13. Engineering and Computer Science in Action: A Course on "The Structure of Engineering Revolutions"

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Abstract
This class provides an integrated approach to engineering practice in the real world. Students research the life cycle of a major engineering project, new technology, or startup company from multiple perspectives: technical, economic, political, and cultural. Research involves interviewing inventors, reading laboratory notebooks, evaluating patents, and looking over the shoulders of engineers as they developed today's technologies. Developed in 1997 as a joint effort between the MIT Electrical Engineering and Computer Science Department and the Program in Science, Technology and Society, "The Structure of Engineering Revolutions" illustrates how history can successfully enrich the education of advanced computer science and engineering students.

MIT launched the flagship course "The Structure of Engineering Revolutions" in 1997 under the joint impetus of the Electrical Engineering and Computer Science (EECS) Department and the Program in Science, Technology, and Society (STS). The course aimed to bridge the gap between the excellent technical education received by MIT EECS undergraduate and graduate students and the methodologies used by anthropologists and historians in STS to study technological development, practice, and culture.

The course began as the brainchild of Professor David A. Mindell, who designed it as a vehicle for teaching students about engineering and computer science practice in the real world. Although MIT graduates exhibited a high degree of technical proficiency when they entered the job market, faculty and alumni had expressed concern that, in general, EECS students lacked an overall understanding of how non-technical factors contributed to the successful development of new technologies. Students, they felt, needed an appreciation for the diverse roles engineers played and a deep understanding of engineering cultures and their effects on design. Faculty also expressed a desire for students to increase their experience working in teams, improve their skill giving oral presentations, and be able to think critically and argue across disciplines.

Building on these perceived deficiencies in the EECS curriculum, Mindell created a course that allowed students to gain a better understanding of engineering practice by conducting original research on the history of a technology, company, or individual scientist or engineer. Through these historical case studies, students learned about the day-to-day realities of engineering as documented in laboratory notebooks, personal interviews with project participants, archival sources, and the technologies themselves.

The course targeted advanced students, typically fifth year students completing a Masters in Engineering. In theory, the fifth year was designed to "broaden" a student's educational experience, but in practice students were using the additional year to deepen their expertise in a particular technical area. "The Structure of Engineering Revolutions" addressed this gap between theory and practice by giving students the opportunity to use the skills honed in their other technical classes and apply them within a different analytical framework.

The course fulfilled a technical requirement within the EECS curriculum. It was not an add-on to a technical education, but part of the core, technical and non-technical, of what it means to be educated as an Electrical Engineer or Computer Scientist at MIT. Support from the EECS department for the educational goals of the class contributed significantly to its success and helped with enrollment levels while the class was still a relatively unknown entity. To encourage the interdisciplinary merging of EECS and STS, the course has frequently been taught jointly by instructors from both departments. Mindell is both an historian of technology and a practicing electrical engineer, and every teaching assistant involved with the course has possessed a dual background in history and EECS.

Course Themes

Classical engineering and science education encourages students to search for the best technical solution. The typical problem set presents a situation with a series of controlled conditions and one right answer. Nothing exists outside of this technical realm, or if it does it is viewed as unimportant, suspicious, or even bad science or engineering. This emphasis on the technical fosters a popular myth among students that simply building the next killer app or disruptive technology will automatically lead to fame and riches. However, as history has shown time and time again, the successful development, implementation, and marketing of new technologies depend on a broad range of skills, many of which are often dismissed as politics.

The material presented in "The Structure of Engineering Revolutions" encourages students to break down the artificial barrier between the "technical" and the "political" and learn that politics exists in every aspect of technological production, from the creation of an engineering culture to determining the criteria that define reliability and success. These political, or perhaps social, considerations are not irrational as students may initially believe, but rather reflect the rationality of a particular engineering culture, market, or set of social relationships.

If we take this as a starting point, it then becomes easy to see how history and the interdisciplinary field of Science, Technology and Society can provide a crucial addition to engineering and computer science education.

To cite a few examples:

- Instead of thinking about technology and its social effects, a deterministic model that places human beings in the position of helplessly conforming to the introduction of new technologies, students learn that the technologies themselves are social creations, brought about by a particular historical context, series of negotiations, and individual choices.
- Students learn to question technological trajectories such as Moore's Law and analyze the complex socio-technical networks that permit these trajectories to masquerade as the inevitable path of progress.
- We study a variety of engineering cultures (e.g., Microsoft, Data General, and the MIT Instrumentation Lab), and through these case examples illustrate how managers historically have cultivated particular working conditions in order to shape engineering practices, technological design, and company identity. By studying the heterogeneous factors that contribute to and maintain a particular engineering culture, students learn to think beyond the strictly technical sphere of the lab and ask instead how their work environment has been constructed and the effect it has on the work produced.

- We take apart the myth of the single genius inventor, the origin story, and idea of "vision." History clearly shows that invention and innovation are processes rather than individual moments. Inventors depend upon laboratory, government, or other social or institutional infrastructures to create their famous works, rather than simply relying on genius. Likewise, visionaries do not convey prophecies of what will be. They convince others to share their vision and help make their interpretation of the future into a reality.
- In contrast to the problem set model that places technical considerations above all, students learn to put people, their choices, and their decisions at the heart of technological development.

Course Structure

The course is divided into two parts. The first half follows a traditional format with lectures, readings, and short writing assignments akin to problem sets that introduce students to the themes mentioned above and permit early feedback on their writing skills.

The syllabus also includes a workshop on working in teams, a lecture from a patent lawyer on the basics of reading a patent, and a presentation by the MIT archives on how to access and incorporate the rich collection of laboratory notebooks and other primary source documentation in students' final projects. A unit based on Edward Tufte's work on visual representation encourages students to think critically about the way they use and display visual information in their written work and oral presentations.

In the second half of the course, the students divide up into teams and write their own case histories of a technology, company, or individual of their choosing. This is similar to the case method used in business schools, except the students have the opportunity to write the cases themselves and select the research questions they find most interesting. In addition to presenting a well-reasoned argument, students are required to demonstrate a solid technical understanding of the technologies relevant to their case history. Students typically worked in teams of four to six students and presented their work in a public forum on the MIT campus at the end of the semester.

The second half of the course is largely unstructured, but nonetheless time-intensive for both students and teachers. Although students were free to use class time to visit the library, conduct interviews, or have group meetings, we maintained a hands-on relationship with each group, helping them frame research questions and suggesting additional source materials. As the projects advanced, we provided detailed critiques of written drafts and oral presentations. Due to the amount of time invested in each student, the interactive style of class lectures, the need to limit groups to six students (four is preferable), and the requirement that each group publicly present their work in an open forum at the end of the semester, we have not been able to scale the course beyond fifty students. An enrollment of sixteen to twenty students is ideal.

From the student perspective, the work assigned for this class rivaled the workloads found in their other EECS classes, especially during the final phase of the semester. For this reason, in later syllabus revisions we decided to give students more class time to work on their final projects. The projects also introduced students to the numerous benefits and difficulties of working in teams. Assignment guidelines required students to produce a seamless final document that did not illustrate an obvious division in labor and/or writing style. Some groups also opted to construct a project website in addition to the final written document.

Despite the historical framing used in the course, the goal was not to teach students to become historians of technology; nor was it to impart any particular historical narrative. Rather, history served as a vehicle to teach an awareness of complexity in technology and to impart critical reading and thinking skills. The projects that students examined contained all the contradiction, ambiguity, and uncertainty of historical accounts. In resolving these difficulties, students learned to identify the broad parameters of engineering practice and developed a conceptual vocabulary with which to describe the evolution of a technology to themselves and to others.

By the end of the semester, the students had created a sophisticated historical analysis of engineering and computer science in action that drew upon a broad range of primary and secondary source materials. While many educators fear the increasing and uncritical dependence on Google exhibited by students in recent years, the course structure provided an opportunity for students to utilize a combination of interviews, standards, patents, laboratory notebooks, history texts, technical diagrams, code, technological artifacts, and photographs in the creation of an original historical narrative and argument.

Apart from these educational objectives, the course augmented ties among students, alumni, local businesses, and various university resources. By requiring students to select a project history associated with MIT in some form, we encouraged interaction among the students and these diverse university and technological communities with positive results. University alumni have enjoyed contributing to student education outside of annual giving campaigns. Project interviews can similarly lead to job interviews for students or create networks for the future. The diverse sources used in writing the project histories also allowed under-funded but important resources like university archives to claim a visible contribution to undergraduate and graduate teaching. These positive aspects of community-building could potentially be transferred to other universities by implementing a modified version of the course curriculum.

Conclusion

Young engineers and computer scientists face a world that demands a multidisciplinary approach to engineering and computer science, where technology does not develop in a vacuum. It is a world in which graduates will spend a majority of their time communicating and where they must exercise judgments based on diverse and imprecise information. The themes addressed in this class encourage students to synthesize their strong technical skills with insight into political and social processes, abilities in teamwork, communications, and career-long learning. This last is perhaps the most subtle and difficult to teach; it must combine the thrill of learning with the ability to read, think, and write critically across disciplines. Here the disciplines and methods of history and STS have the most to contribute.

MIT and the Boston area have provided an environment rich in resources for the themes and ideas presented in this class, but they are not unique. Every engineering and computer science department boasts a history of technological innovation, an alumni network, and a local academic or industrial high-tech community. Since this class encourages students to situate engineering and computer science practices in a real world environment, departments may choose to couple this class with a pre-existing professional practice requirement or internship program, perhaps encouraging students to select projects of relevance to their future employers. Restructured, this course could address histories and practices in science and engineering fields outside of EECS. It could also be tailored to stress the particular research and teaching strengths of a given university or EECS department, while still encouraging students to develop and apply a range of interdisciplinary skills outside of those found in the existing curriculum. For universities hoping to enrich their humanities curriculum with facets of science and engineering education, the human-centered approach to technology building presented here could appeal to humanities students and allow them to think about technology-related issues at a high level of sophistication.

"The Structure of Engineering Revolutions" has consistently received positive student reviews, with some students claiming it has been the most valuable course of their MIT experience, and has resulted in the university's highest teaching award for Mindell. Interested readers are encouraged to visit the course website (http://mit.edu/6.933/www) for links to class handouts, notes, and copies of final project histories. Material from "The Structure of Engineering Revolutions" is also available publicly as part of MIT OpenCourseWare (http://ocw.mit.edu/index.html).

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David A. Mindell is the Frances and David Dibner Associate Professor of the History of Engineering and Manufacturing in the Program for Science, Technology and Society at MIT. His research interests include technology policy (historical and current), the history of automation in the military, the history of electronics and computing, and deep-sea archaeology. Professor Mindell heads MIT's "DeepArch" research group in Deep Sea archaeology. He is the author of *War, Technology and Experience Aboard the USS Monitor* (2000), and *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (2002). *Author's address:* Program in Science Technology and Society, MIT E51-194C, 77 Mass Ave, Cambridge, MA 02139 USA. Email: mindell@mit.edu.

Appendix A. List of Final Projects Relevant to Computer Science[128]

Fall 2001

- Mathematical Theory of Claude Shannon: A Study of the Style and Context of his Work Up to the Genesis of Information Theory
- Information Theory and the Digital Age
- The MIT Student Information Processing Board: The Social and Technical Impact of an MIT Student Group
- Bolt Beranek and Newman Inc.: A Case History of Transition
- A Marriage of Convenience: The Founding of the MIT Artificial Intelligence Laboratory

Fall 2000

- Down from the Top of its Game: The Story of Infocom, Inc.
- The World Wide Web as an Engineering Paradigm
- The Selection of the Advanced Encryption Standard
- Mode S: An Air Traffic Control Data-Link Technology
- LEGO Mindstorms: The Structure of an Engineering (R)evolution

Fall 1999

- Project Athena: Success in an Engineering Project
- Logo: A Project History

Fall 1998

- Ethernet: An Engineering Paradigm
- Symbolics, Inc.: A Failure of Heterogeneous Engineering
- Dragon Systems

Fall 1997

- The Apollo Guidance Computer
- Thinking Machines
- Lotus
- Magnetic Core Memory
- RSA Data Encryption

[128] A full list of projects is available on the course website, http://mit.edu/6.933/www/projects_whole.html.

Appendix B. Course Syllabus

6.933J / STS.420J
The Structure of Engineering Revolutions
Course Outline
Fall, 2001

I. Introduction and Background

September 5: (Wed)
Introduction, course overview.

II. Engineers in Action

September 10: (Mon)
Reading: Latour, Science in Action Introduction (pp.1-17), Chapter 3 (pp. 103-144)
September 12: (Wed)
Reading: Latour, Science in Action Chapters 4-6 (pp. 145-259)

III. The Construction of Technological Systems

September 17: (Mon) NO CLASS
September 19: (Wed)
Reading: Mindell, "Opening Black's box: Rethinking feedback's myth of origin" (Xerox/pdf)

IV. Invention and Engineering Culture

September 24: (Mon)
Reading: MacKenzie, Inventing Accuracy Chapters 1-2
September 26: (Wed)
Reading: MacKenzie, Inventing Accuracy Chapters 4, 7, 8.
Assignment Due: Response paper #1

V. Innovation and Marketplace

October 1 (Mon)
Reading: Christensen, The Inventor's Dilemma Chapters 1, 2, 4, 9, 11

October 3: (Mon)
Reading: Discussion of methodology, research methods, library, techniques, source materials, etc.
Assignment Due: Response Paper #2

VI. Using Sources Effectively
October 8: (Mon) NO CLASS - COLUMBUS DAY

October 10: (Wed) **Lab Notebooks and Project Documentation**
Meet in MIT Archives 14N-118, introduction to Edgerton/Forrester notebooks

VII. Group Work and Collaborative Writing

October 15: (Mon) Presentation "Working effectively in groups", in class group work
October 17: (Wed) In Class Group Work, Presentation of project history proposals, discussion and ranking.
Assignment Due: Individual project history proposals

VIII. Project History Work

October, 22: (Mon) In class group work
October, 25: (Wed) In class group work

IX. Visual materials and argumentation

October 29: (Mon)
Reading: Edward Tufte, Visual and Statistical Thinking (packet)
October 31: (Wed) In class group work

X. Understanding Patents

November 5: (Mon) Presentation "How to read a patent", in class group work
November 7: (Wed) In class group work
Assignment Due: Visual argumentation exercise

XI. Project Histories

November 12: (Mon) NO CLASS

November 14: (Wed) In class group work
Assignment Due: Group proposal/plan of project history
November 19: (Mon) In class group work
November 21: (Wed) In class group work

THANKSGIVING
November 26: (Mon) In class group work
November 28: (Wed) In class group work

XII. Final Preparations

December 3: (Mon) Presentation rehearsals

December 5: (Wed) Presentation rehearsals
Assignment Due: Written draft for groups presenting

XIII. Presentations of Project Histories

December 10: (Mon) Group Presentation of Project Histories
December 12: (Wed) Group Presentation of Project Histories
LAST DAY OF CLASSES

Final projects due Friday December 14, 5pm.