The CS Napkin

A compilation of thoughts, notes, and ideas from my undergrad education

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21 Nov 2023*

*First drafted on 19 Nov 2023

Contents

1 Foreword

If you're reading this, you're most likely planning to pursue the CS major at Duke University. You've probably taken either 101 or 201 (or both), and are wondering where to go next. The start of the Duke CS major is pretty cut-and-dry: you take 201, then one of 250/210 (the introductory systems courses) and 230 (Discrete Math). Eventually, you'll take 330. Pretty straightforward, right? But what comes after? What comes in-between?

Beyond its core classes, the CS major has plenty of room to explore, but its flexibility sometimes gives rise to a good deal of confusion about dependencies. When should I take X class? Do I know enough to take Y class? And why should I even take Z class at all?

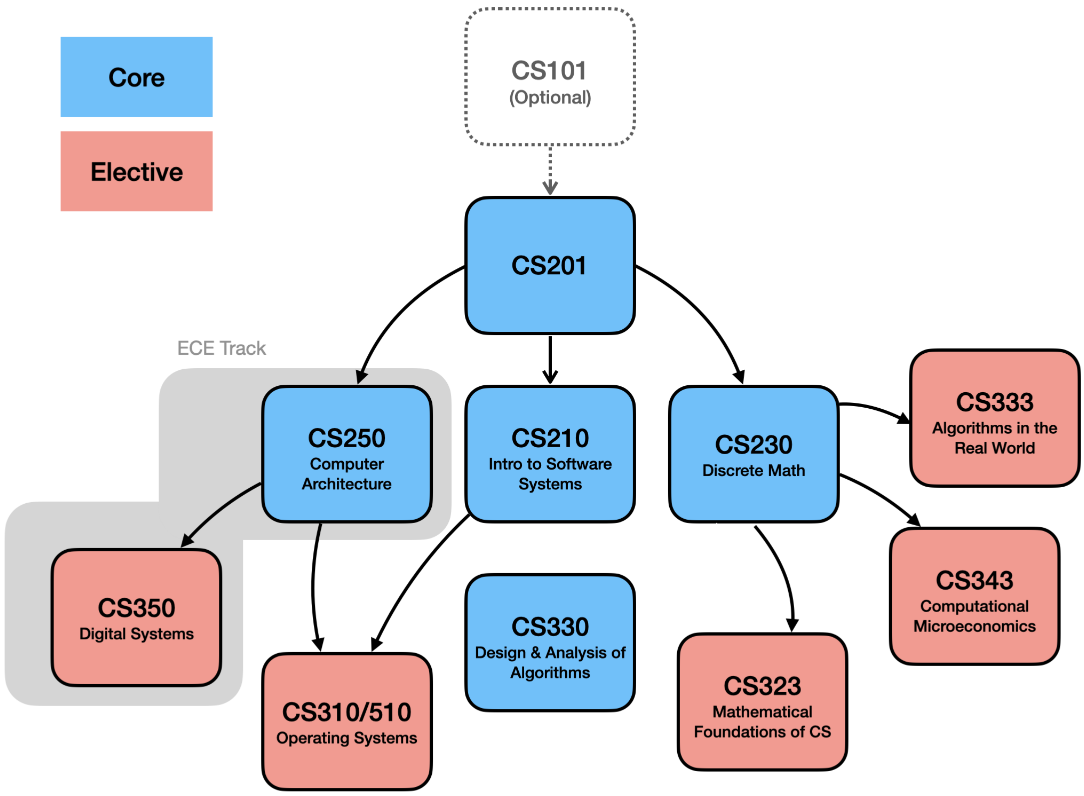


Figure 1.1: This is not all the Duke CS major has to offer, but just a subtree of some of the paths that open up to you via the core classes.

We hope that our CS "Napkin" will help answer some of these questions for you. It provides an overview of the content of each class; each section is a bit more detailed than a syllabus with (hopefully) helpful tips sprinkled throughout. Not only do we provide summaries of the class, we also start each section with a short meta-commentary that explains where each class slots into the big picture of a bachelor's in CS, and why you might want to take said class in the first place.

We were heavily inspired by Evan Chen's napkin about college-level math, and we highly recommend checking it out.

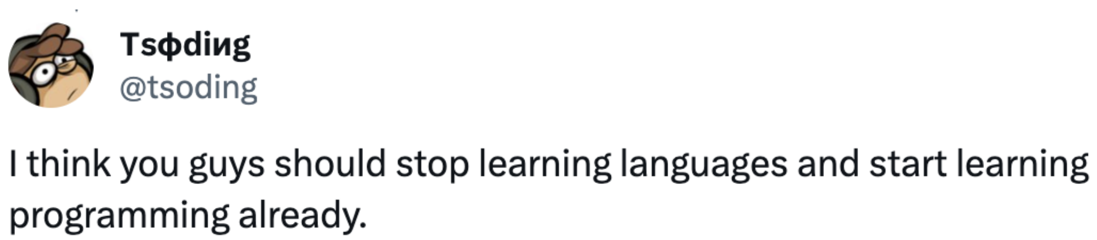
2 Prerequisites

We expect readers of the Napkin to have programmed before, on the scale of anything including but not limited to:

- that CS50 online course offered by Harvard
- any CS101 college course, including the one at Duke
- AP CS Principles... something along those lines?

We expect you to have understood and used basic programming concepts such as: for/while loops, conditional control flow, variables, and functions.

The Napkin is programming-language-agnostic, though we do mention course-specific languages and their details (Java, C, etc). But in the wise words of software developer Tsoding, we strongly believe that:



3 The Missing Semester

Who'da thunk it? The geniuses at MIT have pioneered what we think is a fantastic idea: the missing semester for CS majors. Their rationale (**emphasis** ours):

> Classes teach you all about advanced topics within CS, from operating systems to machine learning, but there's one critical subject that's rarely covered, and is instead left to students to figure out on their own: **proficiency with their tools**. We'll teach you how to master the command-line, use a powerful text editor, use fancy features of version control systems, and much more!

They run the gamut of practical skills, most if not all of which we believe are invaluable tools for a computer scientist in almost any context. These skills aren't covered in any significant depth at Duke either! We'll briefly go over some of them in the Napkin, but we highly suggest checking out the original MIT website.

- Version control/Git crash course
- Basic terminal commands
- Unit testing
- Debugging

Version Control & Git

Git was created by the same guy that was behind the first Linux kernel: computer programmer Linus Torvalds. It is a powerful piece of software that allows for non-linear development across multiple branches, across multiple machines. In other words, a **distributed version control system**.

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Intro to the terminal & shell scripting

What is the terminal? aka the shell, aka the command line? These terms are all used interchangeably, and they all mean pretty much the same thing. Let's go through a brief history of the terminal: once upon a time, terminals were the only way to interact with computers. **UNIX**, a very important operating system, was written in such an era[1]. There were no graphical user interfaces (GUIs), much less a notion of a desktop with icons for apps and folders.

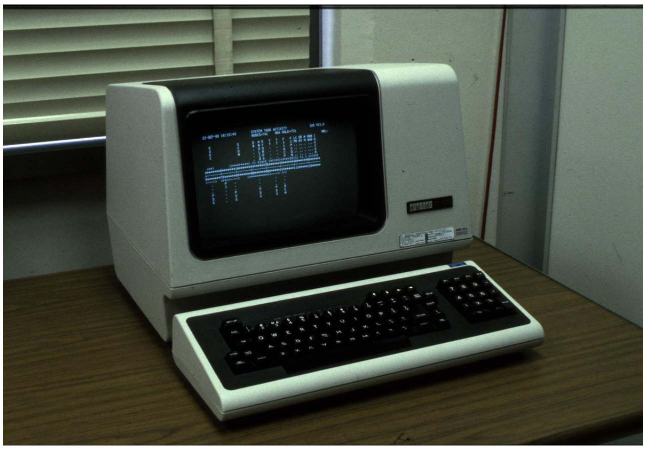

Figure 3.1: The DEC VT102 terminal, with a CRT monitor. It was common for monitors to be 80 characters wide, a convention that still carries over today for many programmers' coding style guidelines (e.g. in the Linux kernel)

They were and *still are* powerful ways to interact with computers! In many use-cases, the terminal is much more efficient than the click-drag-drop interface of a GUI, and hell of a lot more configurable. Though it may seem intimidating at first, once you get comfortable with a handful of commands, popping open the terminal will soon feel more like a superpower than fumbling with a black box.

All of the commands we mention here will be applicable to both MacOS and Linux (oh, the joy of working on UNIX-likes!). We assume that your shell is either **bash** (the default on most Linux distributions) or **zsh** (the default on MacOS). If you aren't sure, you can always type `echo $0` into the command line and press enter; the terminal should tell you what shell you're using.

Before we start for real, a quick word about **man pages**. These are basically documentation files that are stored on any UNIX-based system. The Linux man pages specifically are available online, and you can also download them from this git repo. MacOS also has its own man pages.

[1] If you want to learn more, I highly recommend *The Unix Programming Environment* by Brian Kernighan, which is slightly outdated but serves both as a delightful artifact of CS history and a helpful introduction to the Unix command line (and also C programs!).

You can access any man page of any C standard library function, or shell command simply by entering `man function-name` in the terminal, i.e., `man printf` or `man grep`. It is an invaluable tool for any systems programmer. Although they may be hard to read at first, eventually it becomes second nature, and they are infinitely better than those janky w3schools pages (which are misleading and often contain genuinely dangerous snippets of C code). If you forget how to use a certain shell command (this occurs often, especially with the countless flags associated with something even as simple as `ls`!) the man pages will always be there for you. And what's more heartwarming than that?

`$ echo blah`
Outputs whatever you put in as an argument. The argument could be a variable, such as in the example of `echo $0` previously shown. Try entering "echo hello world" into your prompt (represented here as a dollar sign). There, you've written your first shell script, yay!

`$ cat file-name1 file-name2 ...`
Outputs the contents of a file. Its name is short for "concatenate", and no surprise, its canonical use is to concatenate different files together into one stream.

`$ ls path-to-directory (optional)`
Lists the contents of whatever directory you're currently in. Common and useful tags (flags that you can append to the original command to get a more detailed output) include -a, which lists even hidden files (files whose names start with ".", these are usually configuration files for various applications), -l, which includes information about size, ownership, permissions, etc. e.g., ls -al is a very commonly used command.

`$ cd path-to-directory (optional)`
Changes the directory you're in. If you don't supply an argument, cd will take you back to your home directory. Take care to note when you're in your root directory (`/`) versus your home (`~/`), because they can seem quite similar though they are radically different places in your file system.

`$ mkdir directory-name`
Creates a directory.

`$ touch file-name1 file-name2 ...`
Creates (a) file(s).

`$ rm file-name1 file-name2 ...`
Removes (a) file(s). Unlike putting your files in the trash can, when you rm a file, it is gone forever, so be very careful. You can be more careful by adding `-i` (interactive) to the command; the shell will prompt you for permission before it deletes anything. You can remove directories by adding `-r` (recursive) to the command, and you can be very uncareful by adding `-f` (force) to the command; the shell will NOT prompt you for permission before it deletes. `rm -rf` for deleting a directory is a very common command, but wield it with caution!

`$ mv old-path-name new-path-name`
Renames/moves a file or directory. The way the UNIX file system is set up, moving files/directories and renaming their paths are technically the same thing

`$ cp old-path-name new-path-name`
Copies original file to a new file. Very useful for quickly making backup files.

`$ diff file-name1 file-name2`
Returns all the different lines between two files. Yes, this is similar to git diff!

`$ grep "string or regular expression" file-name1`
Searches for and prints a regular expression[2]. Grep stands for "**g**et **r**egular **e**xpression and **p**rint", and you can think of it as a powerful, extendable search tool. There's no way we can cover the world of regular expressions in this section, but they are incredibly useful to know. For now, though, just know that we can supply just a string as an argument and grep will print out instances of that string in the file(s) you specify.

`$ head -number file-name`
Outputs however many lines you specify from the start of the file.

`$ tail -number file-name`
Outputs however many lines you specify from the end of the file.

Now that you know the building blocks, we are now able to see where the real magic happens. When computer scientists were building UNIX, they also pioneered what is known as the "**UNIX philosophy**". Simply put, the UNIX philosophy encourages writing simple, modular programs that can be linked together in creative and powerful ways, just by redirecting input/output, either using `">"`, `"<"` or `"|"` (the latter symbol is called a "pipe", and it's ubiquitous in shell scripts). Watch Brian Kernighan himself demonstrate the UNIX philosophy in this video, which I truly believe is one of the best on YouTube. His explanation begins 6 minutes in.

Once you understand how his command line dictionary program works with pipes, you will pretty much be set for life (well, set for a computer science degree). Shell scripting is a relatively obscure art, and its syntax can often feel unintuitive (there are quite a few pitfalls depending on the shell you're using), but its interactive nature makes it very entertaining to tinker with. If you want to move forward and write more substantial scripts, try installing **shellcheck**, which is what it sounds like: a neat static code analysis tool just for shell scripts.

Standalone shell script files (often ending with `.sh`) require something called a "**shebang**" at the top of a file. It looks something like `#!/usr/bin/bash`. Basically, a `#!` followed

[2] Regular expressions (aka "regexes"), invented by computer scientist Stephen Kleene (who also invented recursion theory, among other things), are one of those concepts where if you put in a couple hours upfront to learn their basics, it will pay itself off many times over in the future. https://regexone.com/ is a fantastic website for getting started.

AT&T Archives: The UNIX Operating System

by a path to your shell. It lets the computer know which shell you want to use to run this script. Without a shebang, the script will not run.

Unit testing

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Debugging

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4 Discrete Math for Computer Science

About this class

CS230 is a curious class because it is generally bifurcated, depending on whether you take it in the Spring or the Fall, and depending on the instructor that is tasked with teaching it. Professors Carlos Tomasi and Kamesh Munagala provide a much more conventional course that serves as a solid introduction to theoretical computer science, with a lot of math and some Python programming assignments. Professor Bruce Donald (who is on sabbatical at the time of writing) teaches a much more quirky flavor of discrete math because his course also doubles as an intro course to Scheme, a dialect of Lisp (which is a powerful and extendable functional programming language, with much less of an emphasis on mathematics. Also, one of the only classes on functional programming offered at Duke!).

In Fall '23, when we took the course, it was taught by Professor Kate O'Hanlon, who taught it in the style of Professors Tomasi and Munagala (minus the programming element— there was literally not a single line of code to be written in the class). It's likely that this is the vein that CS230 will continue to be taught in.

In Spring '24 semester, a new course crosslisted with the Math department was announced: CS232, which is what it sounds like: a more math-oriented flavor of CS230 that goes in-depth into Markov Chains. If you're a Math major or minor, it might be better to take CS232 or even just opt for the Math substitution.

Why Discrete Math?

As you continue to progress through your undergraduate education in computer science, it becomes increasingly clear that the entire world of computing is built upon a firm foundation of mathematics. Gaining a basic overview of some of the most important concepts in the will prove to be quite valuable, especially as you encounter more challenging topics within the field of computing, including algorithmic design and computational theory. This section of the napkin will serve to provide a concise introduction to the key concepts of this course.

Structure

The structure of this section of the napkin will be adapted from the discrete mathematics curriculum at Duke University. We will begin by exploring basic logical and proof writing before moving into some more concepts related to probability and counting and will finally end with connecting these ideas to data structures and computer science at large.

Logic

Why Logic?

Logic enables us to clearly express ideas and arguments in ways that are free from the confusions and generalizations of English and language in general.

Definitions

- Proposition: A statement that can have a truth value (true/false) assigned to it.
  - Ex: Ella is a robot.
  - It is important to note that propositional logic does not enable us to convey relationship between distinct objects. We use predicate logic for this instead.
- Terms: Basic objects that can be used in a proposition or statement.
  - Ex: Ella.
- Variables: Placeholders for objects.
  - Ex: X, Y
- Predicate: Propositions with variables. They do not inherently hold a truth value, but can take on such a value in two cases.
  - The variables are replaced with terms.
    - Ex: X is a robot. (See, this does not have a truth value; however, *Ella* is a robot does!)
  - All variables are quantified.
- Formula: Compound predicate

5 Intro to Computer Systems

About this class

First, some background. CS210 is a relatively "young" class. It was first offered in Fall 2021 as an alternative to the introductory systems course requirement (before, all CS students had to take CS250, Computer Architecture). It's juggled around by various systems faculty (except for the one time that Professor Fain co-taught it). Where CS250 focuses more on hardware and processor design, CS210 deals with big ideas in systems from a software programmer's point of view.

There's pros and cons to 210's newness. A pro is that its syllabus is relatively flexible compared with 250, so the course structure is more open and malleable to student feedback throughout the semester. A con is that there aren't as many resources (such as past exams and answer keys) to study from, and indeed the syllabus varies more from instructor to instructor than 250 does, so what you get might differ a bit from what we have laid out here. For context, we took 210 in Spring '22 when it was co-taught by Professors Jeff Chase and Matthew Lentz.

Both classes have significant overlap with regards to:

- C programming
- Binary representation of data
- Assembly language (notably, you are expected to produce MIPS assembly code in 250; you are not expected to write assembly for 210)
- Processes
- Caching
- Virtual memory

250 notably lacks content about the C toolchain (make files, linking, loading, etc) and lacks more detailed discussions about concurrency (mutexes, condition variables, the producer-consumer paradigm). 210 notably lacks content about logic gates, processors (pipelining, for one), coding in assembly, and lacks more detailed discussion on caching (e.g. cache coherence).

A major pro of taking 210 (when it is taught by either Professors Danyang Zhuo (as it will be in Spring '24!) or Matthew Lentz) is that it sets you up pretty perfectly for the other class that they share teaching responsibilities over: 310, or Introduction to Operating Systems. I recommend trying to take 210 and 310 in consecutive years or better yet, semesters—though this requires some amount of planning, as 310 is currently not offered every semester. However, 310 (or its grad equivalent, 510) is guaranteed to be offered at least once per year.

If you are planning to do an ECE major or minor, you must take CS250. If you're not, then by all means, come along for the 210 ride!

History of UNIX, C and systems programming

When you first learn about the history of computer systems, you realize that most of the field's brightest breakthroughs started off as the brainchildren of researchers at a privately-owned laboratory called Bell Labs (yes, named after Alexander Graham Bell!). Among these wizards were Brian Kernighan, Ken Thompson, and Dennis Ritchie, two of whom you might recognize as the authors of one of the most iconic CS textbooks of all time: **The C Programming Language**, often referred to as "K&R" (after Kernighan and Ritchie's initials).

The C language and **UNIX** are very much intertwined, and form the basis of many computer systems. UNIX is one of the most influential operating systems of all time. Parts of its kernel, written in the 1970's, live on in Apple's XNU kernel (which itself was inspired by the UNIX-like Berkeley Software Distribution, or BSD), in the Linux kernel (which powers countless embedded machines and forms the base of Android's OS) and in every supercomputer, distributed server, real-time systems in self-driving cars—you name it!—that we run now.

You literally can't be a computer scientist without learning about UNIX. It's incredible that something built more than 50 years ago is still so applicable and relevant today, and it really speaks to the meticulous thought that went into creating and maintaining these early systems. There's so much to learn from them, so why not dive in?

The Von-Neumann model of a computer

We didn't go over this in much detail for this class (for all the gory bare-metal detail, see CS250, where you get to simulate a CPU in C) but I think the high-level overview is still worth knowing and talking about for any introductory systems course.

Broadly speaking, the Von-Neumann model of a computer is the one that virtually every computer uses today. What defines it is the central processing unit (CPU), often referred to as a "core", composed of an arithmetic logic unit (ALU) and a control unit. The CPU fetches instructions from a pool of data called "main memory" (or random-access memory (RAM)) and executes each instruction sequentially.

Importantly, as a consequence of this design, an instruction fetch and data operation cannot occur at the same time.

Processes are running instances of programs that live in main memory. Programs are static code and data that live on the disk. It's a subtle, but important difference that we'll be leveraging soon!

For now, processes are the smallest, simplest units of execution that we'll be talking about. Each process has its own execution context, called the process control block (PCB), that it uses to store important information throughout its lifetime. For example, the arguments that are passed into it, and the address of its next instruction, and so on. One process runs on one CPU at any given time.

Binary representation of information

As humans, we interact with information almost constantly. The words on this page are such an example. Think about the units and metrics of reading text: we comprehend text on the order of sentences and words, and sometimes (though rarely consciously) letters. You have probably fed a string of text into a computer program before, and most definitely written a print statement that spits out "hello world". But does the computer also see these words? At what level does it interact with data?

From the viewpoint of the CPU, everything is binary: expressed in 1s or 0s.

Programming in C: Things to Take Note of

Compile, Assemble, Link, Load!

The lifecycle of a C program.

Pointers

The bane of all C programmers' existences (just kidding, kinda).

Memory Management

What makes C special in a cool way.

Vulnerabilities

What makes C special in a bad way.

Assembly (Intel x86)

While we don't learn how to write assembly in 210, and are never asked to produce assembly code, it's still important to be able to read it and get the gist of what a simple assembly program is trying to do. In many ways, knowing at least a little bit about assembly makes you a more self-aware programmer.

Exceptional Control Flow

Here we introduce the kernel.

Virtual Memory

One of the most important abstractions of all time.

Concurrency

6 Operating Systems

About this class

CS310 is an old class, and it used to be required for the CS degree until Fall 2019, when the Duke CS department decided to loosen the restrictions for the systems course requirement, thereby letting CS students take their pick among the systems courses offered in lieu of 310. It was mainly headed by Professor Jeff Chase (who at the time of writing this, is on sabbatical) and Professor Bruce Maggs also taught it at some point. 310 underwent a **major** revamp when Professor Danyang Zhuo was hired. He took inspiration from courses at the University of Washington and MIT, which use a toy UNIX OS called **xv6** in order to teach OS concepts. Now most of the labs are done in kernel space, a big switch-up from the 310 of yore.

A notable change from the pre-Professor-Danyang to the post-Professor-Danyang era, aside from the xv6 stuff, is that servers, security, and networking is covered to a lesser extent. This does make sense, though, as Duke offers separate specialized courses for each of those topics: Intro to Computer Network Architecture (CS356), Intro to Computer Security (CS351), and Distributed Systems (CS512).

310 is tough but fulfilling and opens your eyes to the sheer amount of ingenuity that basically holds up the sky for your computer. Despite the requirement for 310 being dropped, I highly recommend taking 310 as an elective at some point in your CS degree. Also, it is a prerequisite to CS585 (Secure Software Systems, taught by Professor Matthew Lentz) and CS512.

What *is* an OS?

What is the role of an OS? I heard an analogy once that really stuck with me:

> An operating system is like the nervous system. You don't consciously force yourself to shiver when it's cold— on a deeper biological level, your body is "programmed" to maintain homeostasis. Similarly, on a computer, a process doesn't consciously decide to yield the CPU to make way for another, more urgent job. The OS does this for you.

At the macro level, the OS's job is to divvy up the resources on a computer so that all programs can live in safety and harmony, just like your nervous system is constantly trying to keep you healthy and alive... and the OS does all this without the userland programs even knowing about much of what's going on behind the scenes. Of course, this is easier said than done. Countless policies and complex subsystems go into this management of resources.

Another pithy but useful description of an OS's job is that it:

- **Multiplexes** hardware resources,
- **Abstracts** the hardware platform, and
- **Protects** software principals