



## Semiconductors and Society: A First-Year Seminar

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### Abstract

Since the invention of the transistor 73 years ago, semiconductor technology has improved at an exponential rate following the self-fulfilling prophecy of Moore's Law. Improvements in semiconductor technology have in turn enabled remarkable improvements in communication and information technology, leading to major changes in the way people communicate, compute, acquire and use information, and seek entertainment.

This paper describes a First-Year Seminar taught in 2017 and 2019 in which students from a range of different majors explore the history and societal impact of semiconductor and related technologies throughout the semiconductor era. The goals of the seminar are to provide students with a qualitative understanding of how semiconductors are designed and manufactured, an appreciation for how the technology has evolved and enabled new products and services, an awareness of the physical and economic factors that suggest an end to exponential improvement, and a perspective on how the end of exponential improvement might further impact society. Students can use this perspective to make informed decisions about semiconductor and related technologies and to participate in the broader conversation about the technological choices faced by society.

The course is structured as a historical survey that begins with precursor technologies that motivated the development of semiconductors, followed by the invention of the transistor and the integrated circuit, and the ongoing symbiotic relationship between semiconductors and communication and information technology that led to a "virtuous cycle" of exponential improvement. Students engage in reading and discussion along with short lectures describing the design and manufacture of semiconductors. Hands-on experiences involving coding and integrated circuit design are used to strengthen student understanding of basic concepts. Student writing assignments include reflections about their personal history experiencing technological improvements, reactions to the hands-on experiences, and a book report in which they explore one particular aspect of semiconductor technology and its societal impacts.

Assessment of student writing assignments showed that students gained a qualitative understanding of semiconductor design and manufacturing and an appreciation for the changes brought about by advances in semiconductor technology and its applications. Future refinements to the course will include broadening coverage of impacts of semiconductors in the present day including environmental concerns, privacy/surveillance issues, and job losses due to automation.

### Introduction

*"The world has arrived at an age of cheap complex devices of great reliability; and something is bound to come of it."*

*-- Vannevar Bush, 1945 [1]*

Since the invention of semiconductors – first the transistor in 1947 and then the integrated circuit in 1958 – the capabilities and performance of these devices have improved exponentially for decades in a trend which has come to be known as Moore's Law [2]. This trend has led to major changes in the ways in which individuals use this technology to compute, communicate, control

other devices, acquire and use information, and seek entertainment, with significant societal impacts.

Consumers now rely on semiconductors in an increasingly wide range of products and have come to expect that these products will be replaced in a few short years with newer, cheaper, and better ones. Companies have based their product development strategies on the assumption that larger, more powerful integrated circuits will be available to support future products. At the same time, no trend of exponential improvement is sustainable in the long term, and indications are that, due to technical and economic limitations [3], the era of Moore's Law is coming to a close.

The 2002 National Academy of Sciences report *Technically Speaking: Why All Americans Need to Know More About Technology* [4] notes that "the United States is experiencing a whirlwind of technological change" and argues that *technological literacy* – "an understanding of the nature of history and technology, a basic hands-on capability related to technology, and an ability to think critically about technological development – is essential for people living in a modern nation like the United States."

The NAS report characterizes three dimensions of "characteristics of a technologically literate citizen", as shown in Table 1: 1) *knowledge* of the technology; 2) *ways of thinking and acting* about the technology; and 3) *capabilities* of individuals to use the technology. Traditional engineering courses involving semiconductor technology focus on developing the in-depth technical knowledge needed for practitioners to design systems using semiconductor technology. However, these courses are not accessible to a more general audience of students who could benefit from increased technical literacy. Moreover, because these courses focus primarily on technical details, they often have limited coverage of the broader characteristics of Table 1 that focus on the interaction of technology and society.

<p><b>Knowledge</b></p> <ul style="list-style-type: none"><li>• Recognizes the pervasiveness of technology in everyday life.</li><li>• Understands basic engineering concepts and terms, such as systems, constraints, and trade-offs.</li><li>• Is familiar with the nature and limitations of the engineering design process.</li><li>• Knows some of the ways technology shapes human history and people shape technology.</li><li>• Knows that all technologies entail risk, some that can be anticipated and some that cannot.</li><li>• Appreciates that the development and use of technology involve trade-offs and a balance of costs and benefits.</li><li>• Understands that technology reflects the values and culture of society.</li></ul> <p><b>Ways of Thinking and Acting</b></p> <ul style="list-style-type: none"><li>• Asks pertinent questions, of self and others, regarding the benefits and risks of technologies.</li><li>• Seeks information about new technologies.</li><li>• Participates, when appropriate, in decisions about the development and use of technology.</li></ul> <p><b>Capabilities</b></p> <ul style="list-style-type: none"><li>• Has a range of hands-on skills, such as using a computer for word processing and surfing the Internet</li><li>• and operating a variety of home and office appliances.</li><li>• Can identify and fix simple mechanical or technological problems at home or work.</li><li>• Can apply basic mathematical concepts related to probability, scale, and estimation to make informed judgments about technological risks and benefits.</li></ul>
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**Table 1 - Characteristics of a Technologically Literate Citizen (from [3])**

This paper describes a First-Year Seminar at an undergraduate liberal arts college entitled *Technology and Society: The Semiconductor Era*. It is intended to help students from a range of majors develop technological literacy in semiconductors by providing them with a qualitative understanding of semiconductor technology and its applications and a perspective its history and its societal impacts. The course has now been offered twice, during the Fall 2017 and Fall 2019 semesters.

The FYS is built around lectures that explain the basics of semiconductor function, design, and manufacturing along with readings that provide a historical survey of the evolution and application of semiconductor technology, along with its current status and future potential. Students are asked in discussions and writing assignments to reflect on how they have been personally impacted by the significant changes that have occurred just over their lifetimes. Hands-on experiences help reinforce students' understanding of semiconductors and applications. Writing assignments help students develop "ways of thinking and acting" with semiconductor technology with the goal of gaining the perspective needed to participate in the larger conversation about the current relationship of semiconductor technology with society and its prospects for the future.

The course is open to first-year students from all majors and is intended to benefit the general population of students in understanding how a technology that they use every day came to be and where it might be heading. It should also benefit students intending to major in directly related disciplines by introducing them to the societal impacts of the technology that they will be learning about in detail in coming semesters.

The engineering education literature contains an extensive discussion of different pedagogical approaches to developing technological literacy and awareness of societal impact technology. These topics are often addressed in first-year introduction to engineering courses (e.g., [5,6]) that provide students with early exposure and hands-on experience with digital design and semiconductor design tools. These courses are primarily technical in nature. Other introduction to engineering courses (e.g., [7]) take a broader approach to introducing engineering as a social-technical system while focusing on the engineering design process and its broader societal implications.

Another approach has been to use history of technology courses to introduce students to the societal impact of engineering through the study of multiple technologies ranging from pre-industrial to modern eras [8,9]. In many cases, these efforts have been billed as a way to address ABET criteria mandating knowledge of the societal impact of technology in engineering students.

A third approach is to design an entire program to address the interaction of technology and society through the interaction between liberal arts and engineering [10,11]. This provides a much greater opportunity for breadth and depth in studying this topic to the smaller set of students that enroll in these programs.

The FYS described in this paper is a hybrid of the first two approaches. It focuses more narrowly on semiconductor and related technologies (e.g. communication and information technology) with the goals of providing 1) a qualitative understanding of how semiconductors work and how they are designed and manufactured, 2) a historical perspective on the exponential trajectory of semiconductor technology and its societal impacts, and 3) a perspective on the current state of the art and the anticipated end of exponential improvement of the technology.

The contributions of this paper are as follows. First, it describes an effort to address the history and societal impacts of a specific technology in a focused, single-semester course. Second, it describes a framework for introducing the technology and its impacts using a historical survey and identifies potential readings and other sources that may be useful for others developing similar courses. Third, it describes how hands-on experiences can reinforce students' qualitative understanding of technology when they have limited or no prior exposure.

The remainder of this paper is organized as follows. Section 2 describes the context of the course as a component in a broader first-year seminar program, its primary learning outcomes, and the general strategy of the course. Section 3 describes the structure of the course and surveys the readings and other materials used in the course. Section 4 describes the assignments used in the course and their assessment. Section 5 reports on the results of the course, while Section 6 concludes the paper and suggests future directions for the course.

## **2. Course Context and Learning Outcomes**

The course described in this paper was developed and is offered as part of the First Year Seminar program at Lafayette College. As described in the College catalog [12], these seminars are “designed to introduce students to intellectual inquiry through engaging them as thinkers, speakers, and writers.”

FYS courses are part of Lafayette's Common Course of Study and required for all first-semester students. To achieve a common set of goals across a range of topics, all FYS courses must include a common set general learning outcomes and information literacy outcomes shown in Table 2. To support the information literacy outcomes, each FYS section is assigned a librarian who conducts two class sessions in which students learn to use library resources for research and serves as a consultant during student research assignments.

FYS courses are writing-intensive and affiliated with the Lafayette College Writing Program (CWP). Students are expected to complete at least 20 pages (5,000 words) of reviewed, out of class writing. The CWP emphasizes process writing through the creation and review of drafts followed by revision and submission of a final draft. Students receive feedback on drafts from the FYS instructor and a student Writing Associate who is trained by the CWP to give students detailed feedback and suggestions for improving their writing during a sequence of four writing conferences over the course of the semester.

Within this framework, each individual seminar course is developed by a faculty member who chooses a topic and serves as instructor for the course. The range of these topics is quite broad, including science, technology, history, current events, and literature; a full list of current topics can be found in [13]. Once a topic is chosen, the instructor develops a set of course-specific learning outcomes within the larger FYS framework and then creates a set of readings, discussion topics, and assignments that are appropriate to the specific topic.

Table 3 summarizes the course-specific learning outcomes for the FYS described in this paper. In the following paragraphs we discuss the rationale for each outcome:

*Outcome C1: Describe in a qualitative way how semiconductor circuits function, are designed, and are manufactured.*

In order to participate in an informed conversation about semiconductor technology and its societal impacts, students need knowledge of the basic concepts behind semiconductor devices along with an understanding of how they are designed and manufactured. In the context of the

“Characteristics of a Technologically Literate Citizen” described in Table 1, this includes exposure to “basic engineering concepts” and familiarity with the “engineering design process” as it relates to the design and manufacturing of semiconductor products, including some knowledge of the underlying economics of semiconductor manufacturing.

Students completing an FYS course should be able to:	
FYS1	Develop strategies for interpretation and evaluation
FYS2	Examine personal assumptions and biases, thereby building informed perspectives
FYS3	Engage in writing as an act of intellectual and critical inquiry
FYS4	Acquire an introductory understanding of research skills necessary for academic writing
FYS5	Begin to develop strategies for participating in discourse communities beyond the classroom
IL1	Identify and articulate the need for information relevant to a specific purpose or goal.
IL2	Select the most appropriate investigative methods for different information needs and develop and employ effective search strategies to locate useful information.
IL3	Evaluate information and its sources critically and incorporate selected information into personal knowledge bases and value systems.
IL4	Understand the economic, legal, and social issues surrounding the use of information and access, and use information ethically, wisely, and legally.”

**Table 2 – Lafayette College FYS General Learning Outcomes**

Students completing FYS 035 (This Course) should be able to:	
C1	Describe in a qualitative way how semiconductor circuits function, are designed, and are manufactured.
C2	Describe how as semiconductor technology has evolved over time, it has enabled new ways for people to do things (e.g. learn, work, communicate, and control other devices and systems)
C3	Elaborate on how technological improvements have enabled 50+ years of “Moore’s Law.”
C4	Describe the factors that are likely to limit further technological improvements in semiconductors.
C5	Describe potential societal impacts of the end of Moore’s Law.

**Table 3 –FYS 035 Course-Specific Learning Outcomes**

*Outcome C2: Describe how, as semiconductor technology has evolved over time, it has enabled new ways for people to do things (e.g. learn, work, communicate, and control other devices and systems)*

The rate of change in semiconductor technology has been rapid enough that first-year students easily appreciate the changes they have experienced over their lifetime. However, this outcome requires that they gain a broader historical perspective. In terms of Table 1, this includes developing an understanding of some of the “ways technology shapes human history and people shape technology”, understanding some of the “trade-offs and balance of costs and benefits” of applying semiconductor technology, and understanding that developing technology “reflects the values of culture and society.”

An important part of achieving this outcome is developing an understanding of the symbiotic relationship between semiconductor technology and the communication, computing, and information technologies that use semiconductor devices as building blocks. Many of these technologies preceded semiconductor technology but created a demand for better switching and amplification devices, which motivated the initial invention of semiconductor devices. The application of these devices in communication and computer systems led in turn to new products, increasing demand for better and more capable semiconductor devices, leading to a “virtuous cycle” [14] in which the interrelated technologies improved together in terms of cost and performance.

Another important part of achieving this outcome is developing an understanding that the advancement of semiconductor technology was not just the work of a few “great inventors” but instead required collaboration between multiple individuals and organizations. Further, most advancements in semiconductor technology were incremental and often developed simultaneously. Ongoing development and growth of the technology and its applications depended heavily on the ways in which governments, companies, and individual consumers made use of the resulting products, which often occurred in unanticipated ways.

*Outcome C3: Elaborate on how technological improvements have enabled 50+ years of “Moore’s Law.”*

While Gordon Moore famously predicted in 1965 that semiconductor device density in integrated circuits would periodically double every 18 months, the prediction only came true due to ongoing, intentional investment in research and development, heavily subsidized in its early days by government, military, and aerospace and only later by the semiconductor industry itself. It was not in any sense “inevitable” even though it appears to be so in hindsight. A closer examination of the history of semiconductors and their applications shows that progress was not uniformly positive – some companies took “wrong turns” that were ultimately unsuccessful, while other companies could not adapt to the economic disruptions of the developing technology and ultimately ceased to exist.

Achieving this outcome requires that students explore how the photolithography process that is the heart of semiconductor manufacturing has changed over time, along with the development of new device structures and interconnection schemes.

*Outcome C4: Describe the factors that are likely to limit further technological improvements in semiconductors.*

Achieving this outcome requires first of all an understanding that trends of exponential improvement are not sustainable. While predictions of the end of Moore’s Law are as old as Moore’s Law itself, physical limitations of the wavelength of light used in photolithography along with economic limitations as the cost of manufacturing increases point to its imminent end. This outcome focuses on developing and understanding of these limiting factors.

*Outcome C5: Describe potential societal impacts of the end of Moore’s Law.*

Individuals, corporations, and governments have for some time been able to assume ongoing exponential improvements in performance and cost of semiconductor devices. For example, for many years, microprocessor manufacturers have designed new products assuming the concurrent development of a new manufacturing process that provided increased device density, higher performance, and lower unit costs [15]. Other consumer products have been designed in a

similar fashion. Barring the development and widespread adoption of a completely different technology, this trend is ending. Achieving this outcome requires students to discuss how the end of this trend will impact society.

The next section describes how the course is structured to accomplish these learning outcomes.

### 3. Course Structure

As shown in Table 4, the course is organized as a historical survey of semiconductor and related technologies and is divided into a series of distinct time periods, beginning with precursor technologies that motivated the development of semiconductors and ending with the current day. This long-term survey addresses course outcome C2 by examining how semiconductor technology has evolved and how it has been applied over time, while in each section technical concepts are introduced to address outcome C1.

This portion of the course is structured as a series of reading assignments followed by in-class discussions. As technical concepts such as transistors, integrated circuits, digital logic, and computer hardware and software are introduced, readings and discussions are supplemented with short lectures, handouts, and instructional videos that explain these concepts along with hands-on exercises intended to reinforce student understanding. Lectures and discussions are often accompanied by a display of physical artifacts that illustrate semiconductor design and manufacturing, including transistors, integrated circuits, silicon wafers, and masks. Other artifacts include vintage consumer electronic products including an early game console, portable music player, and a 1970s-era personal computer prototype. Course outcomes C3-C5 are covered in a similar fashion using lectures with handouts along with reading assignments followed by in-class discussion.

The course uses a number of sources of reading materials to build students' perspective on the development of semiconductor, computer, and information technology. Walter Isaacson's book *The Innovators* [16] – a popular history of computers and information technology – is used to establish an overall framework for the course that is complemented by a number of additional readings, including contemporaneous news and magazine articles and internal memoranda along with retrospectives written by technology pioneers. Films and instructional videos are also used to broaden the overview and provide additional technical background.

1800s-1940s: Precursor Technologies
1940s-1950s: Discrete Transistors
1960s: Early Integrated Circuits and the Mainframe Era
1970s: Microprocessors and the Personal Computer
1970s-1980s: The VLSI Era
1990s-2000s: The Internet and the Web
2000s-2010s: AI, Social Media, & Cyber Conflict
2015-Present: The End of Moore's Law

**Table 4 – Course Topics**

Isaacson's book was chosen for this course because it covers the history of both semiconductors and the communication and information technologies that have been enabled by semiconductors.



While it has been praised for providing a broad overview of these topics [17], it has also been criticized for being too focused on the “Silicon Valley Myth” [18] that disproportionately credits a small group of west-coast individuals while minimizing the influence of individuals in other regions of the country. In the course, some of the additional readings and films were selected to broaden this focus in conjunction with classroom discussions.

### **3.1 Precursors (1800s-1940s)**

This section of the course profiles the development of computation and communication technologies prior to semiconductors – technologies originally based on mechanical, electromechanical, and electronic (vacuum tube) devices. The development and adoption of these technologies created a demand for a smaller and more efficient amplification and switching devices – a need which motivated the eventual development of semiconductor devices.

Reading assignments in this section draw on early chapters of the Isaacson book, which focus on the development of early computing devices, including mechanical computing in the 19<sup>th</sup> century by Babbage and Lovelace, electromechanical computing in the 1940s by Aiken, and the development of vacuum tube computing devices by Eckert, Mauchly, von Neumann, and others. It also discusses the development of programming techniques with profiles of Grace Murray Hopper and others.

These technologies reached their pre-semiconductor peak during and immediately after WWII due to military needs for applications such as artillery calculations and cryptology. By the end of the war, the potential applications of this technology involving business and information management became clear; to gain insight into how the potential for this technology was seen at the time students read Vannevar Bush’s prescient 1945 article “As We May Think” [1], which predicts a future device (the “Memex”) for storing and accessing information that has many of the capabilities we now see in personal computers, tablets, and smartphones connected to the internet.

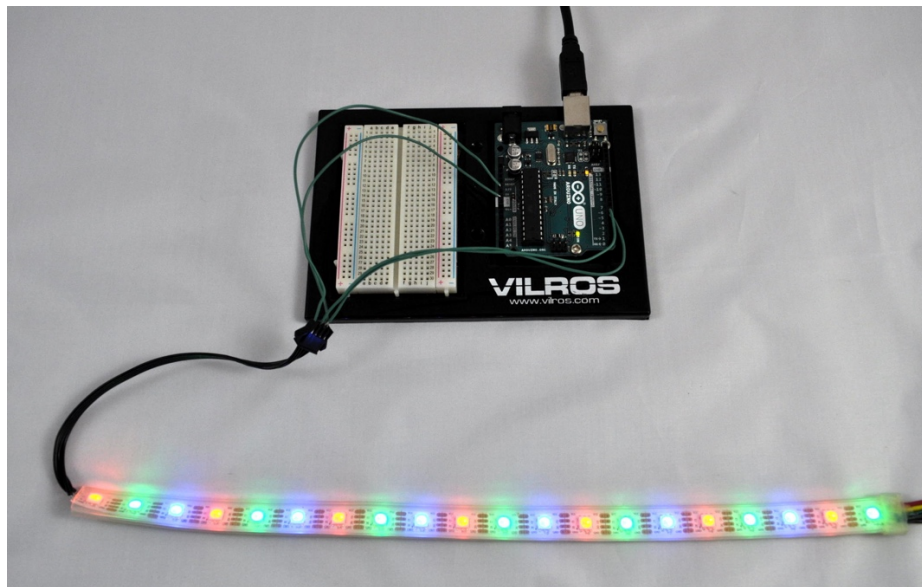
Early computers were both a motivating factor for the creation of semiconductor devices and one of the key customers of these devices after their development. This led to a long-term symbiotic relationship in which improvements in one technology spurred further investment and improvement in the other.

To underline the importance of this relationship, students in this section engage in a hands-on exercise to gain further insight into computer operation and programming. This supports course outcome C2 described in the previous section. The exercise uses Arduino Uno microcontroller boards [19], which were chosen because they are supported by a user-friendly, well-documented programming environment. Each board in the exercise is connected to an AdaFruit DotStar [20] LED strip as shown in Figure 1. The LED strip contains 20 addressable RGB LEDs which can be independently set to varying intensities and colors under the control of an Arduino program.

Students begin the exercise with a lecture that introduces Arduinos and the imperative, step-by-step nature of programming using the control of different LEDs in the strip as an example. They then apply a delay function and simple programming constructs such as if statements, loops, and variables to create interesting animated light displays. After completing the exercise, students complete a writing assignment in which they reflect on their experience.

Including this exercise in the course section involving early computers provides students with a visceral feel for the scale of technological improvement by comparing the massive size and cost

of early vacuum tube computers with a small, inexpensive Arduino board, which for all its simplicity offers vastly more processing power than those early computers.



**Figure 1 – Arduino/LED Strip Hands-On Exercise**

### **3.2 The Transistor (1940s-50s)**

This section covers the invention and improvement of the transistor and some of the resulting impacts of that invention. Readings from Isaacson’s book describe the interaction between Brattain, Bardeen, and Shockley to create the original transistor devices and AT&T’s decision (due to its monopoly status) to widely license the transistor patent to other firms with liberal terms, leading to the growth of an entirely new industry. It also covers Shockley’s creation of his own transistor company, his recruitment of a talented set of employees who became the “traitorous eight” that founded Fairchild Semiconductor and created Silicon Valley. This reading is supplemented by viewing the PBS documentary *Silicon Valley* [21], which includes interviews with many of the founders of the semiconductor industry.

Examples of societal impacts discussed in this section include the development of the transistor radio, which revolutionized consumer electronics, and the transistorized electronic computer, which dramatically lowered the cost of a mainframe computer while increasing its processing power. One societal impact of this development was the replacement of “human computers” with electronic computers. During this section students view the film *Hidden Figures* [22], which depicts how the human computers employed at NASA adapted to this development by learning to program the machines that were slated to replace their jobs.

### **3.3 Integrated Circuits, Mainframes, and Minicomputers (1960s-70s)**

This section discusses the invention of integrated circuits and the impact of their continuous improvement during the 1960s-70s. As described in Isaacson and other sources (e.g., [23]), the early stages of IC development were heavily subsidized by the military and NASA that were willing to pay high prices for the first generation of integrated circuits. This in turn funded refinements and cost reductions in further iterations of the virtuous cycle. During this section

students read Gordon Moore's classic *Electronics* article [2] which first predicted exponential improvements in IC technology and became the basis for Moore's Law.

As IC quality and capabilities improved and prices dropped, they enabled the growth of both more powerful mainframes and a new class of minicomputers, which expanded the range of businesses and educational institutions that could afford to use computer systems. It also allowed the development of early computer networks, including most notably the Arpanet, and the introduction of email as a collaboration method between network users as its "killer app."

This section also describes how forward-looking technologists during this era developed new ways to facilitate human-computer interaction, including the mouse developed by Doug Engelbart at SRI and the graphical user interface envisioned by Alan Kay and others at Xerox PARC. To gain insight into how these efforts were viewed at the time, students read a 1972 *Rolling Stone* article by Stewart Brand [24] that discusses computer gaming on minicomputer systems in university research labs and the nascent research activities at Xerox PARC.

### **3.4 Microprocessors and Personal Computers (1970s-80s)**

In this section students learn about the development of the microprocessor along with concurrent developments in computer hardware and software. This includes the development of the first microprocessor at Intel in 1971 and its progressively more powerful successors, which enabled the first generation of consumer-oriented personal computers. This material is covered in the Isaacson book, and supplemented by historical articles including a *Byte* magazine article by Steven Wozniak that contains a technical description the design of the Apple II computer [25].

Other concurrent developments surveyed in this section include the video game boom, the development of the Alto computer, the graphical user interface, and the Ethernet local area network at Xerox PARC, the adoption of many of these technologies into the first Apple Macintosh, and the evolution of the TCP/IP protocol used to create a network of networks using the Arpanet as a backbone and eventually evolving into the modern Internet. At this point students view excerpts from the PBS documentary *Triumph of the Nerds* [26], which includes interviews of many of the figures who helped to create these products.

Finally, this section covers the emergence of the open source movement as a reaction to the commercialization of software – students learn about this by reading Stallman's "Gnu Manifesto" [27] and viewing excerpts from the documentary film *Revolution OS* [28], which includes interviews with Stallman, Linux creator Linus Torvalds, and other pioneers of the open source movement.

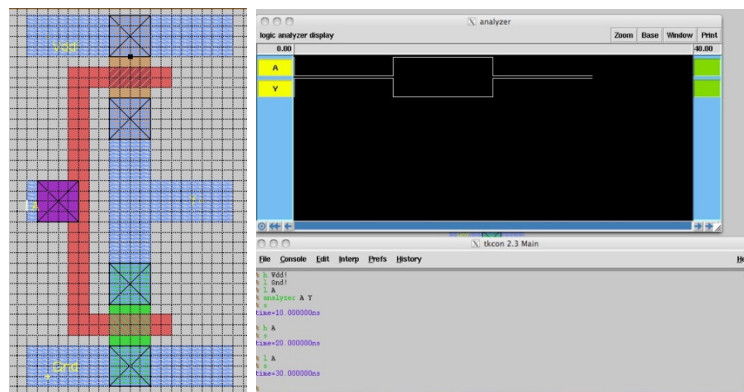
### **3.5 The VLSI Era (1980s-90s)**

This section discusses the development and impact of VLSI Design methods pioneered by Mead and Conway – a development not covered in Isaacson's book, but one that was important in the development of semiconductor technology. In the late 1970s integrated circuit design was an esoteric activity that was not accessible to individuals outside of semiconductor companies. Mead and Conway developed a set of simplified, spatially-oriented abstractions [29] that made integrated circuit design accessible to a much wider range of researchers outside of the traditional semiconductor industry. Students read Conway's retrospective article [30] describing how this came about along with many of the impacts of this work, including the widespread creation of university courses in VLSI design, the development of the foundry model pioneered using multi-project chips and leading to foundry companies and fabless semiconductor

companies. It also describes how this “democratization” of integrated circuit design made it possible for university researchers to develop new technologies such as RISC computer architectures.

During this section students view the *Silicon Run* documentary [31], which illustrates the chip manufacturing process with a focus on how photolithography is used to build circuit structures on a crystal silicon wafer by either selectively diffusing impurities or by patterning layers of material on top of the silicon to create interconnected transistors and wires.

A related lecture presents Mead & Conway’s simplified abstractions for integrated circuit design (generalized to CMOS by [32]) and students learn to design basic gates. Students then use Mead & Conway’s “stick diagrams” to explore circuit structures. Next, they use the venerable Magic [33] layout editor to design masks for a simple logic gate using Mead & Conway’s scalable design rules. They then extract and simulate the equivalent circuit to verify that their layout correctly implements the desired function, as shown in Figure 2. While these design rules are too simplistic for modern nanometer-scale integrated circuits, they provide a useful pedagogical platform to help students understand the spatial, layered nature of integrated circuit design. In so doing, this exercise directly supports course outcome C1. In addition, discussing the value of the lambda scaling factor used by the editor provides an opportunity to acquaint students with the idea of process scaling [34], which is a key concept in understanding the trends behind Moore’s Law (course outcome C2) and the limits of scaling (course outcomes C3-C5).



**Figure 2 – IC Design Hands-On Experience**

### **3.6 The Internet and the World-Wide Web (1990s-2000s)**

This section covers how continued improvements in semiconductor technology made increasingly powerful personal computers and software available to consumers while the communication infrastructure evolved to connect users together. Closed networks such as the Arpanet and NSFNet evolved into the open Internet while new legislation opened the Internet to commercial activity. Private online services thrived at the beginning of this era before being subsumed by the Internet, and the development of broadband networking resulted in major changes in the way in which consumers communicated and did business.

Readings in the Isaacson book cover this time period in detail. Students also read Bill Gates’ “The Internet Tidal Wave” [35], a 1995 internal corporate memo that became public during that

Microsoft's 1998 antitrust lawsuit. This document provides an interesting view of how the potential of the Internet was seen at the time.

### **3.7 Social Media and the Cloud (2000s-Present)**

This section covers the development of new online activities such as blogging and social media, new commercial enterprises such as search and cloud services, and the growth of artificial intelligence. It also discusses recent developments in cybercrime, cyber warfare, and political interference via the Internet. Students read the final chapters of Isaacson's book along with contemporary news articles. Discussion of the rise of social media is supported by viewing the film *The Social Network* [36] (a fictionalized account of the creation of FaceBook) along with articles that provide a fact-check for the film (e.g., [37]). Finally, to consider cybercrime, cyberwarefare, and political interference students view the documentary *Zero Days* [38] that describes the use of malware to attack an Iranian nuclear facility. They also read recent news reports about political interference during the 2016 election.

### **3.8 The End of Moore's Law (2000s-Present)**

Predictions of the end of the exponential improvement promised by Moore's Law have existed as long as Moore's Law itself. Nevertheless, hard physical limits and economic constraints make the end of Moore's law likely in the next few years, and many have declared Moore's Law already dead (e.g., [3]).

This section of the course explores both the advanced techniques that have extended Moore's Law to date along with the factors that are limiting its future. Notes prepared by the instructor explore the challenges of nanoscale semiconductor manufacturing, including transistor leakage, wiring issues, and the limits of photolithography when the wavelength of the ultraviolet light used is significantly larger than the features being patterned on chips. These notes survey some of the ways in which these challenges have been overcome, including mask designs for optical proximity correction, phase-shifting masks, multiple patterning steps, extreme ultraviolet (EUV) light sources, and advanced transistor structures. These notes are augmented by readings about these developments (e.g., [39]).

In a similar vein, the notes explore the economic aspects contributing to the end of Moore's law. For example, increased capital costs have limited the number of firms able to build new fabrication facilities, leading to a reduction in the number of integrated device manufacturers and the consolidation of manufacturing into a few foundries. At the same time this has led to an increasing globalization of electronics manufacturing, especially in Pacific Rim countries. Finally, these notes describe how the up-front non-recurring engineering costs of creating a new chip design have become a barrier to firms designing small-volume electronic products.

The section ends with a brief survey of potential alternative technologies and a discussion of potential social impacts brought about by the end of exponential improvement after it has been taken for granted for decades.

## **4. Student Assignments**

Student work in the course in addition to assigned reading includes participation in discussions, a series of four writing assignments, and a book review presentation at the end of the semester.

Class discussions were organized around a series of reading assignments, which included sections of the Isaacson book along with supplemental readings as described earlier. Each

discussion began with students filling out a brief response form, while the discussion itself was guided using a list of discussion questions prepared by the instructor. Discussion participation was graded using a rubric developed by John Immerwahr at Villanova University [36] and shown in Table 5 [40]. A copy of this rubric was included in the course syllabus to communicate discussion expectations to students.

All FYS courses at Lafayette College are writing courses, and the *St. Martin's Handbook* [41] is used as a secondary text for students learning academic writing skills. They employ a process-writing approach in which students submit first drafts which they then revise after feedback from a peer Writing Associate and the instructor.

The first writing assignment, which is given out during the first week of class, asks students to reflect on their own lived experience with semiconductor technology in terms of how they learn and work, communicate with friends and family, and seek entertainment, focusing on how this has changed over their lifetime. By connecting students' personal history with technology with the course, this writing assignment addresses course outcome C2.

The second and third writing assignments are framed as responses to the two hands on activities involving programming and integrated circuit design, respectively. Each of these assignments asks students to reflect on what they did in the activity, how it changed or reinforced their understanding of both basic technical concepts and the course readings and discussion. By asking students to reflect on their understanding of technical concepts these writing assignments address course outcome C1

The fourth writing assignment asks students to synthesize what they have learned over the course of the semester from readings, discussions, and hands-on experiences and how it has changed their perspective on the societal impact of semiconductor technology. This is a longer paper and students are asked to cite and reference readings that support their paper in APA format using the *St. Martin's Handbook* as a guide. As a synthesis of the previous assignments, this assignment addresses both course outcomes C1 and C2.

The final assignment for students is a book discussion assignment in which students in groups of two read a book related to the societal impact of semiconductors and/or related technologies such as computers and information technology. Each group gives a presentation to the class that gives a brief overview of the book. In choosing topics, students are guided to select a book that covers at least one of the five course outcomes, with the majority addressing course outcomes C1 and C2.

Course outcomes C3-C5, which focus on the end of Moore's Law, were not directly addressed by course assignments in either the 2017 or 2019 offering, although they were covered in lecture and discussion. Assignments will be revised to address these outcomes in future offerings.

Writing assignments were graded using rubrics. As an example, Table 6 shows the rubric for the fourth writing assignment. This rubric is divided into two parts – the first part evaluates the content of the paper, while the second part evaluates paper mechanics including organization, grammar, citations, and participation in process writing. This rubric was distributed to students as they worked on the assignment to communicate expectations about the paper.

## **5. Results**

At this writing FYS 035 has been offered in Fall 2017 and Fall 2019. During each semester 16 students enrolled in the course. During the 2019 offering the ordering of topics was altered

slightly by moving material about “The End of Moore’s Law” (described in Section 3.8) to immediately follow coverage of “the VLSI Era” (described in Section 3.5). This had the advantage of keeping technically related information together at the expense of departing from a strict chronological ordering of topics.

**Class Participation Rubric**

(Source: John Immerwahr, 8/15/2008,

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	<b>Strong Work</b>	<b>Needs Development</b>	<b>Unsatisfactory</b>
<b>Listening</b>	Actively and respectfully listens to peers and instructor	Sometimes displays lack of interest in comments of others	Projects lack of interest or disrespect for others; “checks out” and
<b>Preparation</b>	Arrives fully prepared with all assignments completed, and notes on reading, observations, questions	Sometimes arrives unprepared or with only superficial preparation	Exhibits little evidence of having read or thought about assigned material
<b>Quality of Contributions</b>	Comments are relevant and reflect understanding of: assigned text(s) or assignments; previous remarks of other students; and insights about assigned materials	Comments sometimes irrelevant, betray lack of preparation, or indicate lack of attention to previous remarks of other students	Comments reflect little understanding of either the assignment or previous remarks in seminar
<b>Impact on Class</b>	Comments frequently help move class conversation forward	Comments sometimes advance the conversation, but sometimes do little to move it forward	Comments do not advance the conversation or are actively harmful to it
<b>Frequency of Participation</b>	Actively participates at appropriate times	Sometimes participates but at other times is “tuned out”	Seldom participates and is generally not engaged

Class participation deserving of an A grade will be strong in most categories; participation that is strong in some categories but needs development in others will receive a B; a grade of C reflects a need for development in most categories; D work is typically unsatisfactory in several categories; and F work is unsatisfactory in nearly all categories.

**Table 5 – Participation Rubric [Immerwahr08]**

Students enroll in FYS courses at Lafayette by reviewing course descriptions and providing an ordered list of preferred courses. A matching process is then used to place students into one of their top choices, although placement in their first choice is not guaranteed. Table 7 characterizes the students in each offering by declared major. It shows a heavy bias towards students in STEM majors, suggesting that more work is needed to attract a broader range of students to the course.

Student response in course evaluations was very positive during the Fall 2017 offering, with a numeric rating for the overall course of 4.63/5.00. Written comments were also very positive for the most part. One student wrote, "This class deeply enhanced my understanding of semiconductor technology. My understanding of computer technology and the development of the digital age have deepened my interest in the field of tech." Other comments favorably mentioned the combination of lectures, discussion, videos, and hands-on experiences. Scattered comments indicated that a few students found the lecture slides unhelpful and the material covered to be dense and difficult to understand.

	Exceeds Expectations	Meets Expectations	Needs Improvement	Grade
<b>Content</b>				
1. Initial Perspective	Includes a thoughtful discussion of the author's initial perspective on semiconductor & computer technology focusing on multiple areas	Includes a thoughtful discussion of the author's initial perspective on semiconductor & computer technology focusing on a small number of areas	Discussion of initial perspective is sketchy or incomplete; focuses on just one area and/or relies on sweeping unsupported generalizations	/15
2. New Insights	Discusses new insights from the reading citing examples both from the main text and supplemental readings.	Discusses new insights from the reading citing examples both from the main text but not the supplemental materials.	Discusses new insights in vague generalities; does not cite examples from reading.	/15
3. Response to Hands-On Activities	Shows an understanding of underlying concepts of software and IC design based on experience and relates them to the material covered in class readings and discussions; discussion includes interesting insights.	Shows an understanding of underlying concepts of software and IC design based on experience and relates them to the material covered in class readings and discussions.	Sketchy or incomplete discussion of the design experience that lacks understanding of the underlying concepts.	/15
4. Overall Perspective	Summarizes how author's overall perspective has changed about the societal impact of semiconductor & computer technology drawing on earlier sections of the paper and providing interesting insights.	Summarizes how author's overall perspective has changed about the societal impact of semiconductor & computer technology drawing on earlier sections of the paper.	Does not adequately summarize the change in the author's perspective; does not draw on earlier sections of the paper	/15
<b>Total Content Grade</b>				0 /60

<b>Paper Mechanics</b>				
1. Organization	Writing has a compelling introduction, and informative main body, and a satisfying conclusion. Transitions are clear and smooth	Writing has an introduction, main body, and conclusion but could be more compelling. Transitions are clear.	Writing is not well organized and may jump around; missing transitions between sections.	/10
2. Paragraph Structure	All paragraphs have clear topics; details within each paragraph are presented in logical order.	Most paragraphs have clear topics; most details are presented in logical order; a few paragraphs contain unrelated ideas.	Majority of paragraphs have no clear topic and/or present details in a confusing order; paragraphs contain unrelated ideas.	/5
3. Sentence fluency	Writing has well-constructed sentences that are clear and complete.	Writing generally has well-constructed sentences but some are unclear or incomplete.	Writing includes run-ons, fragments, and awkward phrasings that make the paper hard to read.	/5
4. Grammar, Spelling, and Word Choice	Writer uses correct grammar, spelling, and punctuation – no errors. Writer chooses words that are appropriate to the context.	Writer generally uses correct conventions but contains a few errors that are easily fixed. Writer chooses words that are usually appropriate to the context.	Numerous errors make the essay hard to read. Writer chooses words that are inappropriate to the context.	/5
5. Citations	Writer uses APA format for all in-text and full citations – no errors	Writer generally uses APA format for all in-text and full citations; may have a couple of errors that could be easily fixed	In-text citations or full citations missing from paper; citations do not follow APA format	/5
6. Process	Author submitted a substantially complete draft on time; participated in writing conferences with WA and/or Instructor; made substantive improvements to paper based on conference feedback.	Author submitted draft on time; participated in writing conferences with WA and/or Instructor; made some improvements to paper based on conference feedback.	Author submitted draft late; draft substantially incomplete; failed to participate in writing conference with WA and/or Instructor; little or no revision from previous draft.	/10
<b>Total Mechanics Grade</b>				0 /40
<b>Total Paper Grade</b>				0 /100

**Table 6 – Rubric for Final Writing Assignment**

Student evaluations in the second offering were less encouraging with a numeric rating for the overall course of 3.3/5.0. While positive comments remained - one comment noted that "the hands on experiences helped me be able to put myself in the innovator, engineer, or developers



shoes", other repeated comments were less favorable about the course organization and the interest level of the class.

The rubrics for evaluating student discussion and writing assignments worked reasonably well. Writing assignment rubrics were constructed using a spreadsheet, making it easier to tabulate graded work while providing students with feedback via the College's course management system. One challenge with the discussion rubric was providing students with early feedback in terms of their performance; in both offerings of the class the rubric was used to determine the final participation grade. In future offerings some way of providing earlier feedback would be helpful.

<b>Declared Major</b>	<b>Fall 2017</b>	<b>Fall 2019</b>
Engr. Undecided	5	1
Engr. Studies	1	1
CE	2	0
CHE	1	1
ECE	3	2
ME	0	6
BIOCHEM	0	1
BIOL	0	1
CS	2	2
MATH	1	0
PHYS	1	0
PSYC	0	1
<b>Total</b>	<b>16</b>	<b>16</b>

**Table 7 – FYS 035 Enrollment by Declared Major**

Rubrics for writing assignments addressed how students met the requirements of the specific assignments but were not aligned well with the course outcomes, and these outcomes were not directly assessed during either offering of the course. In future offerings the assignments and rubrics will be revised to more directly assess these outcomes.

In an attempt to assess these outcomes after the fact, an additional rubric was developed and applied to the fourth writing assignment. As discussed in the previous section, this writing assignment asked students to reflect on their personal history with semiconductor technology (outcome C2) and their reaction to the technical concepts learned in the hands-on experiences (outcome C1). Students were not asked to directly address outcomes C3-C5, but these outcomes were included in the assessment since this material was covered in lecture and class discussions. The resulting rubric is shown in Table 9. Based on the level of discussion in each student paper, the rubric rated each outcome as either having been achieved, partially achieved, or not achieved.

Table 10 summarizes the results of the assessment. For outcome C1 students' description of their hands-on experiences were rated based on the level of detail with which they described programming and integrated circuit design. Students who described the step-by-step nature of programming and the use of different mask layers to create and connect transistors were rated as having achieved the outcome, while students who did so in a more fragmentary fashion were rated as having partially achieved the outcome.

As reported in Table 10, all students were rated as having achieved or partially achieved outcome C1. While many students wrote that they lacked any awareness of semiconductors prior to taking the course, they noted that the hands-on experiences helped them gain a qualitative understanding of the technology. One student wrote, “the process of making integrated circuits is very complex, but the second lab was able to break down this complexity by having us create a simple integrated circuit. We were able to see what each layer of the circuit was supposed to do. After stacking the integrated circuit’s layers up one by one, it no longer seemed as difficult to understand.”

	Achieved	Partially Achieved	Not Achieved
1. Describe in a qualitative way how semiconductor circuits function, are designed, and are manufactured.	Description of hands-on experiences demonstrates understanding of concepts of IC design/manufacturing and computer programming; relates these concepts to class readings and discussions.	Description of hands-on experiences demonstrates partial understanding of concepts of IC design/manufacturing and computer programming; partially relates these concepts to class readings and discussions.	Description of hands-on experiences does not demonstrate understanding of concepts of IC design/manufacturing and computer programming; does not relate these concepts to class readings and discussions.
2. Describe how as semiconductor technology has evolved over time, it has enabled new ways for people to do things (e.g. learn, work, communicate, and control other devices and systems)	Provides multiple detailed examples of how semiconductor technology has evolved and enabled new ways for people to do things.	Provides a few examples of how semiconductor technology has evolved and enabled new ways for people to do things.	Does not provide any examples of how semiconductor technology has evolved and enabled new ways for people to do things.
3. Elaborate on how technological improvements have enabled 50+ years of Moore’s Law.	Describes in detail multiple technological improvements that have enabled 50+ years of Moore’s Law.	Describes one or two technological improvements that have enabled 50+ years of Moore’s Law.	Does not describe any technological improvement that have enabled 50+ years of Moore’s Law.
4. Describe the factors that are likely to limit further technological improvements in semiconductors.	Describe in detail the physical and economic concerns that limit the continuation of Moore’s Law.	Describe in passing the physical and economic concerns that limit the continuation of Moore’s Law.	Does not discuss the end of Moore’s Law.
5. Describe potential societal impacts of the end of Moore’s Law.	Describes multiple potential societal impacts of the end of Moore’s Law.	Describes one or two potential societal impacts of the end of Moore’s Law.	Does not describe potential societal impacts of the end of Moore’s Law

**Table 8 – Course Outcomes Assessment from Writing Assignment 4**

Outcome	2017			2019		
	Achieved	Partially Achieved	Not Achieved	Achieved	Partially Achieved	Not Achieved
1. Describe in a qualitative way how semiconductor circuits function, are designed, and are manufactured.	12 (75%)	4 (25%)	0 (0%)	11 (68.75%)	5 (31.25%)	0 (0%)
2. Describe how as semiconductor technology has evolved over time, it has enabled new ways for people to do things (e.g. learn, work, communicate, and control other devices and systems)	12 (75%)	4 (25%)	0 (0%)	9 (56.25%)	7 (43.75%)	0 (0%)
3. Elaborate on how technological improvements have enabled 50+ years of Moore’s Law.	2 (12.5%)	9 (56.25%)	5 (31.25%)	4 (25%)	4 (25%)	8 (50%)
4. Describe the factors that are likely to limit further technological improvements in semiconductors.	1 (6.25%)	3 (18.75%)	12 (75%)	0 (0%)	8 (50%)	8 (50%)
5. Describe potential societal impacts of the end of Moore’s Law.	0 (0%)	1 (5.25%)	15 (93.75%)	0 (0%)	6 (37.5%)	10 (62.5%)

**Table 9 – Course Outcomes Assessment Results**

For outcome C2, student assignments were rated based on “examples of how semiconductor technology has evolved and enabled new ways for people to do things.” Students described

advances in communication technology including the development of smartphones, online messaging, and social media, the ubiquity of computing and information technology in education, and advances in entertainment technology ranging from game consoles to streaming media. They noted positive impacts such as easy access to information, rapid communication, and improved tools for computation and education. At the same time, they noted negative impacts, including social isolation, cyberbullying and political interference in social media, privacy concerns, and job losses due to automation.

Since outcomes C3-C5 were not explicitly addressed in the prompt of the writing assignment, it is not surprising that students' submitted work did not provide evidence that these outcomes had been achieved. Although several students alluded to the physical and economic limitations that are likely to end Moore's Law, only a few provided any details. In addition, they did not describe the technical efforts and investments required to sustain Moore's Law or the possible impacts of the end of Moore's Law. In future offerings of the course the writing assignments will be revised to increase the emphasis on these outcomes.

## 6. Conclusion

This paper has described a first-year seminar that has the goal of providing students with a general understanding of semiconductor technology, its impacts on society over decades of exponential improvement, and its potential in the future at the end of exponential improvement. The experience described in this course should be helpful to individuals seeking to create similar courses and may suggest sources of information for faculty looking to embed societal issues in technical courses in digital system and integrated circuit design.

A number of improvements are planned for future offerings of this course. First of all, the course learning outcomes and writing assignments will be revised to be in better alignment and to address societal impacts in more detail. Second, reading assignments will be broadened to focus on additional societal impacts of semiconductor technology, including environmental impacts and recent concerns in information technology such as privacy/surveillance, algorithmic bias, and job losses due to automation. Third, additional hands-on exercises are planned to illustrate the impact of semiconductor improvements like process scaling.

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