of proper maintenance
15/ Germany Millennium Bug Disaster	75		25		January, 2010; Germany Software engineering failure; debit card failure on 1/1/2010
14/ JM Eagle pipe failure	40		35	25	2009-2010; multiple states (US)
31/ Tarcoles Bridge Disaster	60	15	10	15	October 2009; Costa Rica
13/ Sayano - Shushenskaya Hydroelectric Dam Disaster	35		5	60	August 2009; Russia
6/ Middletown Power Plant Explosion	50	10	35	5	February 2010; Connecticut
17/ Big Dig Ceiling Collapse	80			20	July 2006; Massachusetts
24/AA331 flight which overshot the runway	80	20			December 2009; Jamaica
18/ Hilton Head Plane crash	33		33	33	March 2010; South Carolina

25/ Shanghai Building Collapse	60	5	30	5	June 2009; China

A number of useful observations are evident in these results. First, while students were allowed to include "genuine accident" as a cause of disaster, none included this explanation in their reports. No matter what the status of current investigations, student groups all were able to come to their own conclusion concerning the causes of the failures (though many stated that the ongoing investigations may reveal additional evidence and facts which could impact their interpretation). Of the causes given for all the cases chosen, the highest average score was "human factors/ethics" – 57%. Only one group did not include ethics as a cause, but that group implied that ethical issue may have been the indirect cause of design flaws. The second highest average score was for "design flaws" which on average accounted for 20% of all causes, followed by 13% for "materials failure". Extreme conditions and improper maintenance (not included in the original list) were the other cited causes.

Another important observation is that different student groups who studied the same case came to different conclusions about the causes of failure. This is most evident in the case of the Toyota recall and the crash of the Polish Air Force Tu-154 (in which the Polish president as well as a number of dignitaries and military leaders were killed). In both these case, news reports, company press releases, and independent reports varied widely and often disagreed. Hence it is not surprising that this is expressed to some degree in student reports. Both of these cases stimulated spirited classroom discussions. Reports on certain other cases were far more uniform. For example, in the case of the Upper Big Branch mine disaster in West Virginia, general agreement on causes reflects the more uniform news coverage and the general agreement on the causes of failure in initial reports. Likewise, the I-35W Mississippi River Bridge Collapse occurred further in the past (2007), allowing more time for investigations to be concluded and materials published. All student presentations demonstrated strong student opinions, and, due to the multidisciplinary background of students, produced an interesting variety of presentation content. This included an impressive level of business and economic impact analysis (as a large number of business majors and minors took the course), and even a range of artistic expression, including a song on the Upper Big Branch mine disaster and a poem about the Toyota recalls.

Finally, this class exercise was valuable in showing how global issues play a role in engineering education – of the 17 cases considered in the final projects, more than half (8) involved engineering failures occurring outside the United States. Presentations and discussions about these failures indicated that students learned about particular issues impacting engineering on a global scale. For example, students learned how environmental and geographic conditions are important factors in design, how language and communication barriers play a role in failure, how building codes and practices differ in various parts of the world, and how socio-economic conditions in a nation or region can play a critical role in the nature and quality of engineering and maintenance. In many cases, when students recommended solutions for preventing engineering failure in poor regions or where social or political disruption can impact engineering quality, they focused on education and outreach to communities as key components of their solutions.

Results of student course evaluations:

During the final week of the class, student were asked to reply to an anonymous questionnaire, distributed in class, which is used for all courses in the University to identify student views of the course, its content and the instructor. 70 students (of 119 remaining in the course – a retention rate of 97.5%) completed the survey, with the following results (only the results relevant to this report are presented):

Table 3: Results of course post-survey. Numbers represent average value of 70 responses on a Likert scale of 1 to 5, where 1 represents strong agreement and 5 represents strong disagreement.

Student Assessment	Course Average	Department course average	University course average
I found the topics to be clear	1.18	1.75	1.92
I met the learning objectives of the course	1.45	1.78	1.92
I found coursework to be challenging	1.88	1.67	1.87
My coursework was evaluated fairly	1.34	1.54	1.83
I would recommend this course	1.17	1.67	2.01
I learned more in this course than in other similar courses	1.68	1.84	2.14

The students also were provided with the opportunity to comment on the course. Most of the comments were quite positive – 23 specifically commented that they found the subject matter particularly interesting and/or entertaining, 7 specifically stated that they found the course topics applicable to their lives and studies, 8 found the content valuable in enhancing their engineering studies, 2 cited the ethics content, and several also mentioned it enhanced their overall interest in engineering. Students did request that more time be provided for group work, and that follow up topics be pursued more vigorously. Some students did not find the class very challenging, likely because the course level was tailored to a diverse group of learners.

Conclusions:

The course "Learning from Disaster" was found to be a successful and engaging way to enhance undergraduate student learning of the ethical, legal and societal impact of engineering design and engineering decisions. In working together in an active problem-based learning format, with other engineering students as well as with students from business management and arts and science majors, the students gained an appreciation for multi-disciplinary team-based learning. Course work provided evidence of learning about engineering ethics, the value of life-long learning, and engineering in a global and societal context, all areas defined by ABET as critical to successful undergraduate engineering education programs. Student work from the course will be used for direct assessment of ABET Student Outcomes in ability to function on multidisciplinary teams, understanding of professional and ethical responsibility, broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context, and knowledge of contemporary issues. (Design and communication skills, as well as lifelong learning are evaluated elsewhere in the Engineering Science program). The course has also provided an impetus to development of additional on-line learning resources (including a website and a weblog on Learning from Disaster developed by the author[7]), and resulted in new opportunities for outreach to students, other faculty and the general public.

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