

ES 4: Introduction to Digital Logic Circuits

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Welcome to ES 4!

Any sufficiently advanced technology is indistinguishable from magic.

– Arthur C. Clarke

There are few technologies for which Clarke’s statement is more true than microprocessors. Today you can find a microprocessor in almost anything electronic, and yet even those of us who can program them often have very little understanding of their inner workings. In ES 4, we will study microprocessors — and digital electronics more generally — from the ground up. From your past courses, you know how computers work at the physical level (voltages and currents) and at the application level (C++ and other languages); the objective of this course is to connect the dots between the two.

To do this, we begin with the basics of manipulating zeros and ones with circuitry, and start building *combinational* circuits, which produce outputs based on some mathematical combination of their inputs. Then we make a major turn and explore *sequential* circuits, which can store information or step through a sequence of states. With these building blocks in hand, we will take a brief look at the ARM instruction set (which powers your cell phone and a few billion other devices), and learn how to build circuits which can actually interpret and execute software instructions.

When we’re done, you’ll have the skills necessary to design complex digital systems to search through genomes, analyze and manipulate network traffic, mine bitcoin, or play retro video games. Additionally, you’ll be able to actually implement and run these system on reconfigurable circuits known as FPGAs. In short, you’ll be able to work magic.

After successfully completing this course you will be able to:

- Begin with a specification for a digital system and implement it in hardware, by working through the following steps:
 1. Decompose an imperfect or incomplete specification into a set of well-defined digital modules.
 2. Describe the modules as collections of state machines, memories, arithmetic circuits, and other digital building blocks.
 3. Implement these building blocks with combinatorial and sequential logic constructs.
 4. Construct combinatorial and sequential logic elements using using logic gates, multiplexers, and flip-flops.
- Construct digital circuits using a breadboard, FPGA, and discrete components.
- Use the VHDL “hardware description language” to design digital circuits and implement those designs on an FPGA.
- Describe how a microprocessor works in terms of intermediate digital building blocks. That is, you should be able to explain to someone halfway through the course how a pile of logic gates can read a sequence of instructions and operate on a block of data to produce results.

How will this course help you succeed?

With the skills from this course, you’ll be able to design computer systems which can acheive a hundred or thousand times more performance than running code on a traditional CPU. Seriously.

But even if you never design digital hardware in your career, a solid understanding of how hardware works will enable you to write better code — sometimes 10× faster on the same hardware. Moreover, specialized computer hardware is everywhere, from tensor processors in datacenters to neural compute engines in cell phones. These special processors are especially quirky, and only engineers who understand the hardware will be able to wring out every last drop of performance.

And “performance” isn’t just speed: power efficiency is incredibly important in wearable and some IoT applications, and this too requires a solid knowledge of digital hardware, even if you’re “just” writing code.

Where should you look for information?

The **course schedule and materials** will be posted on the course website: <http://www.ece.tufts.edu/es/4>. We will not use Canvas at all.

Course announcements and Q&A will be on Campuswire. You should receive an email invitation just before the course starts.

The **textbook** is “Sarah L. Harris & David Money Harris, *Digital Design and Computer Architecture, ARM Edition.*” ISBN: 978-0128000564

The book is available online through Tisch Library, with no limit on the number of concurrent users. The paper version is available through the usual channels for about \$80.

There are also some (free) online resources for the book, including an electronic-only chapter 9: <https://booksite.elsevier.com/9780128000564/>

All **assignment submissions** and feedback will be done through Gradescope. We’ll provide the signup link once the course gets started.

Quizzes will be submitted through **provide**, a file-submission system used extensively in the CS and ECE departments. If you haven’t already used **provide**, take a look at the introductory video on the course website for a tutorial on how to complete and submit your first quiz.

There are also a number of great websites and videos about digital design. Some of these are posted in the “resources” section of the course website. If you run across helpful resources which aren’t listed, please share them so we can call benefit!

How will you succeed in this course?

Mind the details. There are a lot of “moving parts” in this course: readings, quizzes, labs, homework, etc., so make sure you have a working system to track all these deadlines and complete each on time.

Keep up with the readings. I know that when the semester gets busy, readings are the first thing to go. And the consequences seem minor, even nonexistent. But three weeks later you discover you have no idea what’s going on, and now you’re behind and just as busy as ever. Don’t let this happen to you!

Communicate. Pandemic restrictions have isolated us in many ways, and even during normal semesters it is easy to struggle unproductively (and even suffer) in silence. The course will be difficult at times, and may require you to develop new ways of thinking. Because I am committed to helping you through these challenges, I have an open door policy in addition to my posted office hours. Your TAs host many office hours (both in-person and virtual) throughout the week, and Campuswire is open 24/7 for questions and discussion. I encourage you to collaborate with your classmates on every aspect of the course, the only exception being the individual assessments. Communicate early and often!

Analyze your learning. You may be used to evaluating your progress entirely based on external feedback, i.e., the grades a teacher gives you on assignments and exams. While there are plenty of graded assessments in this course, I expect that you will move toward evaluating and monitoring your own learning. Once you

graduate, external evaluations will be few and far between. The ability to analyze your own thinking and identify gaps in your understanding is a crucial skill, far more valuable than the technical content of this course.

How will you and I evaluate your progress?

The upside to having so many components of the course is that you have many opportunities to check your understanding. Solutions to the odd-numbered problems in the textbook are posted on the publisher's website, and we will share solutions to the homework. VHDLweb (an online coding platform created for this course) gives you immediate feedback as to whether your designs work or not.

Reading quizzes and discussion section exercises (10 %) Each week will feature a short quiz based on the textbook reading. The purpose of the quiz is to force you to read the textbook; it is *not* intended to be a summary of the most important material in the chapter. For this reason, quizzes are graded mostly credit/no-credit. The questions are taken almost verbatim from the text, so if you're not sure about an answer, go back and read the text more carefully.

Labs, prelabs, and lab reports (30 %) We will have lab every week. Most labs have a pre-lab assignment due 24 hours before your regularly-scheduled lab section, which allows your TAs to give you early feedback and avoid wasting precious face-to-face time in lab. Prelabs are graded on a very rough credit/partial-credit/no-credit scale.

Labs projects themselves are graded for completion. Part of each lab is to write up a plan for proving that your design works, so you'll know when you've got it working!

You will write a lab report for each major lab project (roughly every other week). Technical writing is a tough skill to learn, so we will provide abundant feedback on your early reports to help you improve.

Homework and VHDLweb exercises (20 %) Most weeks will have a homework assignment which is intended to help you practice essential skills that may not be emphasized by the lab. The homework should not take more than 2–3 hours; if it's taking longer, please reach out for help.

Individual assessments (20 %) Instead of timed, high-stakes exams, you will complete several untimed take-home assignments. These are similar to homework problems, and you may use any resources you like except for other people (asking classmates, posting on Q&A sites, etc). They will typically ask you to apply your knowledge in new ways, not simply regurgitate facts or grind through an algorithm you've memorized.

Final project (20 %) The final project will allow you to showcase everything you've learned in the course by working in a team to build a digital system that is both complex and fun. Past projects have included arcade games, audio synthesizers, and more. One of the TAs will meet with you weekly to help you set realistic goals and to consult on the technical aspects of your project.

What else do you need to know?

Instructor contact:

If you have a general question about the course content or course logistics, please post on Campuswire rather than emailing the teaching staff. You'll usually get a faster response, and everyone benefits from the answer.

Steven Bell sbell@ece.tufts.edu

Halligan Hall 228D (a few steps down the hall from the 2nd-floor kitchen)

Office hours:

- Mondays 12:30-2:00pm

- Wednesdays 10am-12pm
- I'm also available other times by appointment, or just drop by my office any time the door is open. I'm on campus Mondays and Wednesdays, and available by Zoom the rest of the week.

To minimize distraction, I generally only check email 2-3 times a day. However, I will make a strong effort to answer all messages within 24 hours on weekdays.

Prerequisites:

There are no prerequisites for this course. You will get more out of the course if you have taken (or are concurrently taking) COMP 11 and ES 3 (or EE 20), but I intend for this course to be accessible to everyone, including students in the school of Arts & Sciences.

Late policy:

Life gets crazy during the semester (even a “normal” semester!), so you may use up to 8 late days for homework, lab reports, and individual assessments. You do not need to do anything special to use a late day; just submit your assignment on Gradescope as normal, and it will be marked late. For simplicity of bookkeeping, late days must be used in whole days; i.e., an assignment 5 minutes late counts for one late day, as does an assignment 23 hours late.

You may not use more than 3 late days on any one assignment, since we will release solutions shortly afterward. We will set the late due dates on Gradescope to reflect this.

Assignments later than 3 days or in excess of 8 days total will not be accepted for credit, except in extenuating circumstances such as major illness or a family emergency.

Academic honesty:

I encourage you to collaborate with your classmates on the homework, labs, and (of course) the final project. Talking through problems is one of the best ways to expose knowledge gaps and misunderstandings and to build. But just like physical exercise, those who put in the work get the gains. Thus, the work that you turn in needs to be your own.

Any code you submit may be run through plagiarism-checking software. By the terms of my employment with Tufts, I am required to report any suspicion of academic misconduct to the student affairs office.

ADA accommodations:

If you need special accommodations (extra time on exams, larger type on handouts, etc.), please initiate the process with the Tufts StAAR center (<https://students.tufts.edu/staar-center/accessibility-services>). Accommodations cannot be granted retroactively, so please do this sooner rather than later.