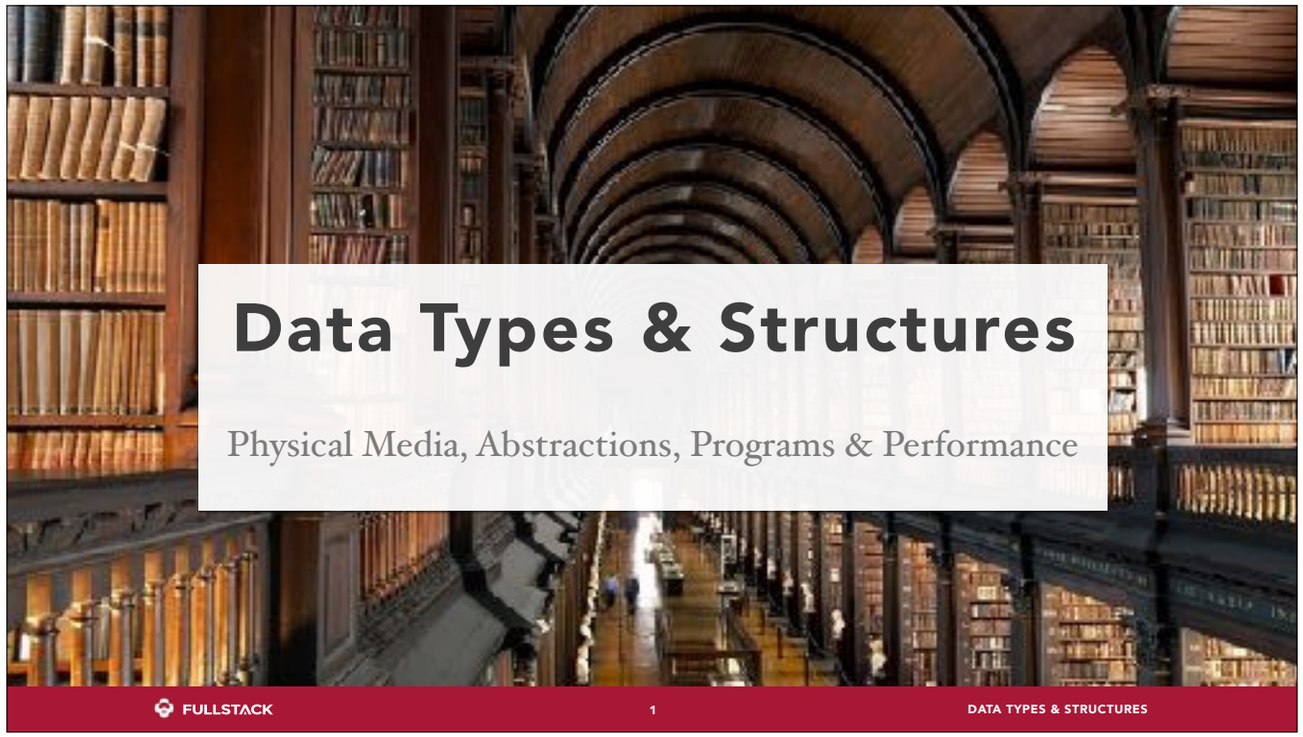


Some quick demos for fun / preview:

```
0.1 + 0.2;
['data', 'Fullstack', 'Lecture', 'structures'].sort();
[19, 20, 1701].sort();
'🍻'.length;
NaN === NaN;
typeof NaN;
```


"[The files are] in the computer... it's so simple."
MakeAGIF.com

(Just Some) Motivations

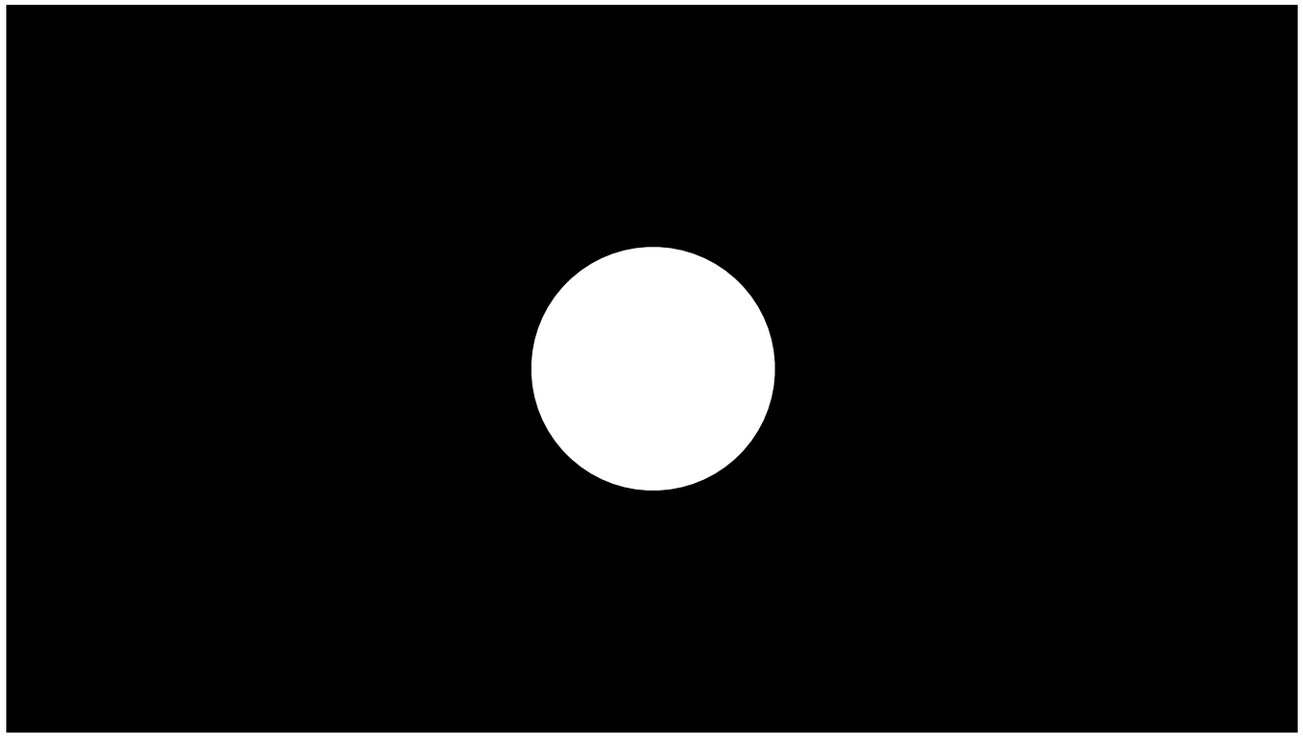
- *Demystify foundations*
- *Gain insight & perspective*
- *Recognize solutions*
- *Write performant code*
- *Continue practicing OOP*
- *Interview well*

- A very academic part of the curriculum, but programmers should have a conceptual grasp of this topic
- Comp sci vs. programming
- Standing on shoulders
- Using the right tools
- Preventing bugs
- Speak intelligently with other programmers

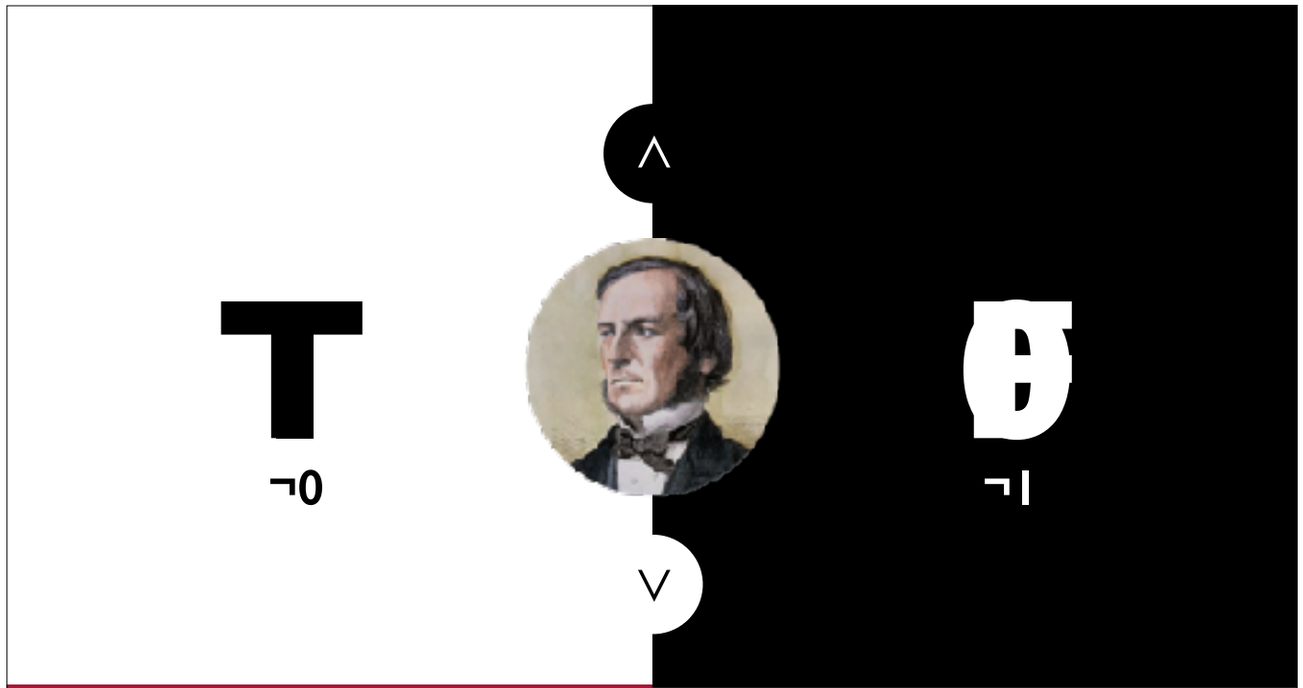
Coming Up

I. Information Theory & Hardware
II. Representations & Encodings
III. Abstractions & Languages
IV. Abstract Data Types & Data Structures
    IV.a. Queues
    IV.b. Linked Lists
    IV.c. Hash Tables
    IV.d. Trees
V. Extras

Part I:
Information Theory & Hardware

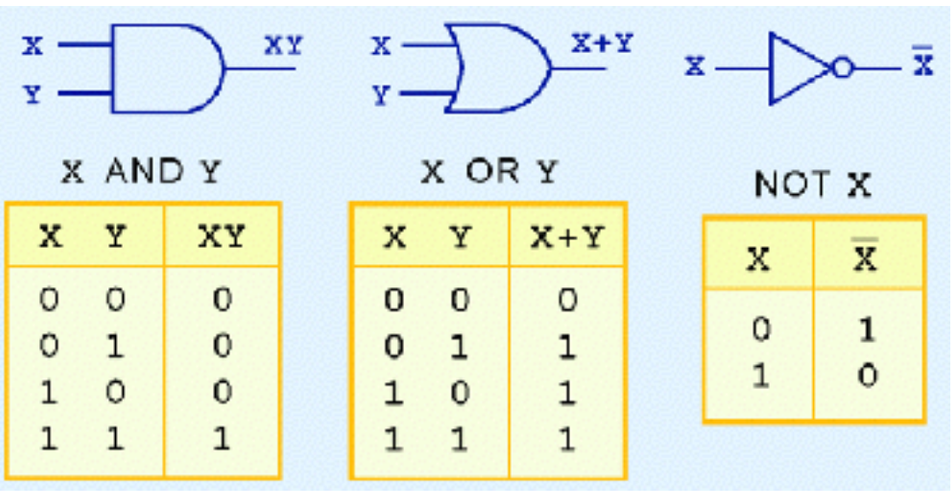


Is this slide communicating anything? If everything was the same, there would be no information (very Zen). But if we add something *different* (click)… now we’re cooking. In information theory, info is a sequence of *symbols*, modeling knowledge. Symbols = differentiation; this vs. that.



1847 & 1854, English mathematician George Boole (1815–1864) published *The Mathematical Analysis of Logic* and *An Investigation of the Laws of Thought*. A symbolic notation for formal logic: Boolean algebra. 1/0 denote T/F.

My name is Boole AND I invented boolean algebra!



X AND Y

X	Y	XY
0	0	0
0	1	0
1	0	0
1	1	1

X OR Y

X	Y	X+Y
0	0	0
0	1	1
1	0	1
1	1	1

NOT X

X	$\overline{X}$
0	1
1	0

Example truth tables. Point out what would be the case if each part of a statement was T/F.

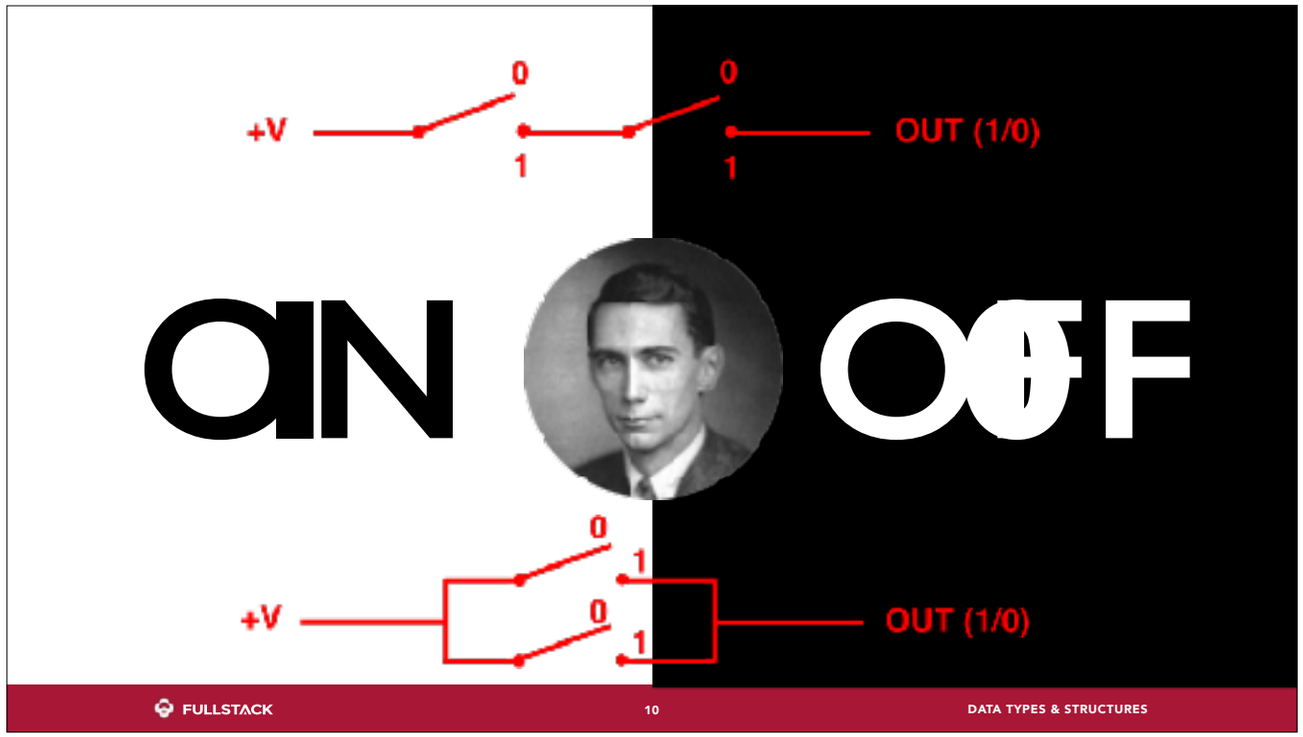
Law	Example	Example
Identity	A ∧ 1 = A	A ∨ 0 = A
Idempotent	A ∧ A = A	A ∨ A = A
Associative	A ∧ (B ∧ C) = (A ∧ B) ∧ C	A ∨ (B ∨ C) = (A ∨ B) ∨ C
Commutative	A ∧ B = B ∧ A	A ∨ B = B ∨ A
Absorption	A ∧ (A ∨ B) = A	A ∨ (A ∧ B) = A
Complementation	A ∧ ¬A = 0	A ∨ ¬A = 1
Distributive	A ∧ (B ∨ C) = (A ∧ B) ∨ (A ∧ C)	A ∨ (B ∧ C) = (A ∨ B) ∧ (A ∨ C)
De Morgan's	¬(A ∧ B) = ¬A ∨ ¬B	¬(A ∨ B) = ¬A ∧ ¬B
Common Identities	A ∧ (¬A ∨ B) = A ∧ B	A ∨ (¬A ∧ B) = A ∨ B
Double Negation	¬(¬A) = A	

∧ means logical AND
∨ means logical OR
¬ means logical NOT

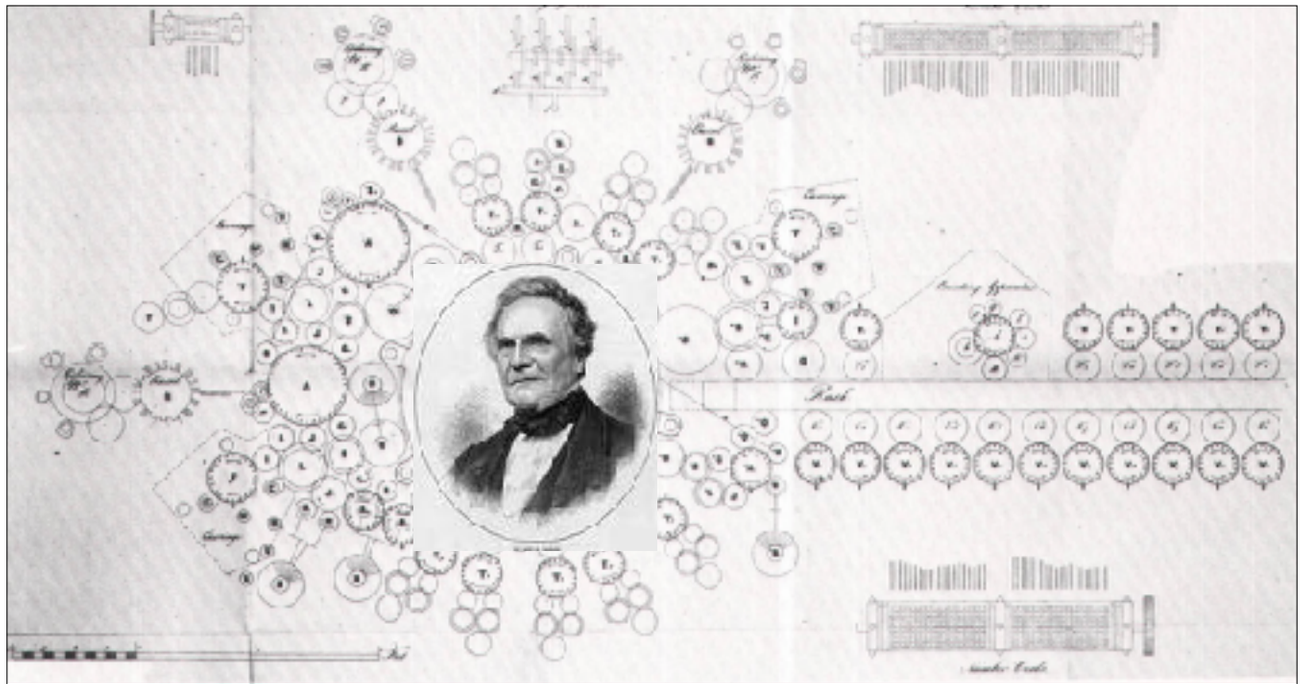
1 means true
0 means false

A/B/C are conditions (what goes inside the parentheses of an `if` statement)

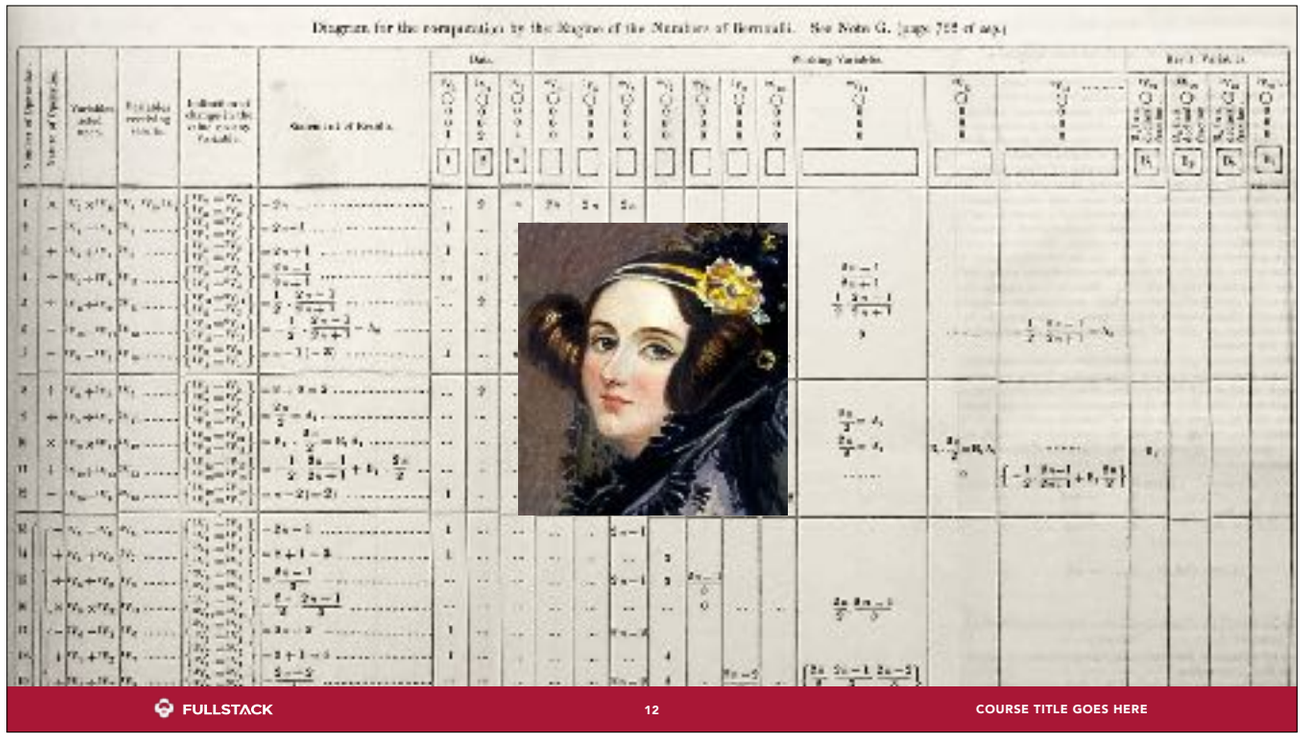
- Laws of boolean algebra. The order of operations of logic
- Can draw them out using big Venn diagrams to prove them to yourself
- Logic can be applied to code (if statements)
- Talk about Epic and simplifying business logic



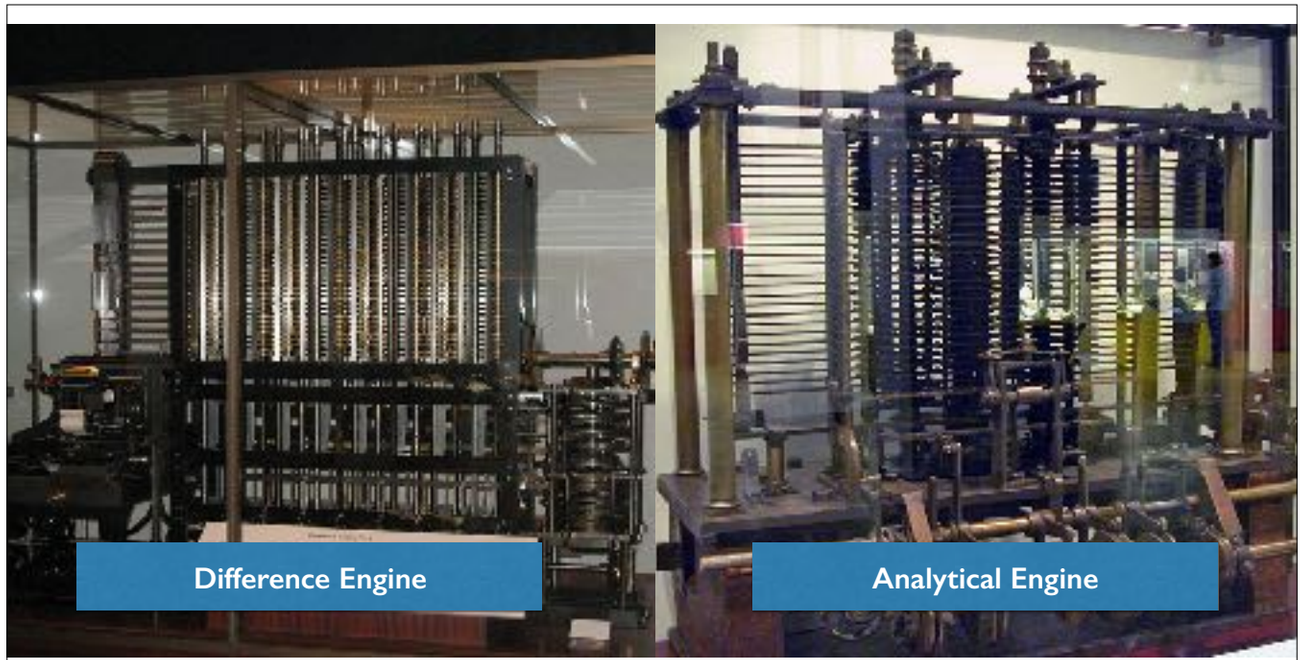
1930s, American mathematician / electrical engineer Claude Shannon (1916–2001), "the father of information theory", realized Boolean algebra can be processed using switches. He created "switching algebra" — physical logic gates (AND, OR, NOT, NOR, NAND, etc.). On-off states represent truth values. But what kind of switches?
**Note for Zeke: Shannon also juggled.*



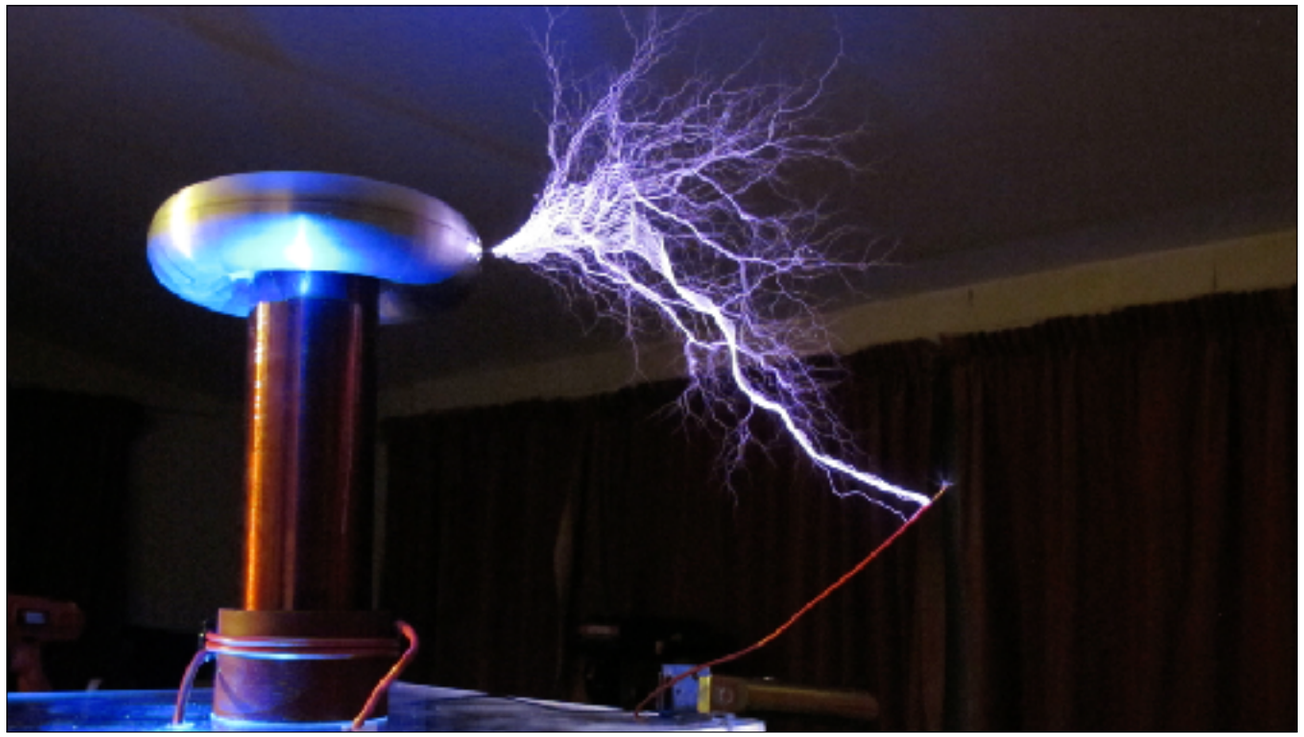
- Plans for the analytical engine, by Charles Babbage
- Babbage came up with the idea for a programmable computer



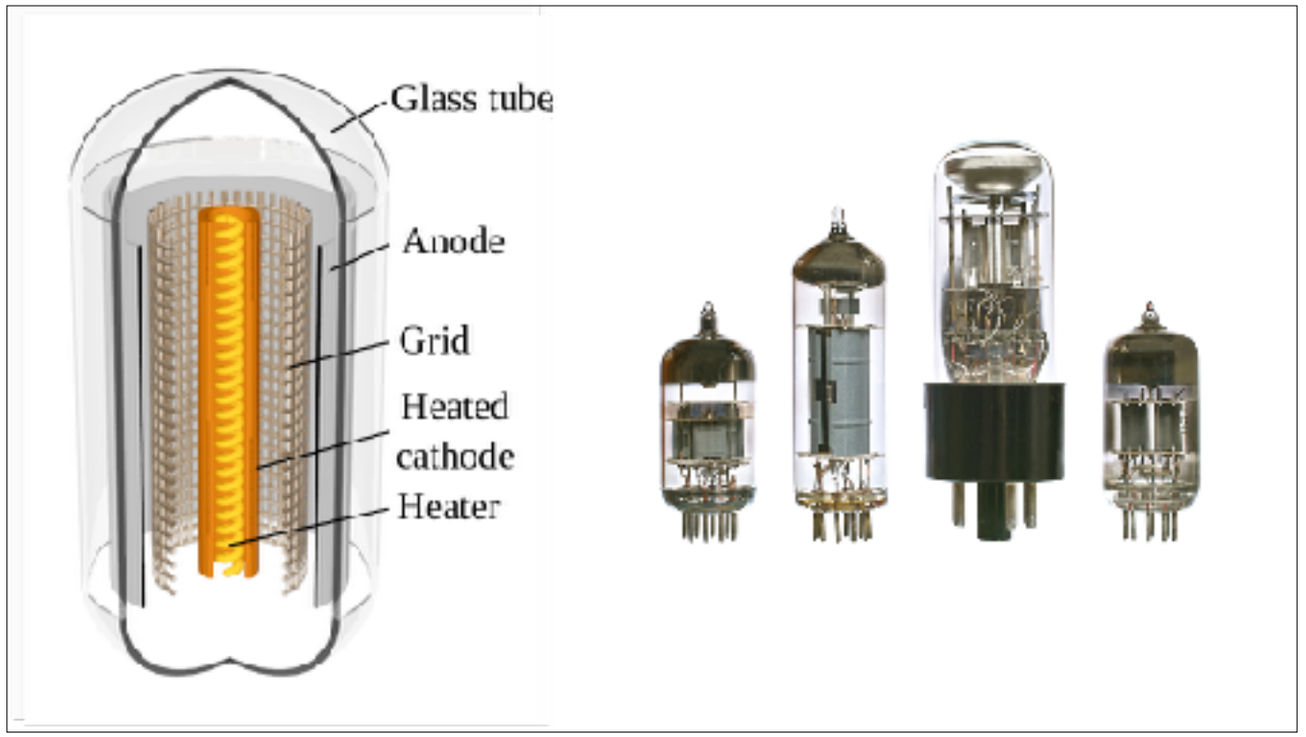
- The first program for the analytical engine was written by Ada Lovelace
- Added notes which we now recognize as distinguishing hardware from software



- The first difference engine was built in 1855; the first analytical engine was built in the 1980s.
- Turns out it’s very hard to build a system with so many mechanical switches. Alternative?



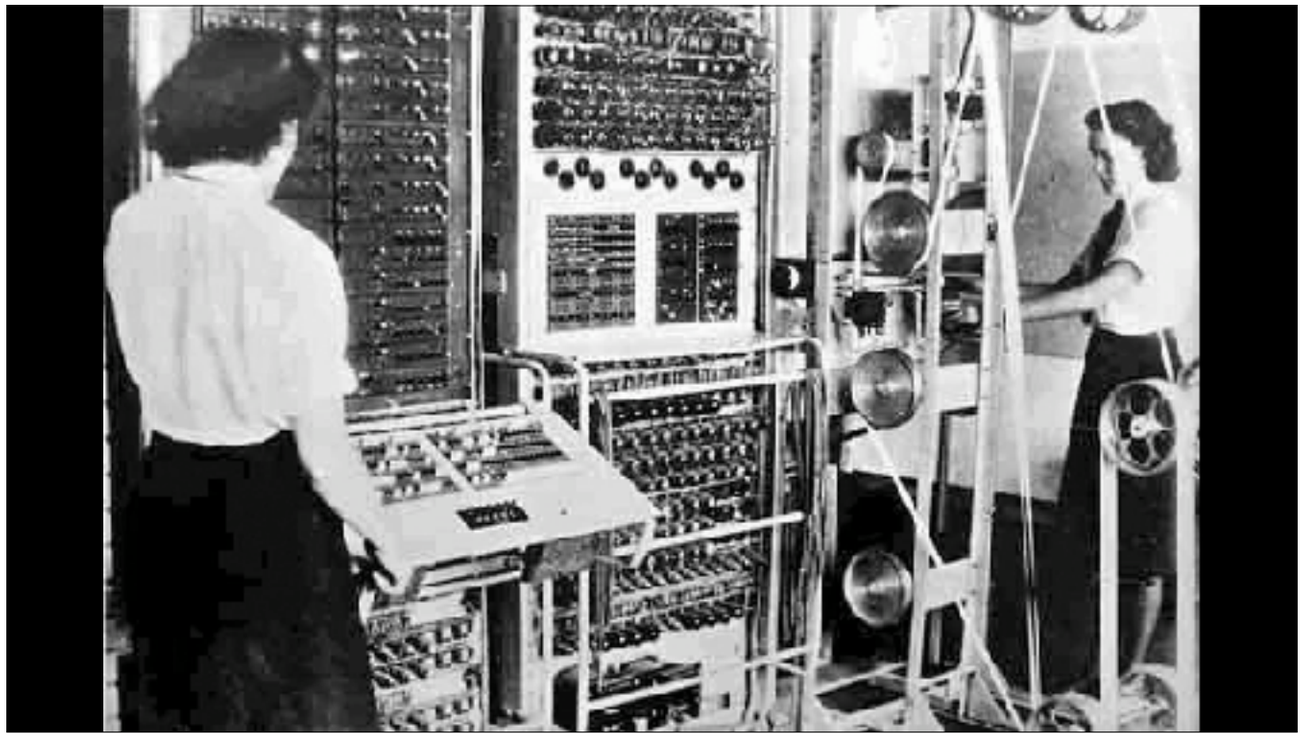
- Electrical current is a remarkably useful medium for boolean algebra.
  - Signal propagation is incredibly fast — 50% to 99% light speed.
  - Electrons are tiny (~5 femtometers [1×10−15 m]), so you can fit many signals in a small space.
  - Electric power directly activates devices; signal becomes action.



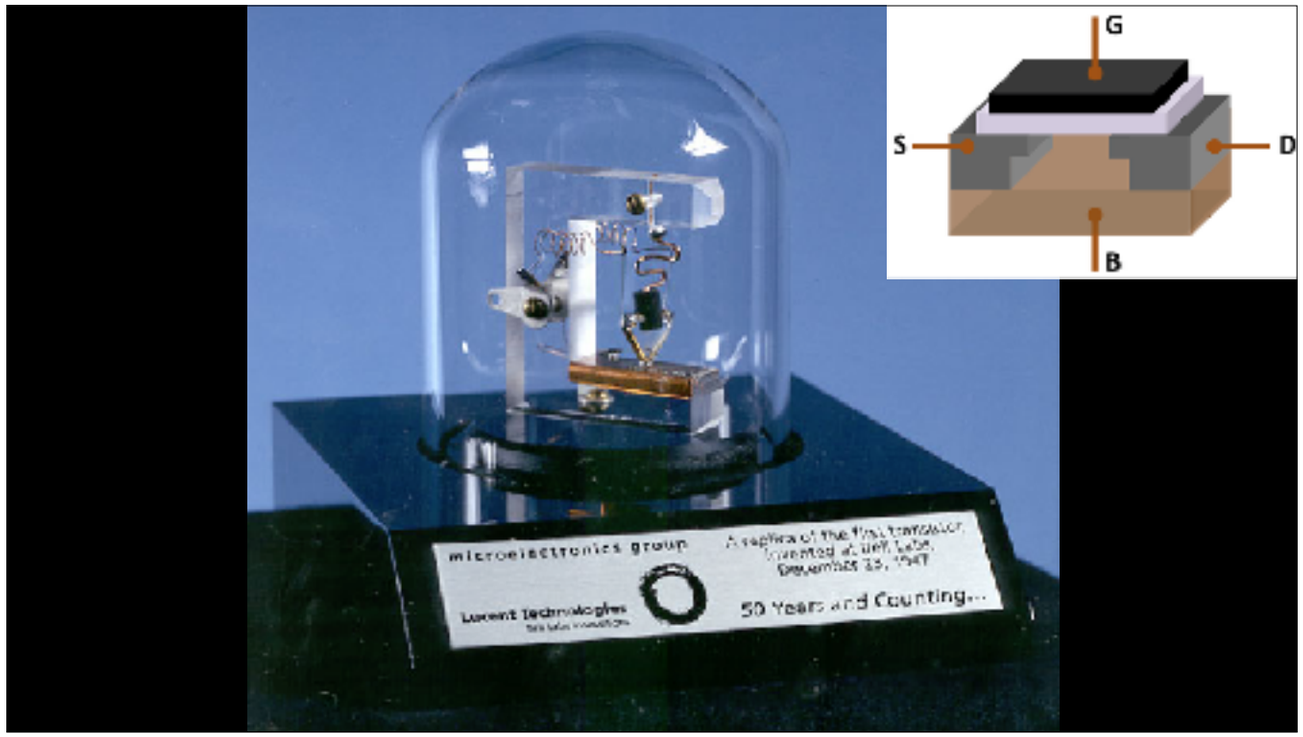
- Vacuum tubes let you switch without moving anything physical.
- Electrons flow from hot cathode to anode, mediated by an intervening charged grid
  - If negative w.r.t. cathode, the grid repels electrons, reducing or stopping current btw. cathode/anode.
- Problems: large, hot, fragile, have to keep them on or they break faster

Wikipedia:

When held negative with respect to the cathode, the control grid creates an electric field which repels electrons emitted by the cathode, thus reducing or even stopping the current between cathode and anode. As long as the control grid is negative relative to the cathode, essentially no current flows into it, yet a change of several volts on the control grid is sufficient to make a large difference in the plate current, possibly changing the output by hundreds of volts (depending on the circuit). The solid-state device which operates most like the pentode tube is the junction field-effect transistor (JFET), although vacuum tubes typically operate at over a hundred volts, unlike most semiconductors in most applications.

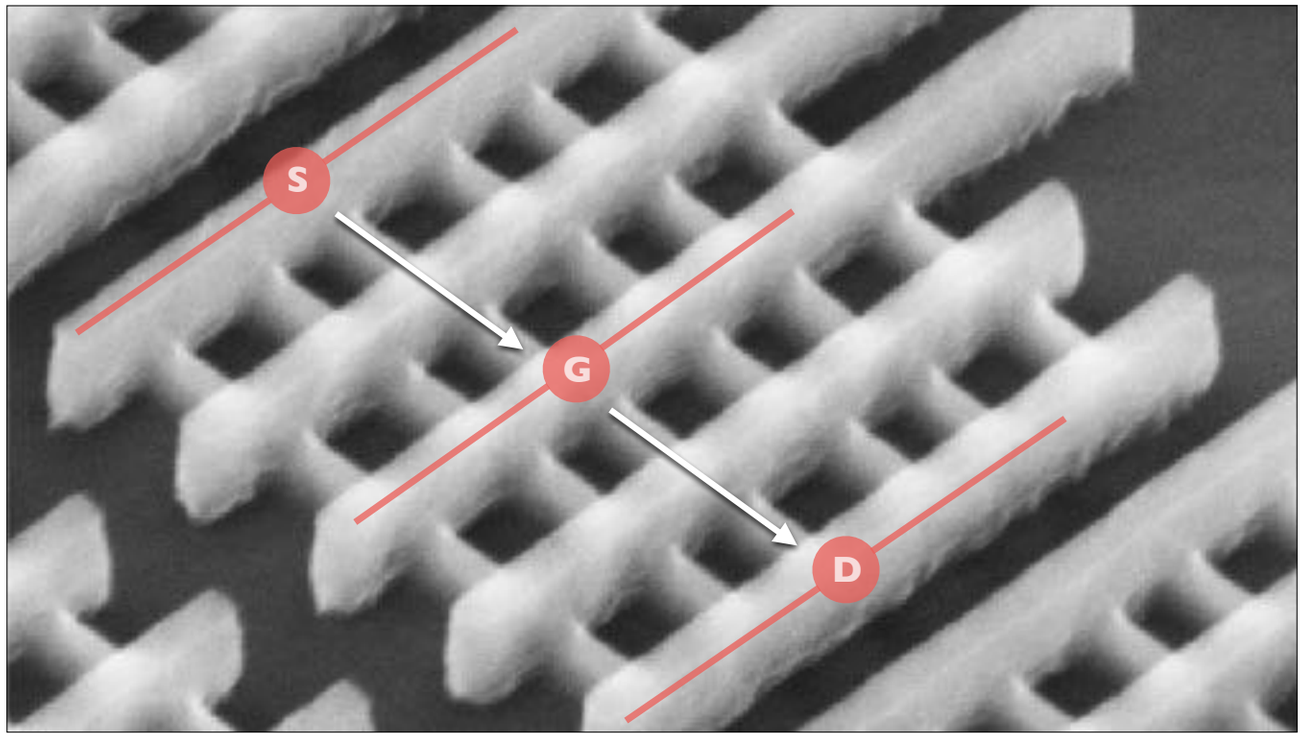


Colossus. 2,400 vacuum tubes. Kind of big, and warm, and constantly breaking.

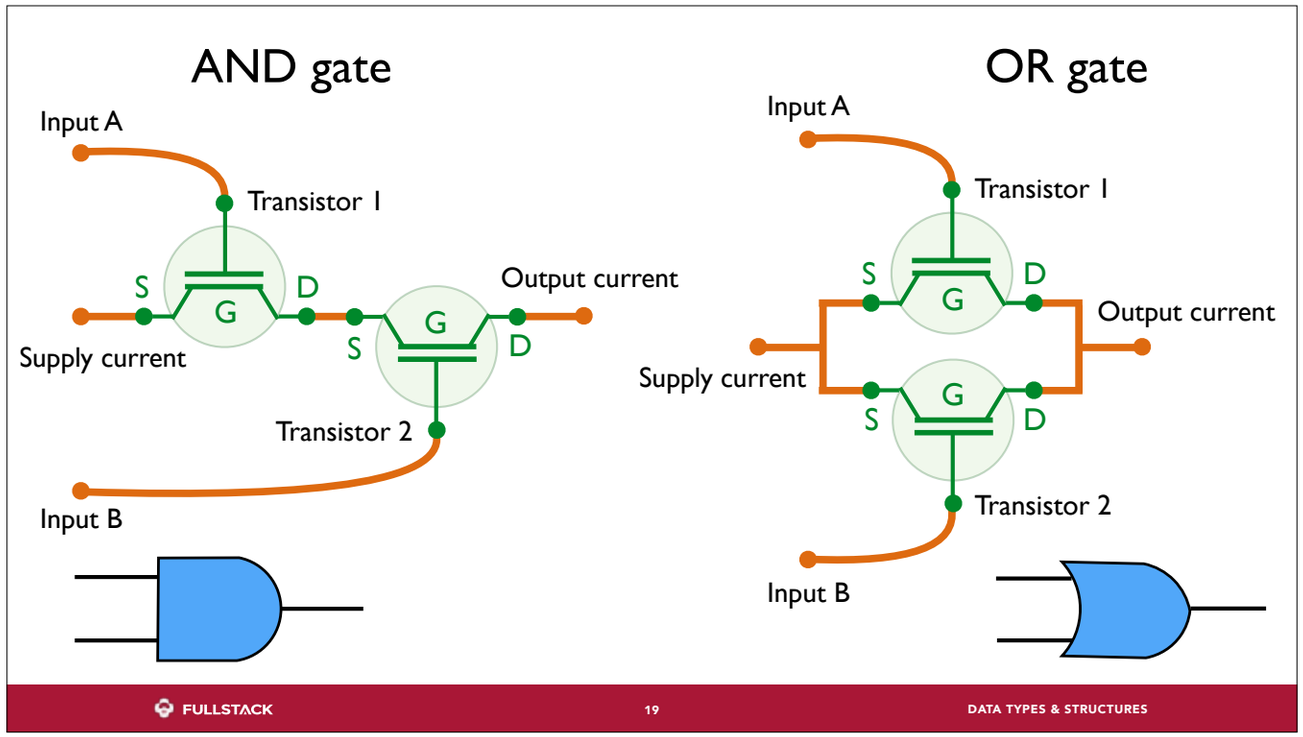


From November 17, 1947 to December 23, 1947, John Bardeen and Walter Brattain at AT&T's Bell Labs in the United States performed experiments and observed that **when two gold point contacts were applied to a crystal of germanium, a signal was produced with the output power greater than the input**.

Inset: MOSFET showing gate (G), body (B), source (S) and drain (D) terminals. The gate is separated from the body by an insulating layer (white).

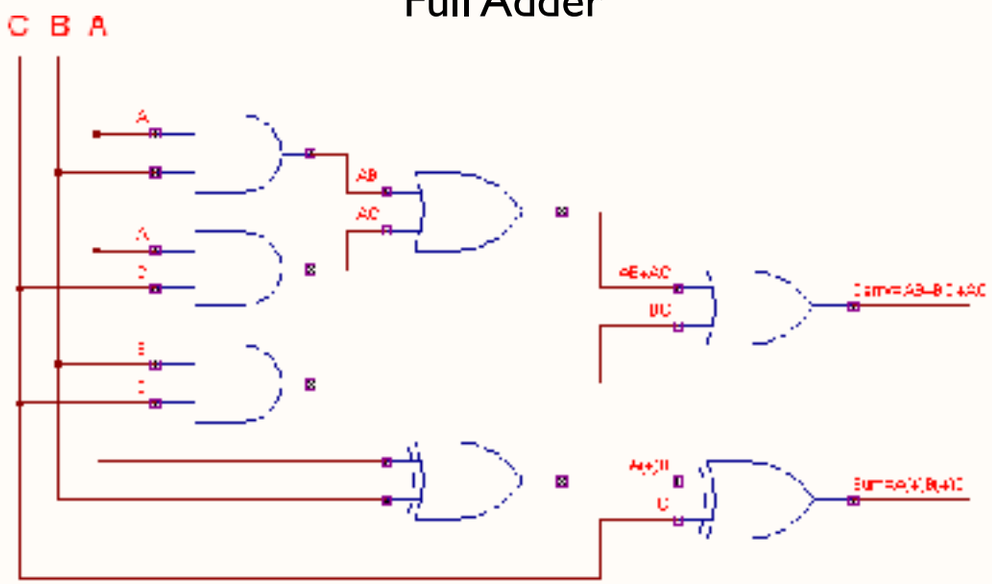


- Making switches tiny: a metal-oxide semiconducting field-effect transistor (MOSFET). Fins only 22 nanometers thick.
  - Viruses 20-400 nm; at 1-5 nm you get weird quantum tunneling.
  - 1.4 billion transistors and ~100 km of wiring on a chip the size of a thumbnail.
- Current from “source” to“drain” terminal switched on/off by voltage to“gate”.
  - Drain of one transistor can be routed to the gate(s) or source(s) of other(s), creating boolean logic gates.
  - Lots of logic gates = a Rube Goldberg-esque calculating machine; a computer!
  - CPU like a brain; transistor like one neuron.

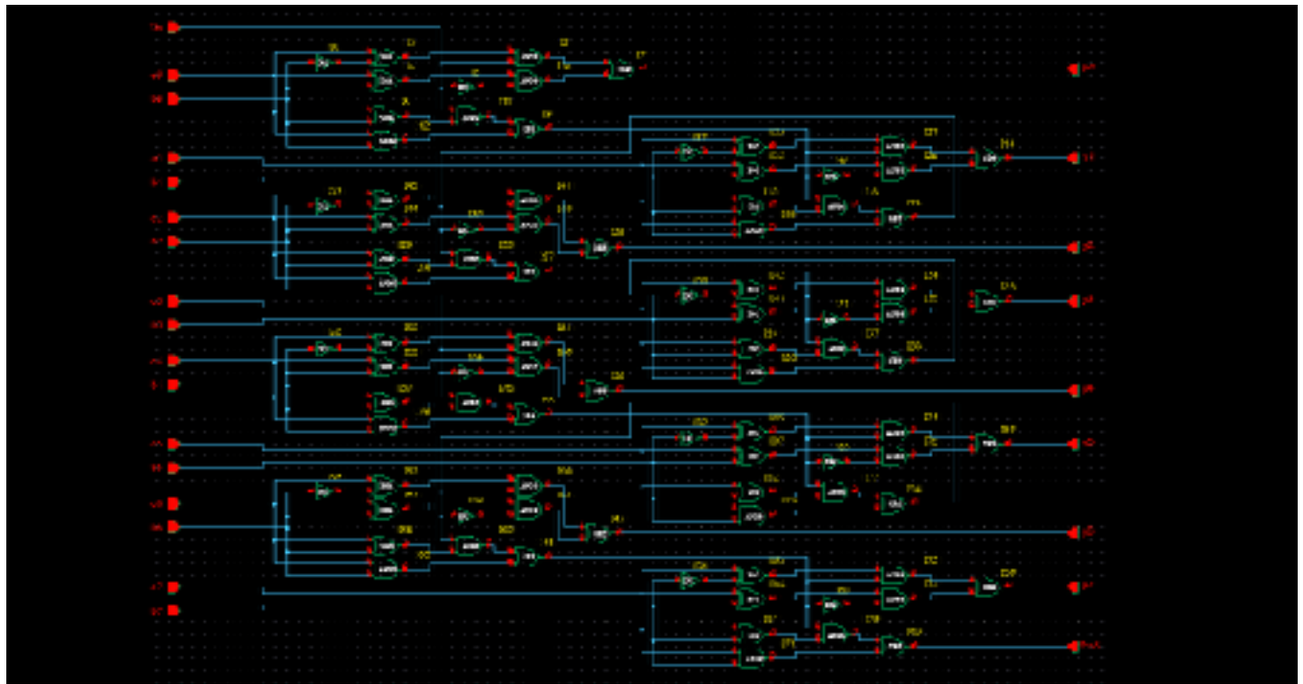


Sequence transistors together to make AND and OR gates, the building blocks of any integrated circuit.

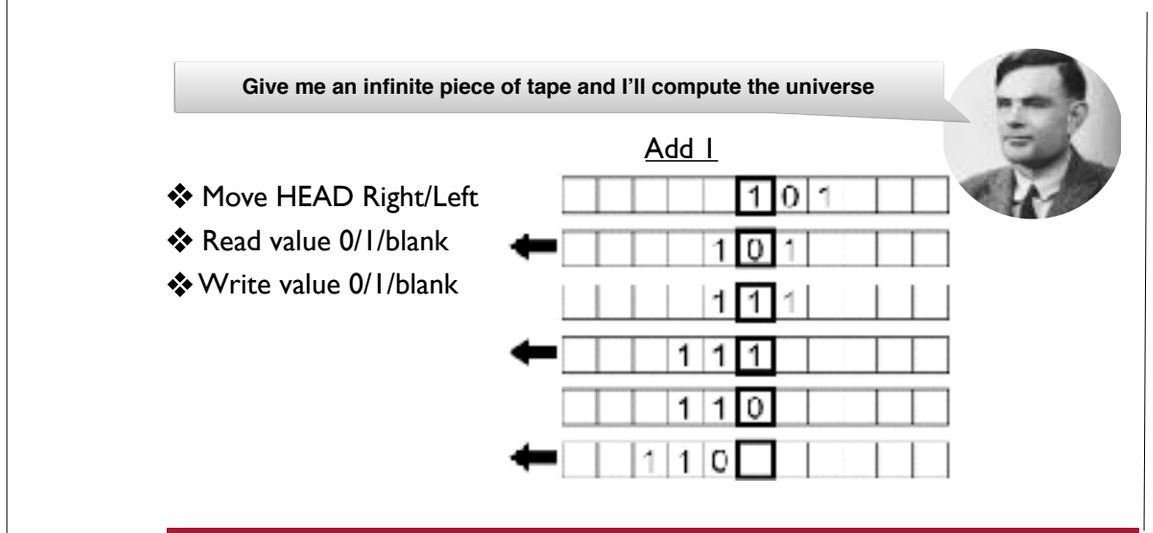
Full Adder



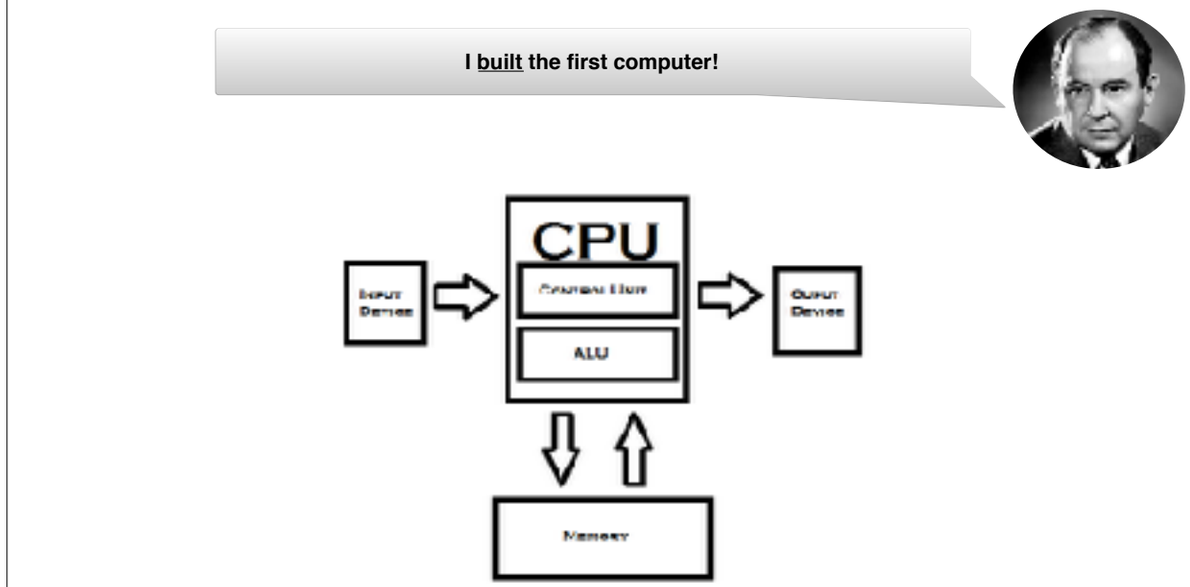
Gates can be assembled together into complicated circuits that can perform calculations. This one adds two bits together.



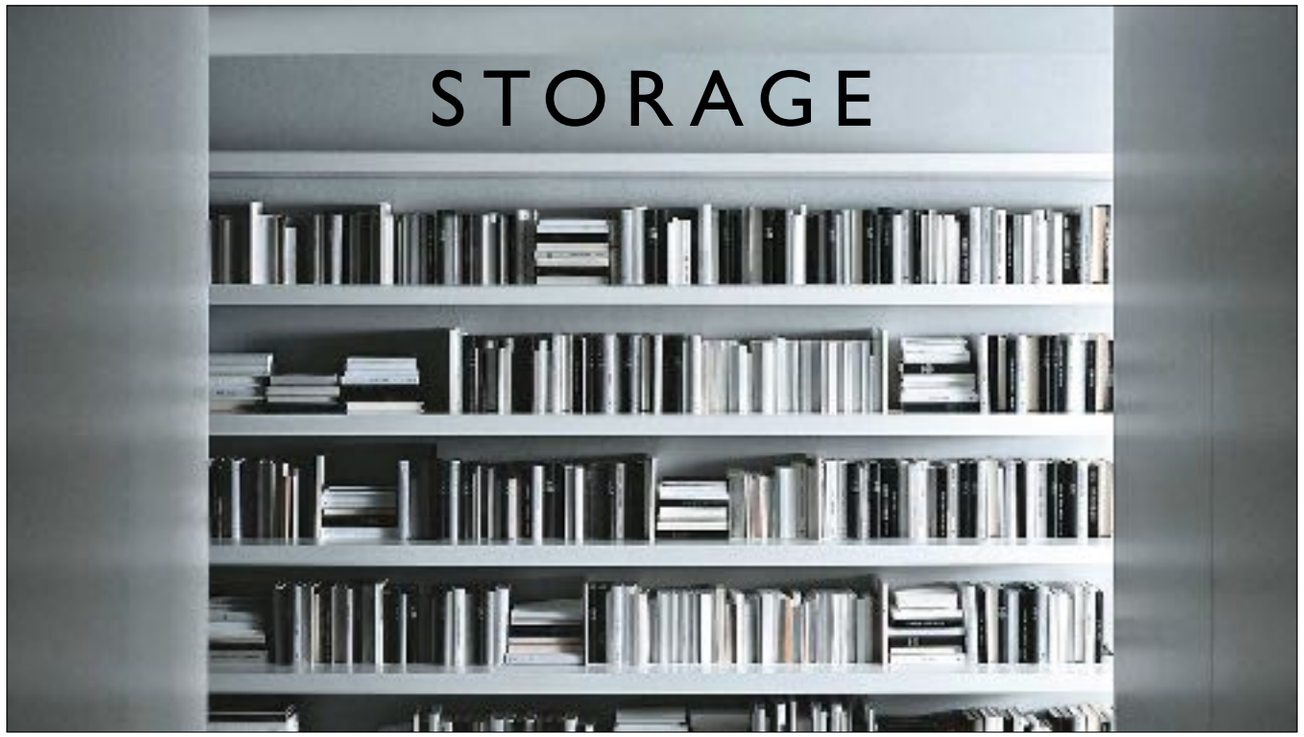
You can think of a CPU as a collection of specialized circuits like this one. But what happens to the output? And where does the input come from?



- 1930s, Alan Turing invented the Turing Machine, the basic ‘idea’ of the computer without any particular implementation.
- He actually did this to solve a math problem called the Undecidability problem.
- We can’t go into enough depth, but Turing proved anything ‘computable’ could be computed using such a machine with very basic abilities.
- It might not be efficient, but the encoding of 1 and 0, infinite memory (tape) and the ability to do a different action based on what is read is all a computer needs.

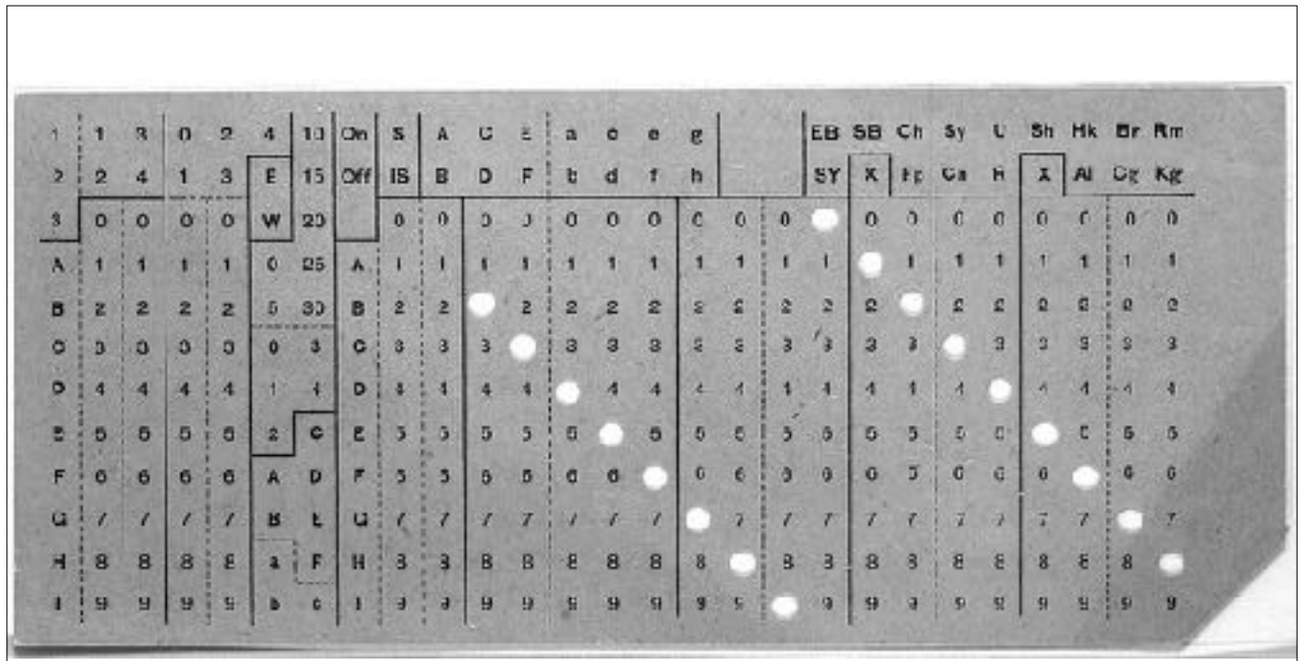


- Von Neuman invented the ENIAC in 1946 - one of the first electronic programmable computers (*https://en.wikipedia.org/wiki/Computer#First_computing_device)
  - It was designed to do calculations for the Hydrogen bomb and was a part of the Manhattan Project
  - A newspaper at the time described it as a ‘giant brain’
  - It weighed 30 tons, cost $6.8 million (in todays dollars) and had a processing speed of 0.1 MHz
- This is called the Von Neuman architecture, and its the most fundamental construction of a computer
  - There is input (the program) that is read by the CPU
  - The CPU has a Control Unit, which reads and executes instructions and tracks the current location in the program
  - The CPU also contains an Arithmetic Logic Unit, the circuit board for doing boolean algebra and math
  - The CPU can read and write to the Main Memory - this is like your RAM, we’ll get more into that later
  - The Output - a printer that would print the result of the computation when it finished

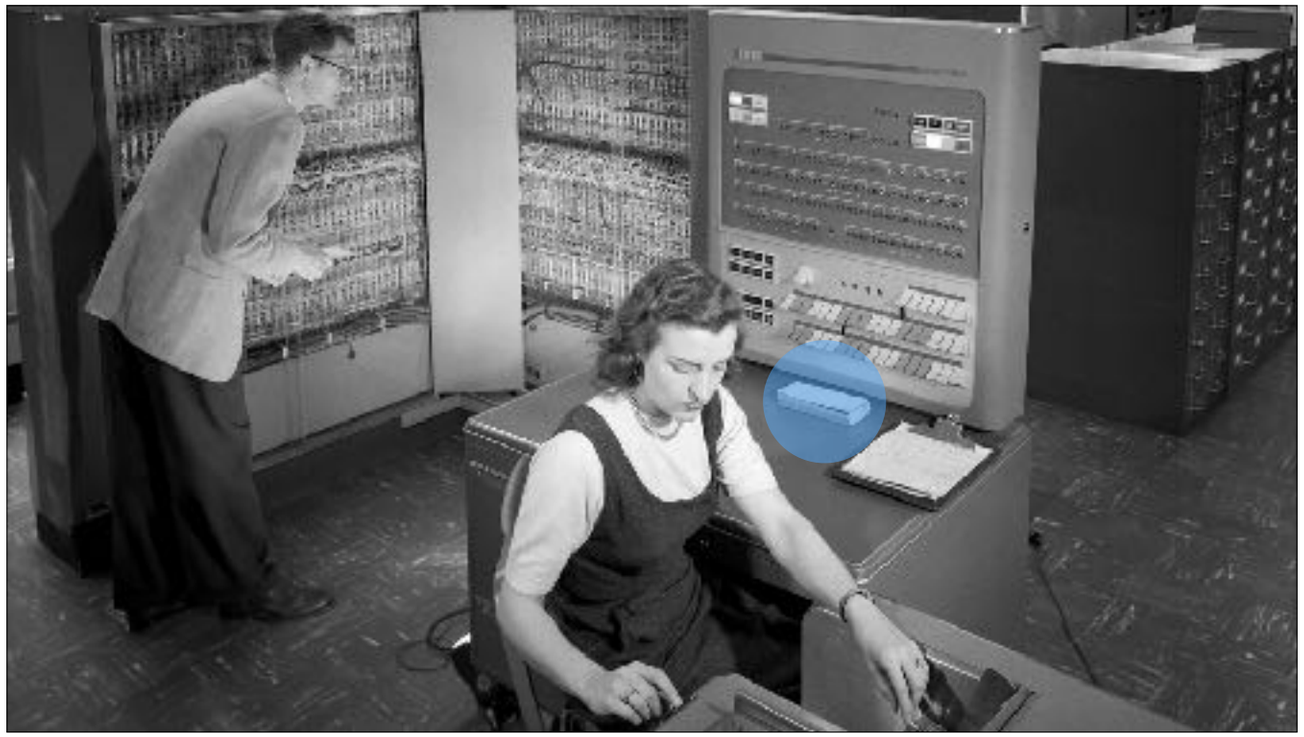


But what forms the inputs for all those calculations? Where do the original on-off switch states come from? Let’s back way up and talk about data storage…

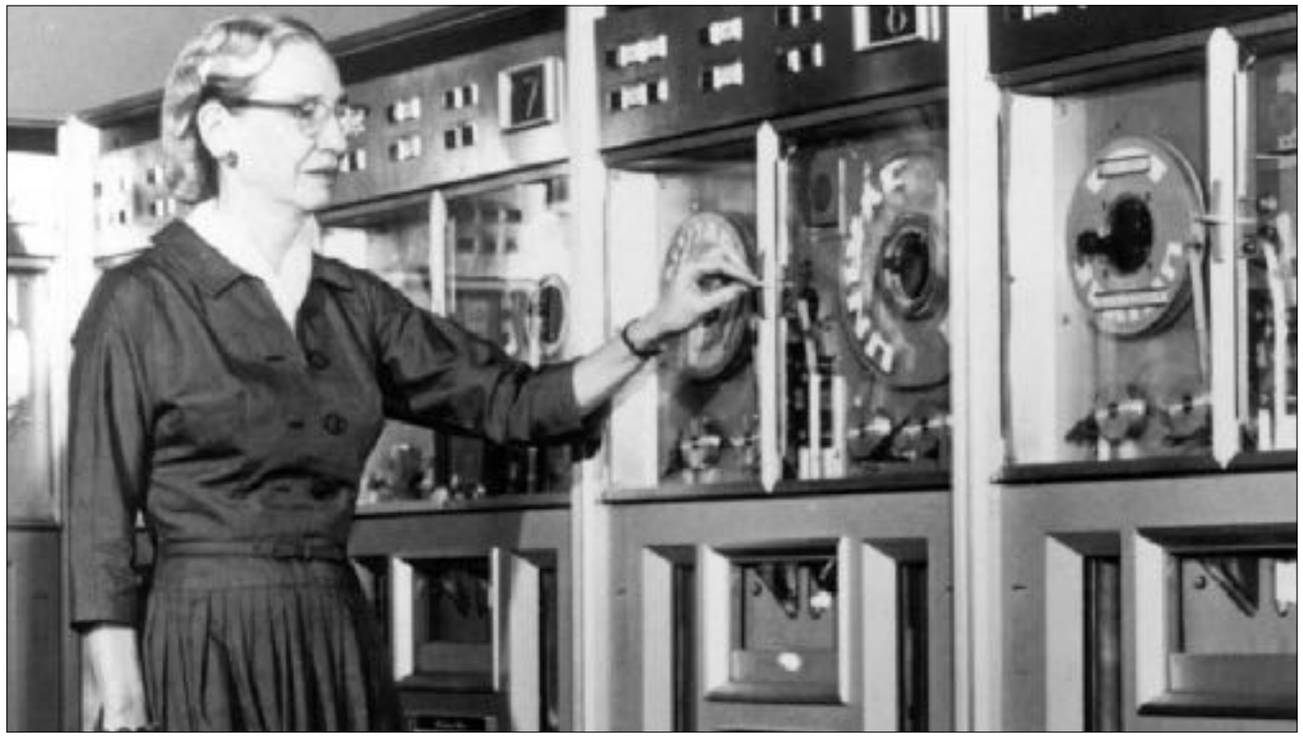
In 1880, the US census takes 8 years. Herman Hollerith (1860–1929; City College of NY, Columbia, MIT)’s doctoral thesis “An Electric Tabulating System” (1889) proposes a certain kind of data storage, plus electrical signals, to count results. The 1890 census takes one year and comes in under budget. How did he represent the data?



Hollerith’s punchcards used electrical contact (on-off, wires brushing through holes) and position to indicate age, state, gender, marriage status, etc. He had essentially figured out the electrical bit: on-off switches. In 1911, his Tabulating Machine Company merges to become the Computing Tabulating Recording Company. Guess what the company was renamed in 1924? …International Business Machines Corporation (IBM).



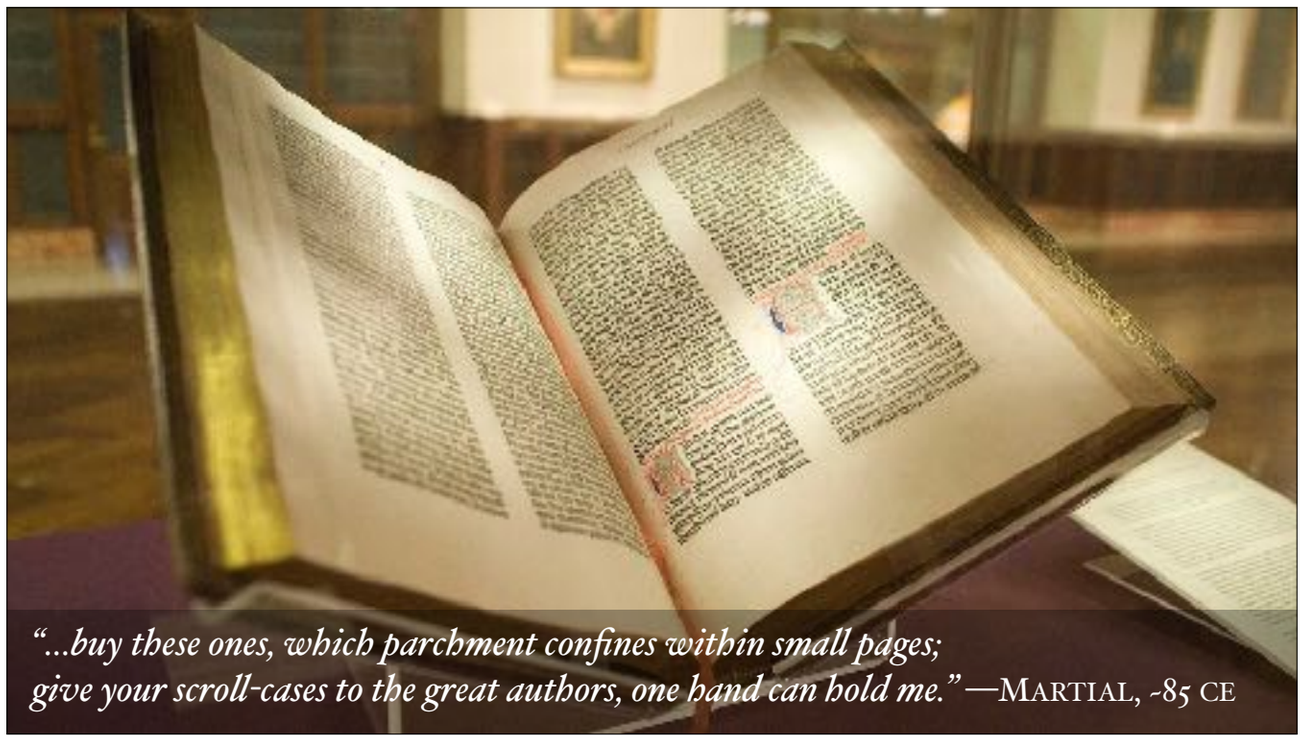
Fast forward to NASA, 1957, where a card reader is still being used for this IBM 704 computer. However, by the 50s punch cards were already on their way out, rapidly being replaced by…



…magnetic tape storage. Magnets have ± polarity. On magnetic tape (e.g. audio cassette, VHS) an electromagnetic read/write head magnetizes sections with one polarity or the other, forming a stream of bits. This is Grace Hopper (1906–1992, Vassar, Yale, USN Rear Admiral) working with a UNIVAC tape store. Invented the first compiler, helped popularize the idea of machine-independent programming languages.

NERSC (National Energy Research Scientific Computing Center) modern tape archive system (High Performance Storage System), in use since 1998. Tape storage is still the most cost & space-efficient massive storage strategy, e.g. for data centers, backup. But it is terribly slow to access different sections.

- In antiquity, important documents were recorded in scrolls.
- Scrolls only offer *sequential access* — you need to *scroll* to a specific point.
- Remember rewinding/fast-forwarding VHS or audio cassettes?
- Tape drives are essentially scrolls. Imagine the inefficiency in copying data from one spot to another.



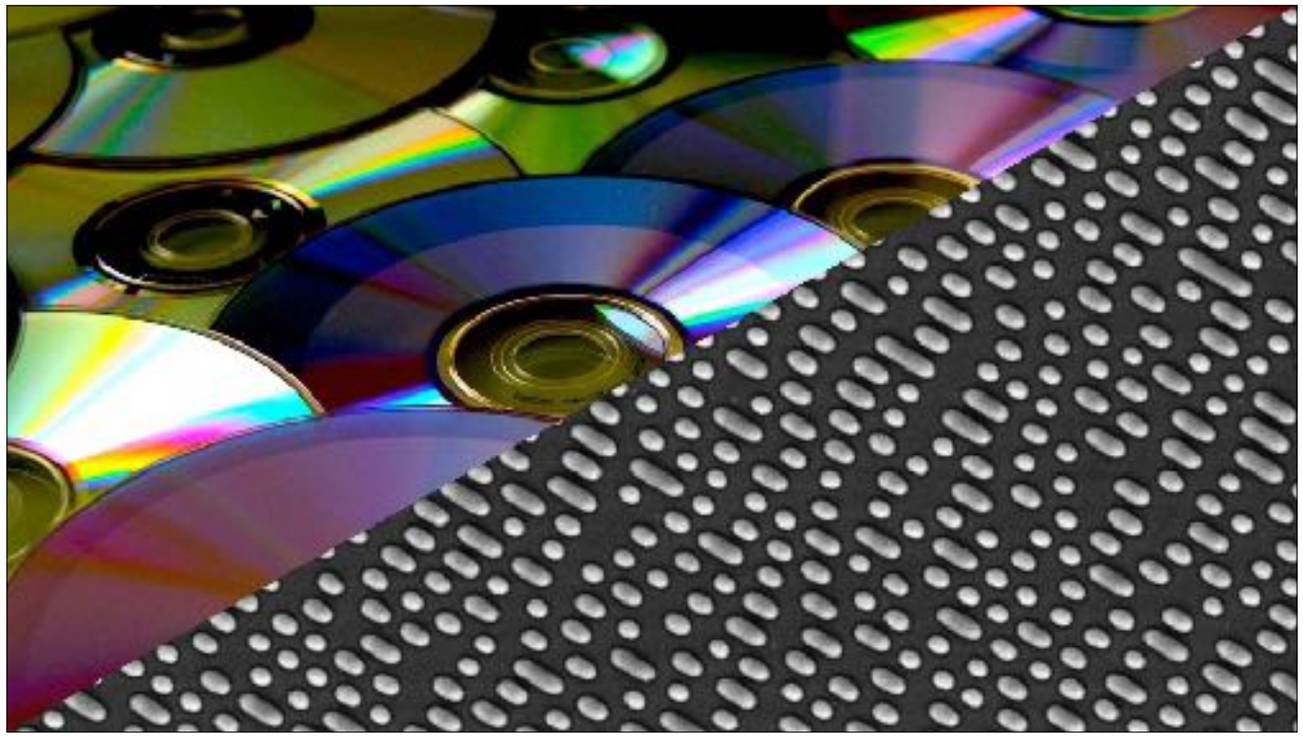
(quote by Roman poet Martial, from his Epigrams.)

- From roughly the 100s through the 300s, the scroll was gradually replaced by the codex (hand-written book).
  - Pro 1: compact/portable, both sides of page
  - Pro 2: **reach different sections quickly** (*random access*).
- Most significant leap in data storage until the printing press (~1440 in the West). Photo: Gutenberg bible.
- After tape drives, computers needed their own "book"…

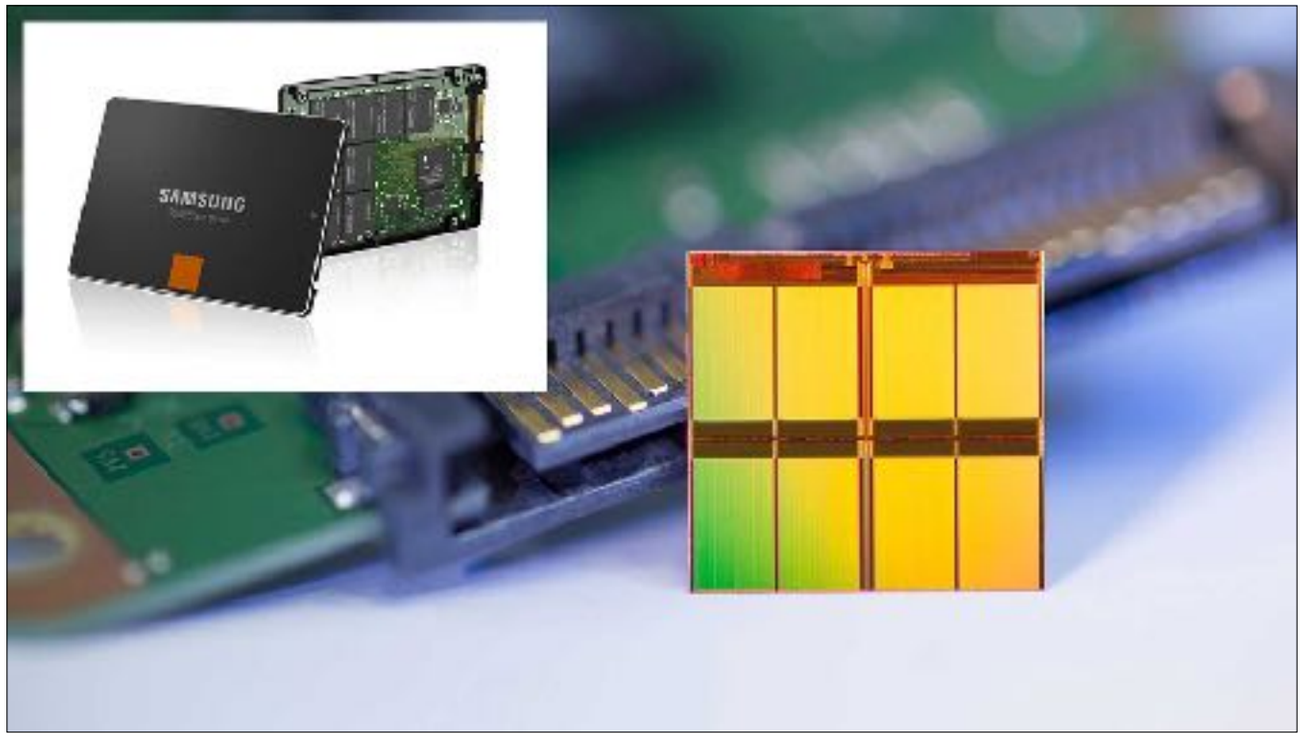
- The hard disk drive, invented in the 50s but common by the late 80s.
- A solid platter ("hard disk") spins at about 5000–10,000 RPM.
- The head reads/writes magnetic ± bits in concentric circles, almost like a record.
- The head can move to any point on the disk, like a finger choosing which page to open in a book.

Fun video: https://www.youtube.com/watch?v=3owqvmMf6No

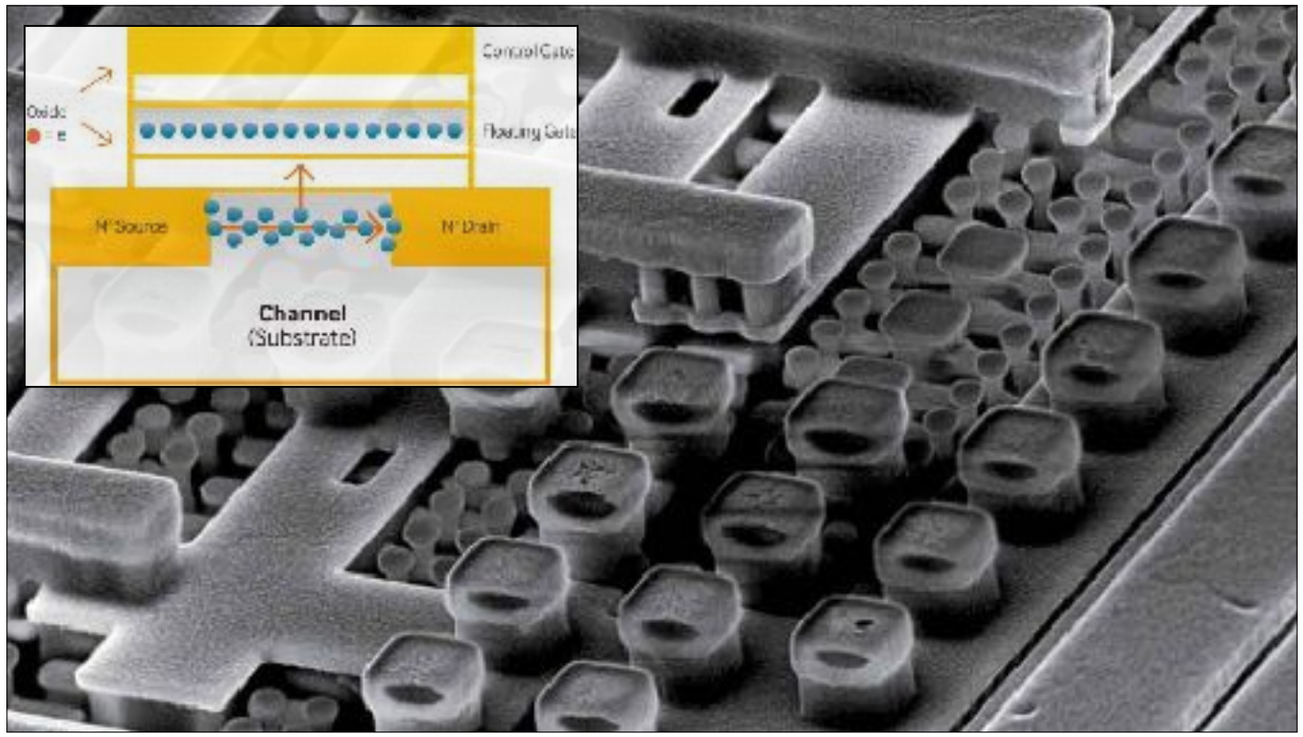
- Portable magnetic disks include large and small floppy disks.
- Basically the platter of an HDD without the R/W head, motor, etc. (that stuff goes in the disk drive).



- Optical disks around for decades (e.g. LaserDisc) but not popular until the 90s.
- Laser reflects off a "land" surface filled with non-reflective "pits".
- Trick question: which are the 1s and 0s?
  - Actually, a pit-to-land or land-to-pit *change* is a 1, and no change = successive 0s.
- Downside: hard to change the physical holes.

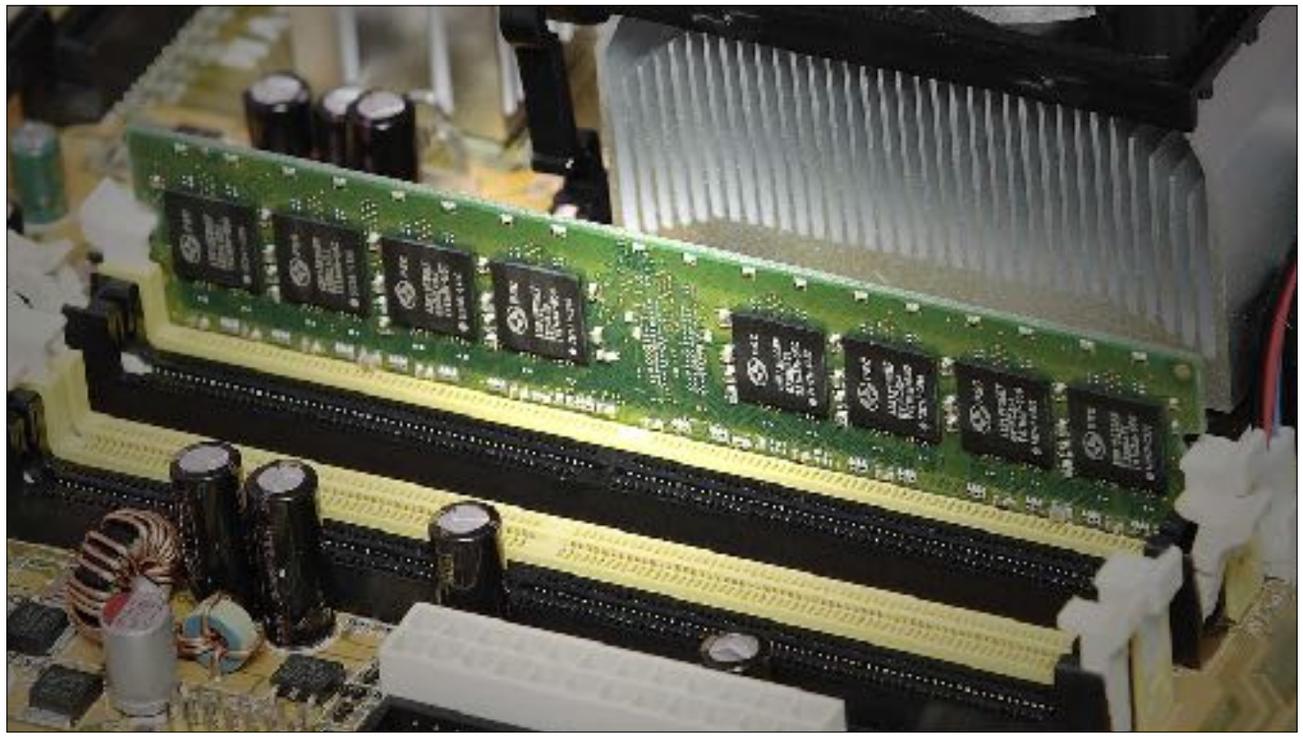


- As the 2000s wear on, solid-state or “flash” memory becomes more economical.
- Originally popular in small camera storage cards & USB sticks.
- Only recently that persistent flash memory has become affordable & large enough for computer drives.

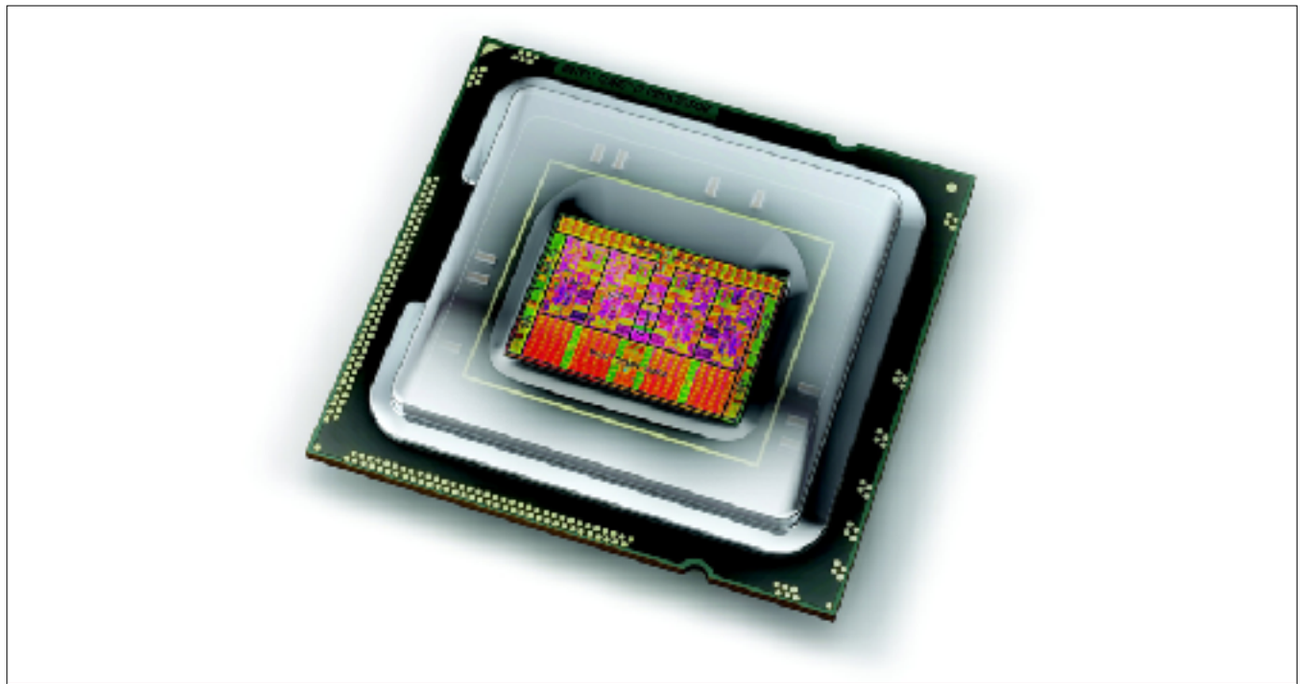


- Solid State Drives (SSDs) have no moving parts; just micro-circuitry.
- Store bits in “floating gate” transistors (**electron traps**), which can store charge for years without power.
- More shock-resistant and far faster than HDDs with moving parts.
- Downsides: poor R/W longevity, complex controller firmware, expense, etc.

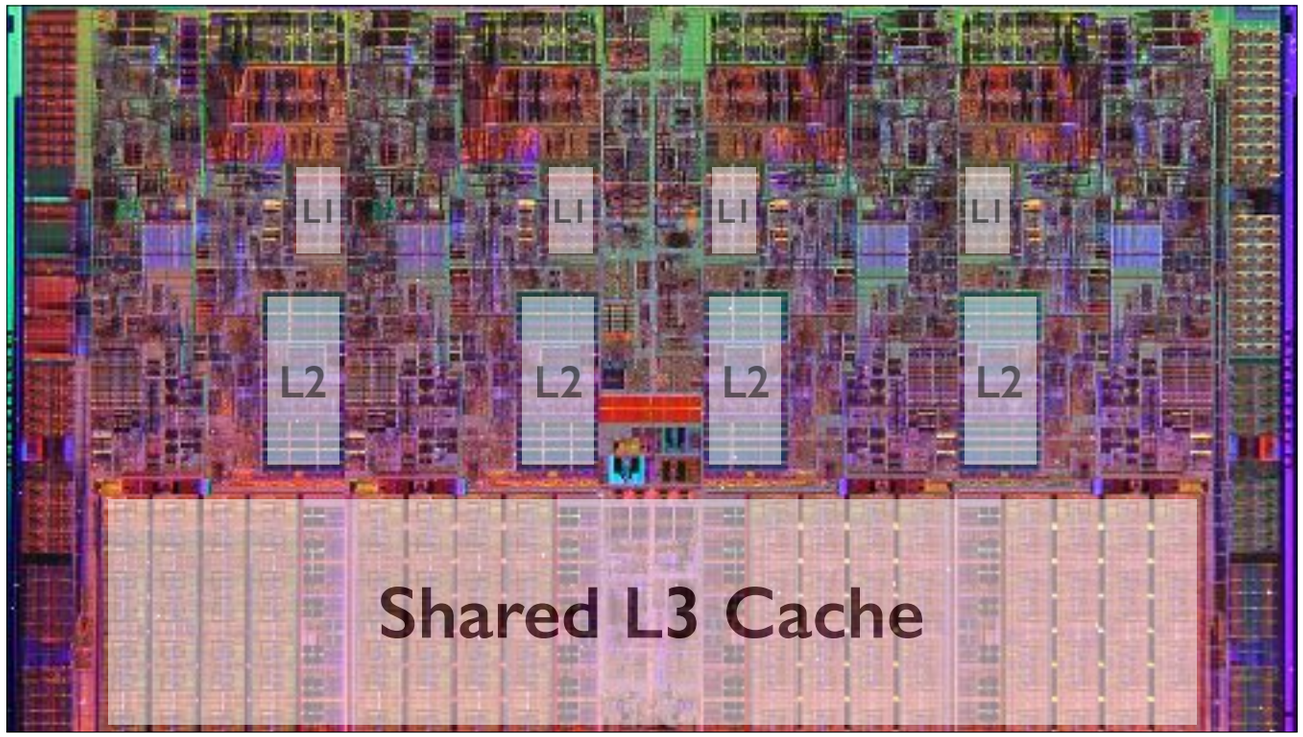
- Tape, HDDs, SSDs = storage: big amounts of data in a "safe" (persistent, non-volatile) place.
- Metaphor: storage is like filing cabinet (big, far, slow), memory like desk (close, fast, small).



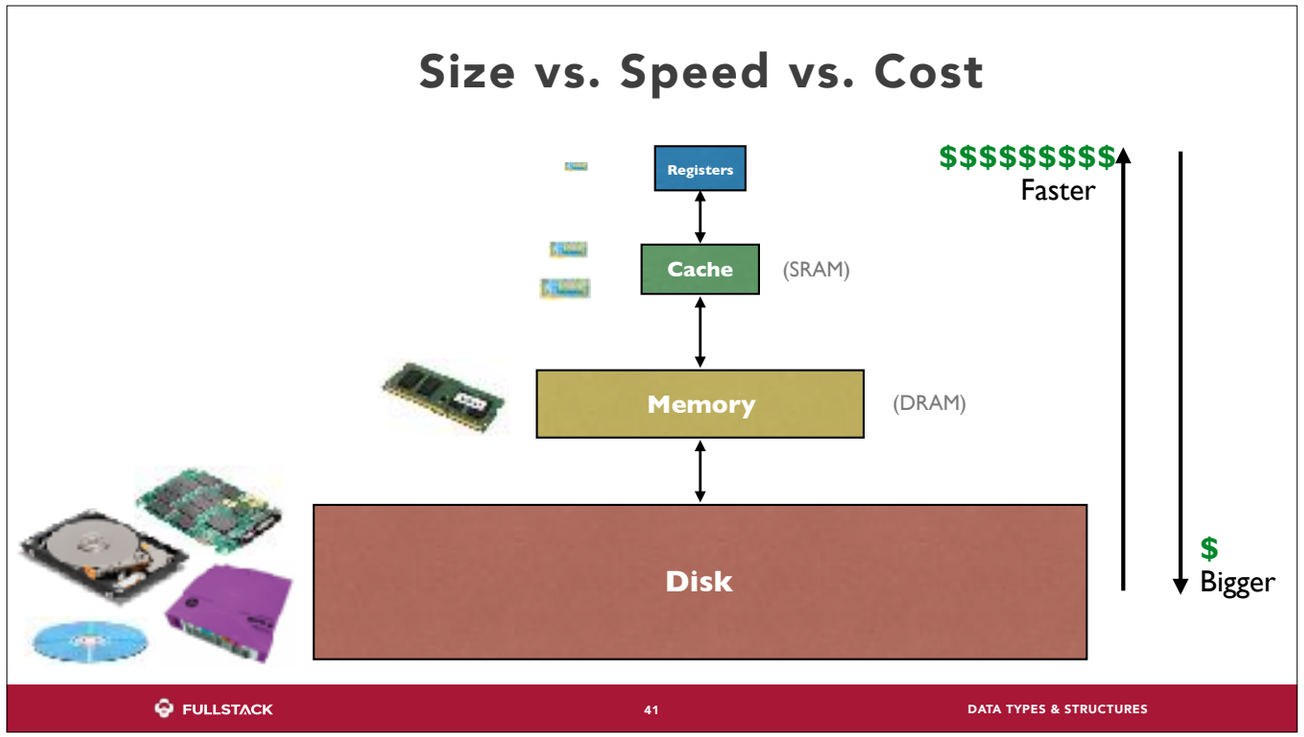
- A stick of DRAM (Dynamic Random Access Memory).
- Stores bits in tiny capacitors (not electron traps)
  - "leaky" — lose their bit if not constantly recharged (like, every millisecond). We call this *volatile*.
  - However, faster than SSDs (capacitors quicker to change than electron traps).
- Processes (running programs) loaded into RAM because far faster than storage.



DRAM is pretty fast, but still hundreds of times slower than a CPU. So directly on the CPU die are a number of even *faster* data buckets.



- SRAM (static RAM) caches (L3, L2, L1 -> increasing speed, decreasing size)
  - Made entirely using transistors — no capacitors or traps. But takes six transistors per bit (expensive!).
  - Still volatile — transistors are only on/off because of applied voltage. No voltage = no bits.
  - Caches improve access speed for files predicted to be needed by the CPU.
- *Registers* are the smallest and fastest bucket: what the CPU can actually perform operations on.
  - The register size (+ data buses, etc.) limits how the CPU can address memory or perform math.
  - ~2000, CPUs mostly 32-bit; now mostly 64-bit. Called a "word" in computer architecture.



- The memory hierarchy has as much to do with cost as with speed.
- Registers hold a handful of variables on a CPU - this is like having a desk of books, its easy to pick any up.
- The cache is a little bigger, but a little slower. It’s like a bookshelf in your room.
- Memory is a lot bigger than the cache, but also even slower to access. Memory is a library a few blocks away.
- The Disk is MASSIVE, but also VERY SLOW. It is like the library of congress, but stored on the moon.
- Luckily, you probably won't ever have to worry about this - Operating System makes sure the data you need to access next is (hopefully) somewhere close by.

"Must Go Faster"

Medium	Typical Size (bytes)	Approx. Access Time
CPU Register	64 bits = 8	one cycle < 1 ns
L1 Cache	64 000	4–5 cycles ≈ 2 ns
L2 Cache	256 000	~12 cycles ≈ 5 ns
RAM	8 000 000 000	70 ns
Solid State Drive	256 000 000 000	100 000 ns
Hard Disk Drive	1 000 000 000 000	12 000 000 ns
Optical Drive	650 000 000	150 000 000 ns
Tape Drive	8 000 000 000 000	60 000 000 000 ns
Network	a big truck?	6e7 – inf∞ ns

"Memory"
primary storage
("non-blocking")
volatile
(goes away if
power off)

"Storage"
secondary storage
("blocking")
non-volatile
(persists even
without power)

- A modern CPU might operate at 2 to 4 GHz; that's 0.5–0.25 ns per cycle.
- Storage cannot hope to keep up, so the CPU will be starved for data.
- The storage-memory distinction is somewhat artificial, based on speed and volatility.
- The CPU can access *main memory*
  - the *register* directly
  - *caches* to improve latency
  - *RAM* for most running processes.

If 1 byte = 1 mL and 1 clock cycle = 1s

Medium	Typical Size (bytes)	Approx. Access Time
CPU Register	8 mL (1.5 tsp)	1 s (on page)
L1 Cache	64 L (17 gallons)	2 s (on desk)
L2 Cache	256 L (2 barrels)	5 s (in a pile)
RAM	8k m^3 (3 pools)	1 min (downstairs)
Solid State Drive	256k m^3 (Hindenburg	1 day (other city)
Hard Disk Drive	2m m^3 (Pyramid)	4 months (Mars)
Optical Drive	650 L (5 barrels)	4.8 yrs (Pluto)
Tape Drive	8 m^3 (Chagan Lake)	2 millennia (stars)
Network	planet?	maybe Alpha C., never?

"Memory"
primary storage
("non-blocking")
volatile
(goes away if
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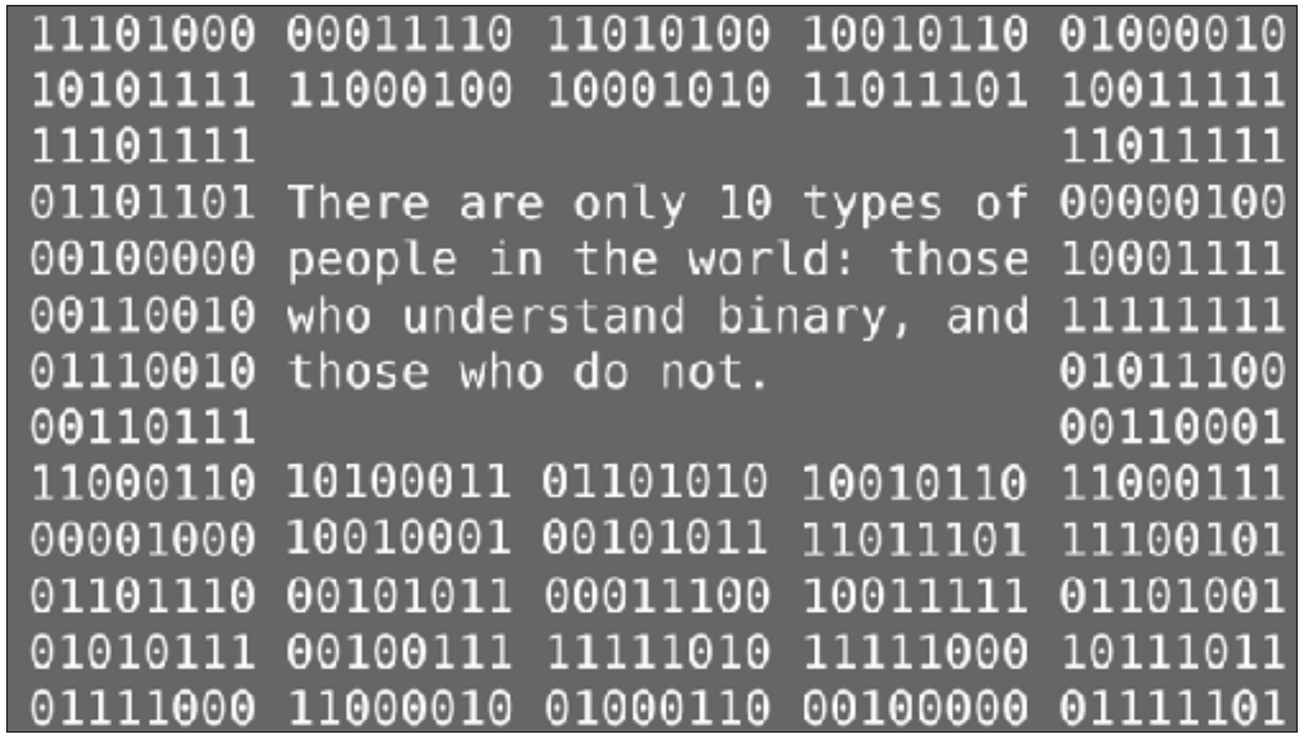
Part II:
Representations & Encodings

So we have storage of physical bits. But how do bits translate to useful information? We've already talked about Boolean values, which may be encoded in a single bit. What else?



Instead of boolean logic values (T/F), bits can of course represent ones and zeroes. Ones and zeroes are not very interesting as far as data goes, but with just ones and zeros you can represent *numbers* — via binary notation.

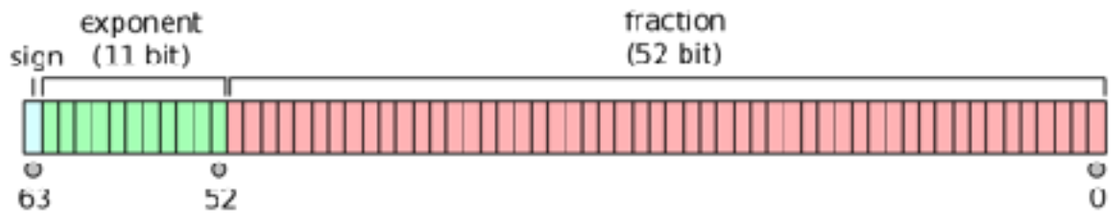
Using {0, 1} to Represent [0, 255]

Physical State	OFF	ON	ON	OFF	OFF	ON	ON	OFF
Binary Notation	0	1	1	0	0	1	1	0
Order of Magnitude	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Decimal Value	128	64	32	16	8	4	2	1
Applicable Value	0	64	32	0	0	4	2	0
Total Decimal Value	102 = 64 + 32 + 4 + 2							

Why right to left? Because we took numbers from Arabic. They write 100 (show R-L, "0" "0" "1") — we borrow the same numbers, but we inscribe them as we write from left to right (going down powers). More natural to do it the Arabic way (write increasing powers) but imagine the confusion if the final visual result was opposite across cultures. [Show on whiteboard / Wacom]. This problem of order is known as “big-endian” vs “little-endian.” Anyway, 8 bits as shown here is conventionally called a “byte.” This begs the question — how many bits should we use to store a number? Can be anything, but clearly one "word" is a good size.

So we have a basic way to represent the Natural numbers {0, 1, 2 …}. But how can we deal with negative numbers, or fractions? In general, the Rational numbers?

IEEE 754: Floating-Point Signed Double



- **64 bits total — "*double*" the previous 32-bit word size**
- **52 bits for the *fraction* of the *significand* (with an implicit "1" bit)**
  - Decimal example: in 1.5204 x 10^4, the *fraction* is 5204
- **11 bits for the *exponent* — where the *bicimal point* should *float* to (order of mag.)**
  - Many special rules – encoding patterns for ± 0, ± infinity, NaN, etc.
- **1 bit for *sign* (0 positive, 1 negative)**

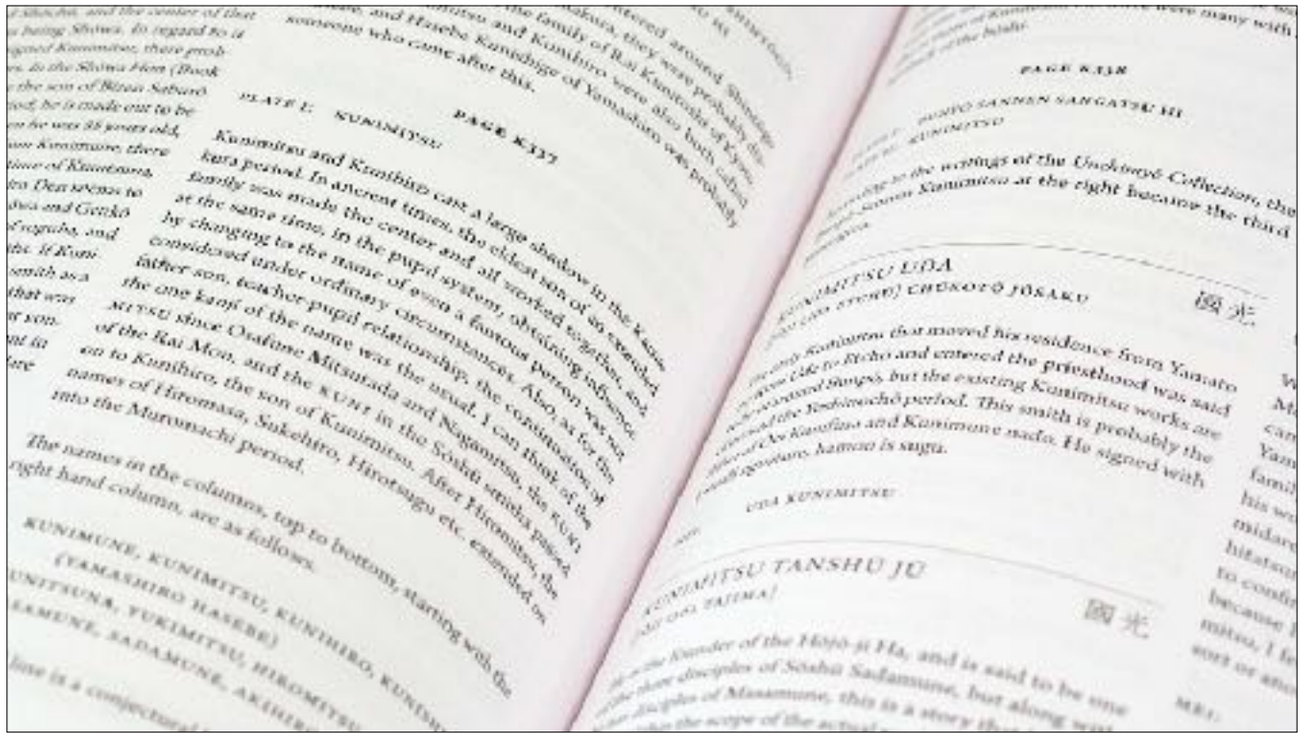
Don't panic, we are not testing you on this! With just numerals, we can only represent integers and SOME rational numbers. But using a bicimal point and a good number of digits we can get close to any rational. **DEMO**: 0.1 + 0.2 in console. 0.1 decimal in binary is 0.0001100110011001100.… Side note: all fixed-length binary can be represented as fixed-length decimal (with enough digits), but not always reverse. Example of a base-n val that cannot be expressed in decimal: 1/3 (0.1 in base 3, 0.333333333… in base 10).

Hexadecimal Notation

Hex. digit	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
Dec. notation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bin. notation	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111

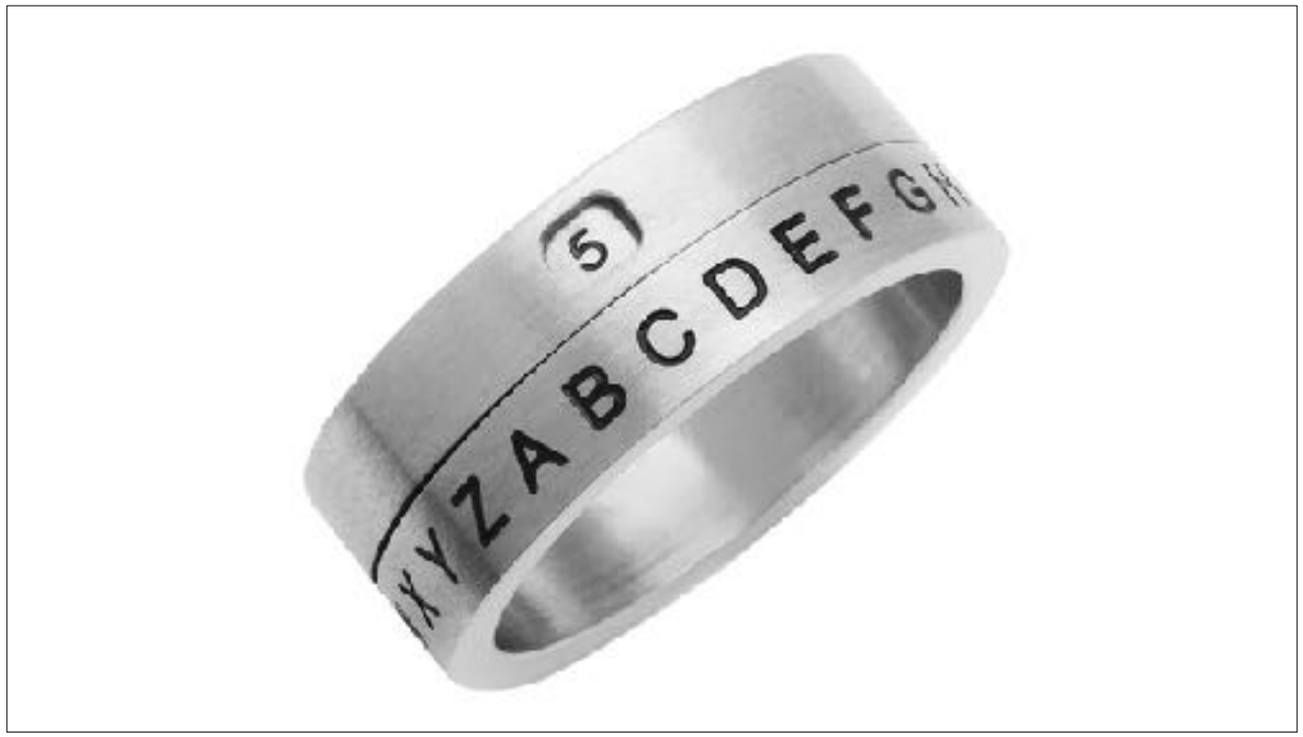
- Base-16: uses sixteen different digits per "place" (order)
- To avoid ambiguity: prefaced 0x or U+ or #, or subscript$_{16}$
- Much easier to convert b2 to/from b16 than to/from b10
- Example: what is 0x2a (i.e. $2a_{16}$, U+2a) in b2? 10111001 in hex?

Don't panic, we are not testing you on this! For more compact representations of values, e.g. memory addresses, programmers often use base-16. The advantage vs. base-10 is that conversion to and from base-2 ends up being much easier. A quick exercise for you and your neighbor: what is 0x2a in base-10? Solution: 2 sixteens + "a" ones = 32 + 10 = 42 (aka the answer to everything). What about base-2? Answer: just concat binary "quartets": 0010 followed by 1010 => 101010.



Numbers are great, but what if we want to store something a little more communicative… like text?

At least one solution from the 1840s: Morse. An electronic, binary representation of text. Patterns of dots and dashes correspond to letters. Based more on the physical demands of hitting a switch (common letters used fewer bits; E is just "dot") than on anything more meaningful.



Now that we have binary integers, it's far more convenient to think in terms of numbers rather than arbitrary bits. We can use an agreed-upon *encoding scheme* that maps letters to/from numbers.

ASCII

- American Standard Code for Information Interchange (1960s)
- 7-bit unsigned integers (stored in 8 bits) = 128 chars… +?

Binary	Decimal	Glyph	Binary	Decimal	Glyph
0010 1110	46	.	0011 1010	58	:
0010 1111	47	/	0011 1011	59	;
0011 0000	48	0	0011 1100	60	<
0011 0001	49	1	0011 1101	61	=
0011 0010	50	2	0011 1110	62	>
0011 0011	51	3	0011 1111	63	?
0011 0100	52	4	0100 0000	64	@
0011 0101	53	5	0100 0001	65	A
0011 0110	54	6	0100 0010	66	B
0011 0111	55	7	0100 0011	67	C
0011 1000	56	8	0100 0100	68	D
0011 1001	57	9	0100 0101	69	E

Don't panic, we are not testing you on this! ASCII from teleprinter code used at Bell. Lots of obsolete control characters now. Spec'd for 7 bits, but stored in 8-bit bytes; the "extra" bit has been used for myriad purposes (language-specific, extra glyphs, checksums), causing compatibility problems. Side note, number glyphs are 011 + binary representation, caps are 100 + binary order, lowercase are 110 + binary order. DEMO: `['data', 'Fullstack', 'Lecture', 'structures'].sort()`. Is JS using ASCII? Well, sort of, but not quite; we'll get to this a bit later.

UTF-8

- **U**niversal *Coded Character Set* + **T**ransformation **F**ormat – **8**-*bit*
- Handles every *code point* of **Unicode** (1.1M+; ~260K assigned)
- *Variable-width*: one to four 8-bit unsigned integers (*code units*)
- Superset of ASCII — backwards-compatible (best for web)

Glyph	Unicode Code Point	Code Unit 1: *singleton* or *lead*	Code Unit 2: *trail 1*	Code Unit 3: *trail 2*	Code Unit 4: *trail 3*
I	U+0049	0100 1001			
❤	U+2764	1110 0010	1001 1101	1010 0100	
J	U+004A	0100 1010			
S	U+0053	0101 0011			
😄	U+1F604	1111 0000	1001 1111	1001 1000	1000 0100

Don't panic, we are not testing you on this! 7-bit ASCII and even extended 8-bit ASCII are obviously not enough for really rich character encoding. Enter UTF-8, which encodes Unicode characters as one to four 8-bit *code units* per *code point*. This is the preferred scheme for web because it is backwards-compatible with ASCII; a UTF-8 file with only ASCII values is identical to an ASCII file. Variable-width encoding is more space-efficient than fixed-length.

• *Code point: an entity from unicode. For example, LATIN CAPITAL LETTER A. Listed as a hex value.*

• *Code unit: a byte which may make up all or part of the actual binary encoding for a code point.*

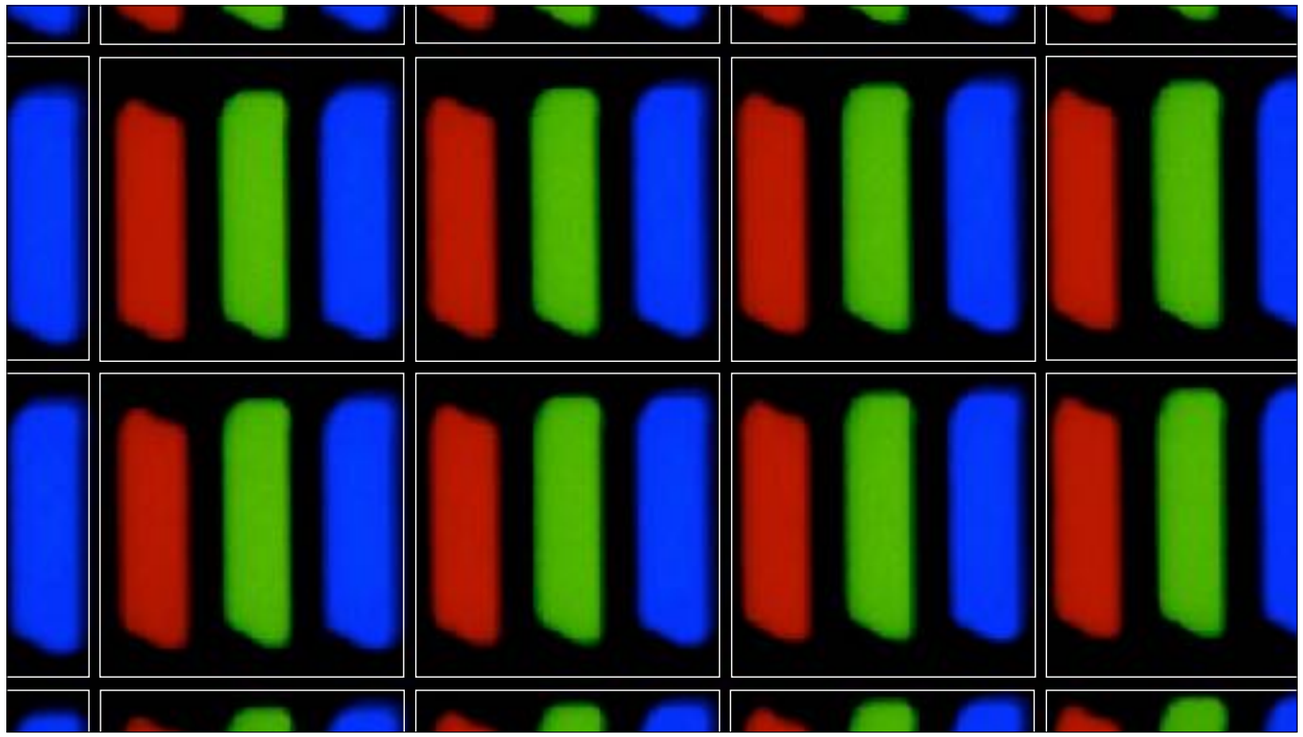
Good article: http://www.joelonsoftware.com/articles/Unicode.html

UTF-16

- Variable-width: one or two 16-bit unsigned integers
- Incompatible with ASCII (no 8-bit blocks)
- byte vs. word stream issues
- byte order ambiguity
- space inefficiency for most languages, even C/J html
- (Sort of) predated UTF-8, which is why stuff inherits it

UTF-16 has almost no advantage over UTF-8. When you have a choice, use the latter.

We have booleans (1 bit), signed floating-point numbers (including 64-bit), variable-length string encodings (e.g. UTF-8). What else? How about images?

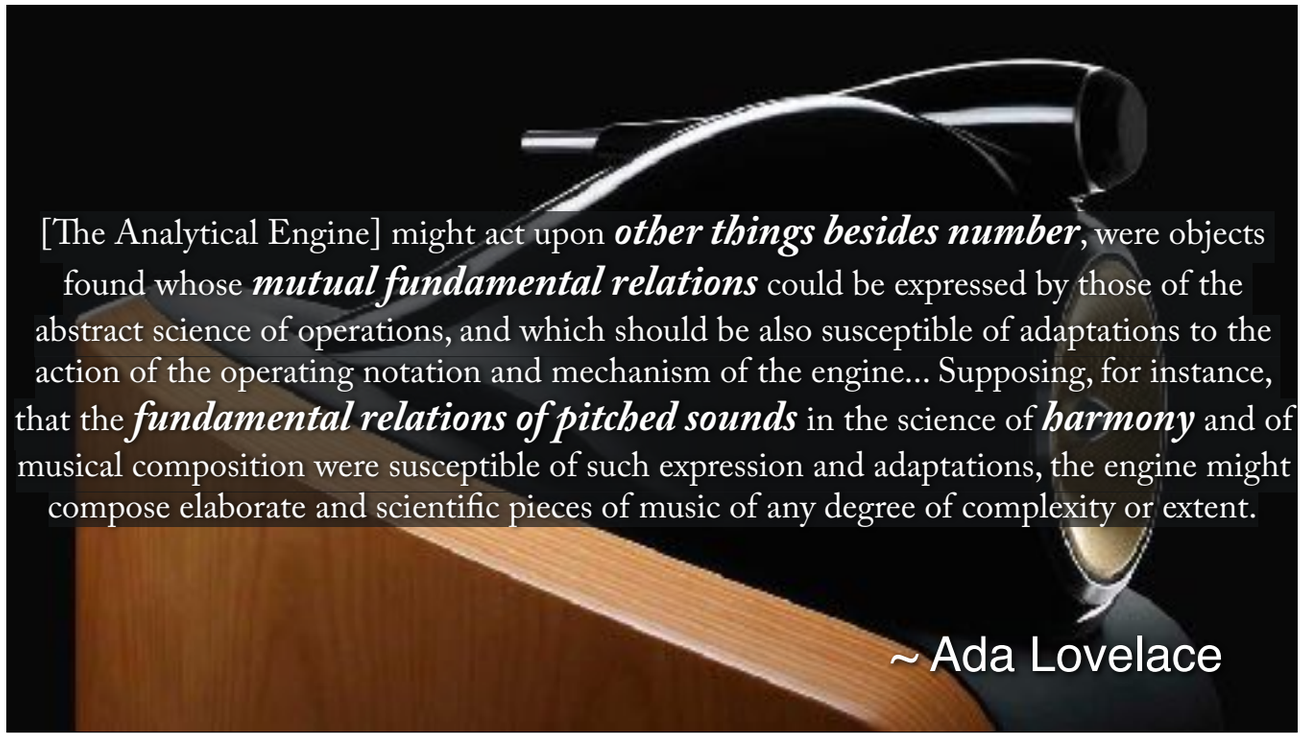


The human retina has three types of color-sensing cone cells, each with peaks at different wavelengths. Three separate colors added together (i.e. too close for the human eye to differentiate) are all that is needed to stimulate all three types of cells to variable degrees — producing the sensation of any color in the visible spectrum. Computer monitors are grids of pixels which each consist of RGB sub-pixels that can be adjusted to different brightnesses.

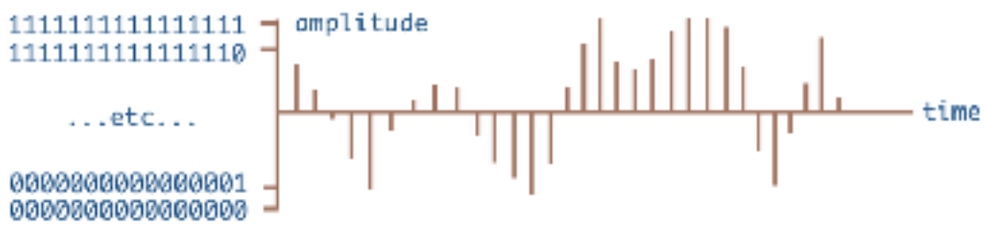
Image Encoding

- **Simple *bitmaps* are triads of 8-bit unsigned ints for RGB values**
- **8 bits makes 256 possible brightnesses per *channel***
- **"24-bit" (8 + 8 + 8) monitors have 256^3 = ~16.8M RGB distinct channel combinations ("colors").**
  - Since grayscale means RGB channels have to be the same, that's still only 256 possible B&W values.

When monitors talk about "bit-depth" they mean how many bits per color channel (R, G, and B); standard modern consumer monitor uses 8-bits per channel, resulting in ~16.8 million color combos. Surprise: many laptop screens are actually 6-bit, but use clever flickering mechanism (FRC) to simulate 8 bits by jumping back and forth between colors. This can result in odd patterns sometimes.


[The Analytical Engine] might act upon *other things besides number*, were objects found whose *mutual fundamental relations* could be expressed by those of the abstract science of operations, and which should be also susceptible of adaptations to the action of the operating notation and mechanism of the engine... Supposing, for instance, that the *fundamental relations of pitched sounds* in the science of *harmony* and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent.
~ Ada Lovelace

Audio Encoding



- Simplest is raw PCM (pulse-code modulation)
- 44,100 *samples* per second; each sample 16-bit *amplitude*
- Different amplitudes over time models an audio wave
- DAC converts values to speaker cone analog signal

705.6 Kbps mono, 1.411 Mbps stereo uncompressed

Part III:
Abstractions & Languages

[BREAK?]. We've established how bits are stored, how the CPU accesses them, and what kinds of things we can encode with them. But what's doing the encoding, and how can we take advantage of this?

Machine Code & Assembly

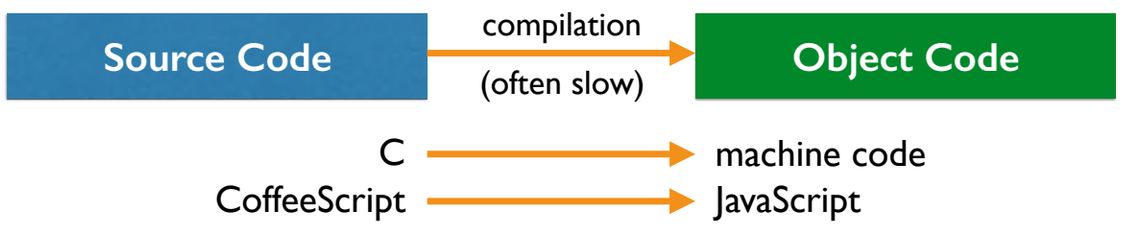
- Every CPU has its own *instruction set* — binary codes that trigger the CPU to perform operations on registers.

	op. code	source register	target reg.	destination reg.	shift amount	function type
instruction	000000	00001	00010	00110	00000	100000
hex	0x0	0x1	0x2	0x6	0x0	0x20
decimal	0	1	2	6	0	32
meaning	arithmetic	register 1	register 2	register 6	no offset	addition
English	*"take the value in register 1, add the value in register 2, place the result in register 6"*					
assembly	`add $t6, $t1, $t2`					

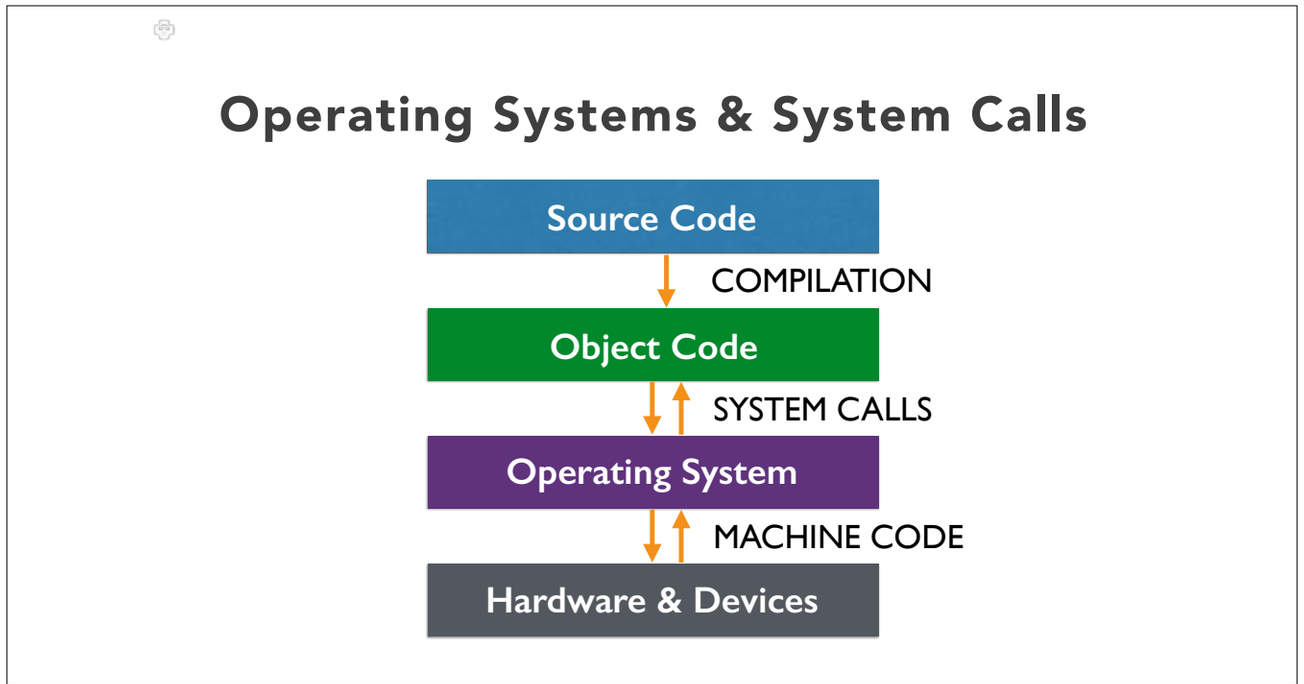
Raw numerical machine code is what ultimately drives all CPUs. Streams of binary words trigger a CPU to follow certain instructions (based on that CPU's instruction set). For example, in the MIPs architecture, this 32-bit code (00000000001000100011000000100000) tells the CPU to add up the values in registers 1 and 2 and place the result in register 6. Writing programs as a sequence of 1s and 0s is exactly as painful as you imagine, so people came up with *Assembly* languages — strings that "assemble" directly into machine instructions, with a 1:1 correspondence.

Compilers & Interpreters

- First compiler written in 1952 by Grace Hopper, for A-0.
- *"[She] helped teach the machines a language, stopped them from speaking in undecipherable numbers."* — 60 minutes
- Followed by Mark 1, FORTRAN, COBOL, etc.

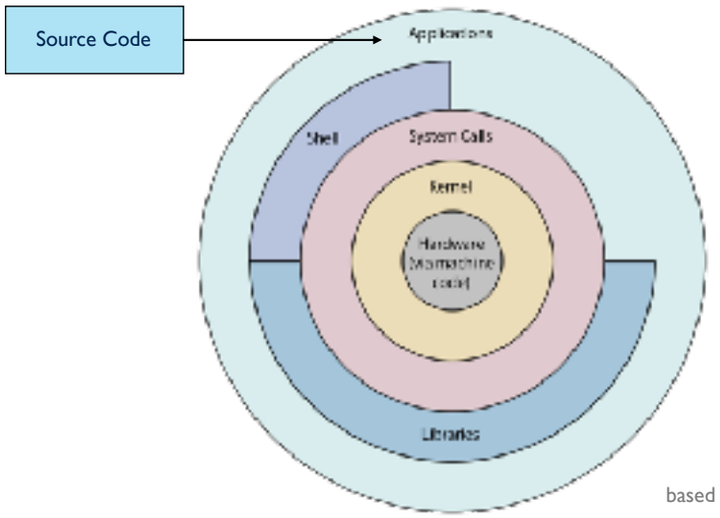


Assembly is still extremely laborious and error-prone — human beings don't think like abacuses. Compilers let programmers use human syntax which may then have to be converted into a series of dynamic machine codes (no more 1:1 correspondence). The distinction between compilation and interpretation is complex and blurry, but in general people think in terms of compiling ahead of time (resulting in a pre-optimized machine code file) vs. interpreting at run time (translating the code on demand). Compilers & interpreters allowed for the type of declarative programming languages we now all use. Compilation can also be from language A to B.



On a simple computer, pure object code might suffice. But that is somewhat restrictive. What if you want to manage running multiple programs simultaneously? Or access various 3rd-party hardware devices (like hard drives or graphics cards)? An *operating system* abstracts away and standardizes accessing hardware and running multiple programs by providing an API of *system calls* that binary code can use.

More nuanced / complex...



based on *Advanced Linux Programming*

Languages & Memory Management

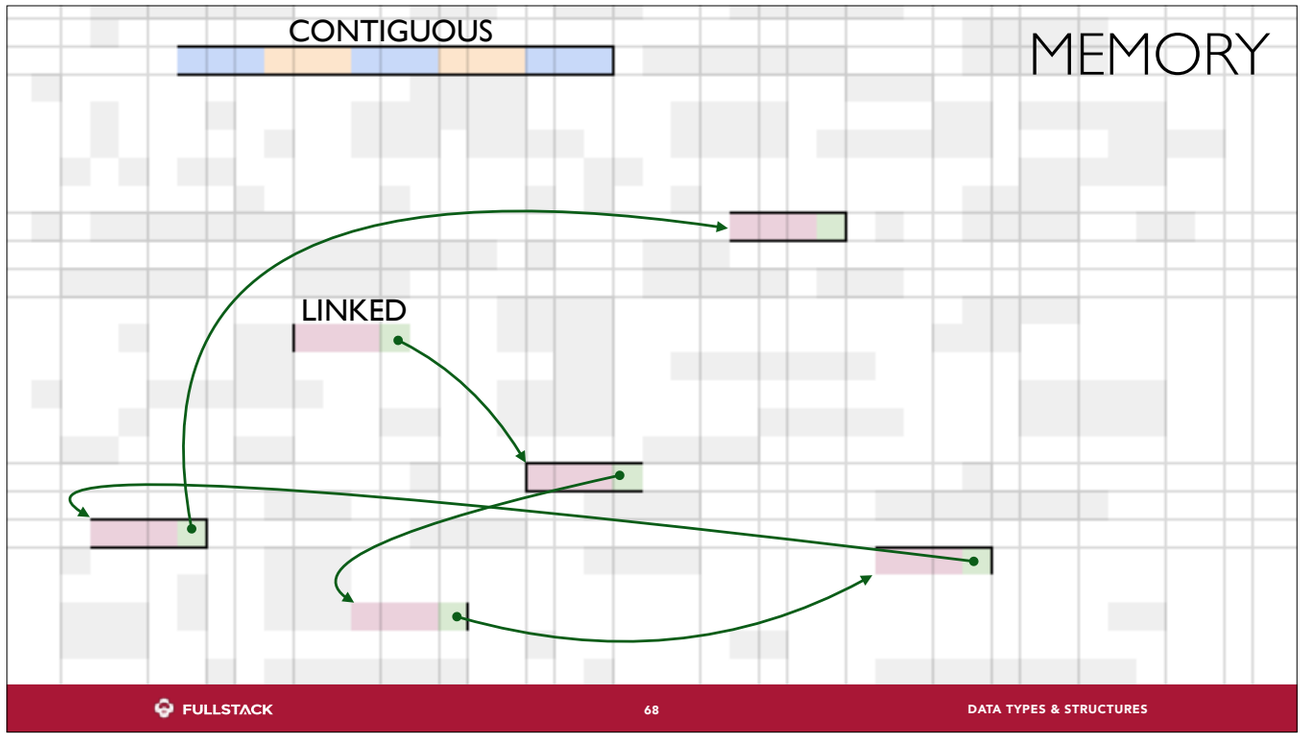
- Languages are a *specification*
- Compilers generate the real instructions to alter registers
- Some languages let you instruct the compiler to attempt to alter memory (C)
- Others only provide high-level *data types*, and it is up to the compiler/interpreter to figure out what to do (JS)

```c
char ch = 'c';
char t;
char *chptr = &ch;
t = *chptr;
```

```javascript
var ch = 'c';
var t = ch;
```


Note: even C programs may not be able to directly alter memory — if they are compiled to an executable for an operating system, what they really do is ask the OS to do various memory operations and the OS will oblige.

Part IV:
Abstract Data Types & Data Structures



Data structures can typically be stored either in one solid block (contiguous) or in many small blocks, each with a memory address for the next block (linked). What are some pros and cons of each approach? Contiguous pros: good physical locality of memory means faster in practice. No wasted space for memory addresses. Linked pros: infinite adding so long as there are open spaces big enough for element + address.

The Array Data Structure (non-JS*)

Pseudocode	Compiler/Intepreter	Memory
`vals = int8 Array(5)`	`` `vals` is 5 bytes at 0x3A6 ``	`_ _ _ X X X X X _ _ _ _`
`vals[0] = 9`	`put `9` at 0x3A6 + 0 = 0x3A6`	`_ _ _ 9 X X X X _ _ _ _`
`vals[3] = 4`	`put `4` at 0x3A6 + 3 = 0x3A9`	`_ _ _ 9 X X 4 X _ _ _ _`
`vals[2] // undef.`	`what is at 0x3A6 + 2 = 0x3A8`	`_ _ _ 9 X X 4 X _ _ _ _`
`vals[3] // 4`	`what is at 0x3A6 + 3 = 0x3A9`	`_ _ _ 9 X X 4 X _ _ _ _`

Now we'll take a look at a specific implementation of the stack — the fixed, typed array. In true arrays, data is stored sequentially in physical memory. Here we see a hypothetical array of 8-bit (1-byte) integers. Every time we access an index of the array, what the interpreter does is simply add that index arithmetically to the starting memory address of the array. Then it can go straight to that memory address. Notice: no matter which space we want to access, it takes the same ("constant") amount of time. Also, arrays have good "locality" — the data is all side-by-side in the physical machine. This aids in performance, e.g. for iterating through the array.

The Stack ADT

- Collection of elements
- Ordered
- Elements can repeat (not a set)
- Some example operations:
  - Make a new stack
  - Add an element to the stack ("push")
  - Retrieve an element from the list ("pop") - *must be LIFO (Last In, First Out)*
  - Check if stack is empty
  - Look at the top element without removing it ("peek")
  - Clear the stack

Stacks are useful for a couple key applications in programs. Remember the RPN calculator? Also very useful for backtracking (command-z, anybody?), holding old values waiting to be processed (*ahem*, call stack or recursion), etc.

The Stack ADT & Array DS

Stack Feature / Operation	Array Implementation with `top`
Collection of elements	Store values at memory addresses
Ordered	Sequential addresses maintain ordering
Create new stack	Initialize a new array
Push onto stack	Insert value at `top` var (next index to use)
Pop off of stack (LIFO)	Use `top` index to return latest value
Check if stack is empty	Return whether `top` variable is 0

By doing some minimal accounting using a variable (like `top`), we can implement the Stack ADT using a true array fairly easily. In fact, the `push` and `pop` methods of a JavaScript array basically use its `.length` property in a similar way. Thought: how performant is pushing and popping using an array to implement our stack? Well, we know that accessing an array element by index (either reading or writing) is a constant-time operation (i.e., it doesn't matter which index we use, it will always take the same time give or take). That's excellent!

ADTs vs DSs

Common Abstract Data Types	(Some) Data Structures
Set	List, Linked Tree, Trie, Hash Table, etc.
List	Linked List, Array
Stack	Array, Linked List
Queue	Linked List, Deque
Map (Associative Array / Dictionary / etc.)	Hash Table, Association List, Red-Black Tree
Graph	Adjacency List, Adjacency Matrix
Tree	Linked Tree, Heap

An ADT is a description of:
1. how information is related (e.g. ordered elements, connected elements)
2. operations we can perform on that information (e.g. add, remove, find)

A DS is a concrete, programmatic implementation of an ADT that determines:
1. how performant the operations actually are

WHAT ABOUT JS ?

Sorta-new concept: Built-In Types

- *ADT* or Abstract Data Type: describes the behavior we want
- *DS* or Data Structure: how to actually implement an ADT
- **Built-In Type: the building blocks provided by a given language**
  - language *might* specify an ADT: compiler authors decide what DS to use
  - language *might* specify a particular DS: compiler should (in theory) use it
  - or even something in between, like "the foo ADT but operation X must be constant time" (which strongly hints at a particular DS)

JavaScript Primitive (Immutable) Data Types

- `Undefined` · default for unassigned vars / nonexistent props
- `Null` · `typeof` is wrong; Null is a primitive, not "object"
- `Boolean` · could be 1 bit, but may not be *
- `String` · ES: engines use UTF-16 †
- `Number` · ES: 64-bit signed double float ‡
- `Symbol` · ES6: a unique token, can be key for objects

* often stored in a byte

† Spec can produce surprising results: `'🍺'.length === 2` . Astral plane characters are "surrogate pairs" of 16-bit code units: `'🍺' === '\uD83C\uDF7A'` . Mitigated in ES6 with Unicode point notation: `` `\u{1f37a}` ``.

‡ JS numbers are specified as 64-bit signed floats; IEEE 754 except that all distinct NaN are treated as a single NaN. HOWEVER, in V8 they are pairs of 32-bit numbers. Also, when using bitwise operators, spec says they should be treated as signed 32-bit twos-complement values.

° **Main point, the interpreter may be implemented in a variety of ways, so long as the behavior "seems" right; if someone asks you how JS data types are implemented, "it depends" is a pretty good answer.**

The JavaScript Non-Primitive Data Type

- `Object`
  - Mutable (can change)
  - Collection of *properties* – key-value pairs ("map")
  - Variable assignment copies reference, not value; it "points to" the object
  - Many other types are actually objects. Examples:
    - **Function**
    - **Array**
    - **Typed Array** (ES6-only)
    - **Regular Expression**, **Date**, others
    - Constructed primitives (**String**, **Number**, **Boolean**, etc.)

Demo — copying object refs, changing object, reflected in different places (vs. same for primitives). Also, demo constructed primitives.

pass by value (primitives)

```
let x = 5
let y = x
x = 8
y // 5
```

```
x → 8
y → 5
```

pass by reference (Objects)

```
let x = { age: 5 }
let y = x
x.age = 8
y.age // 8
```

```
x → { age: 8 }
y ↗
```

Live Demo:
Pass by Ref. vs. Pass by Value

Show primitive variables being changed and not affecting each other
Show values being passed into a function and which ones change vs. which don’t
Variables representing a single object in memory
Etc.


QUEUES &
LINKED LISTS

The Queue ADT

- Like Stack, except FIFO (First In, First Out)
- Collection of elements
- Ordered / sequential
- Operations:
  - Enqueue (add)
  - Dequeue (remove)
  - Peek
  - Clear
  - IsEmpty… etc.

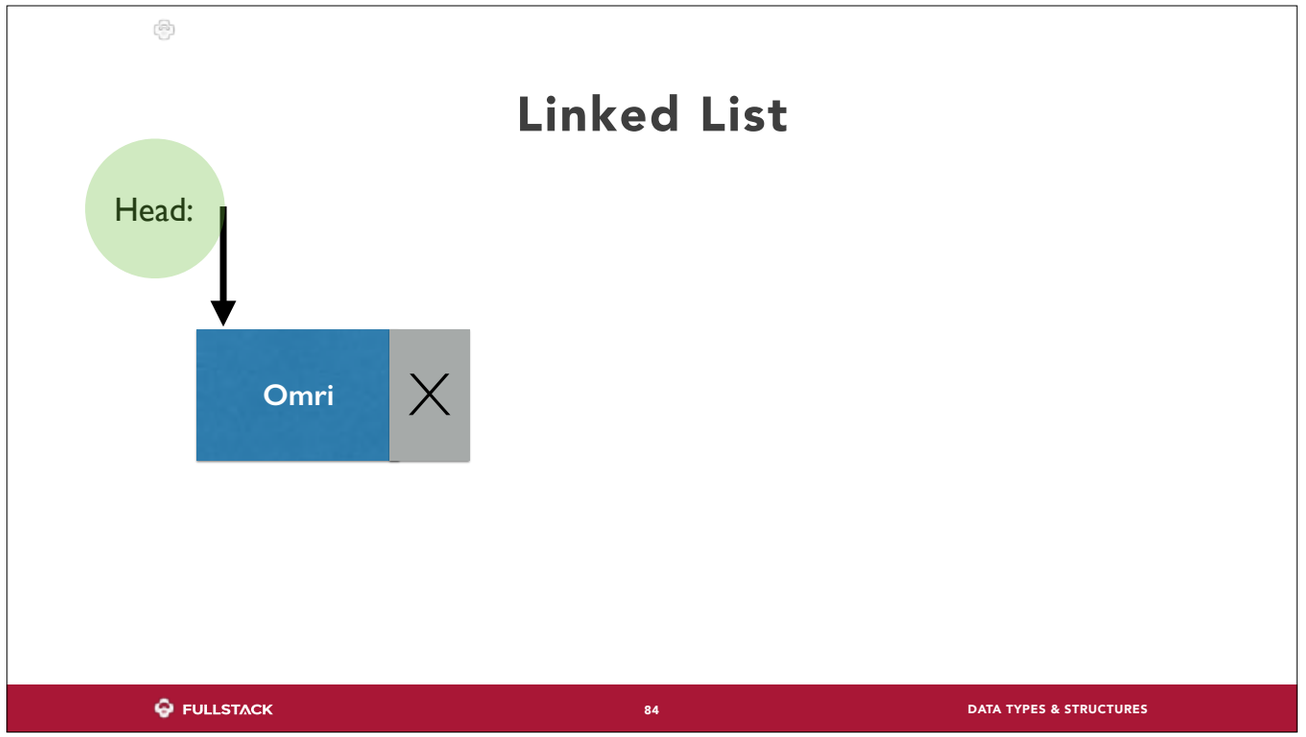
Queues are a natural fit for handling incoming values in a fair way (buffering). In the workshop today you will be implementing the Queue ADT, initially using JavaScript's "array" fundamental type. However, for the academic practice, treat those arrays like "true" arrays and do not use any of the built-in JS helper functions on `Array.prototype`. That means no push, pop, shift, unshift; also, do not use `.length`. The only thing you really have access to is indices. Note that since Queues are an ADT, not a DS, that implies there is more than one way to skin a cat.

The Linked List DS

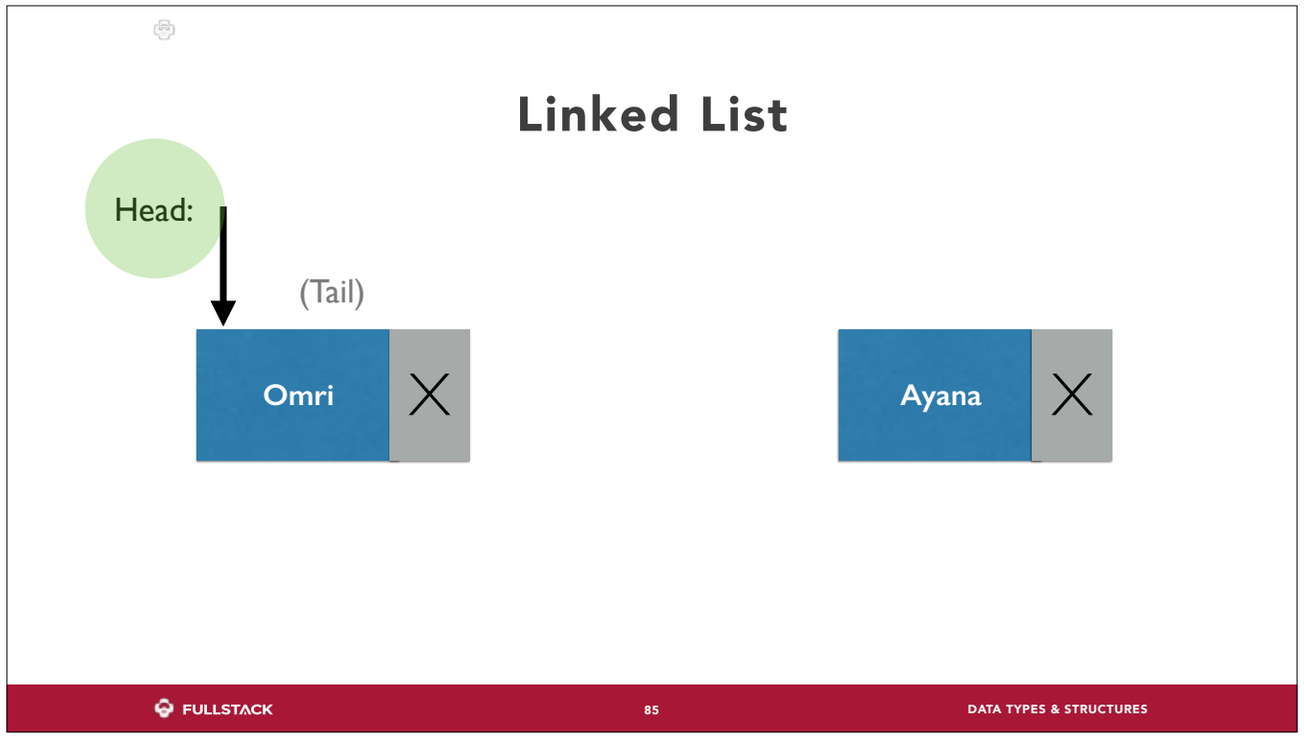
- Data structure used for *list, stack, queue, deque* ADTs etc.
- Uses *nodes* which encapsulate a value and pointer(s)
- Main entity holds reference(s) to just a head and/or tail node
  - the "handle(s)"
- Each node then *points* to the next and/or previous node
  - "singly-linked" (unidirectional) vs. "doubly-linked" (bidirectional)

Linked List

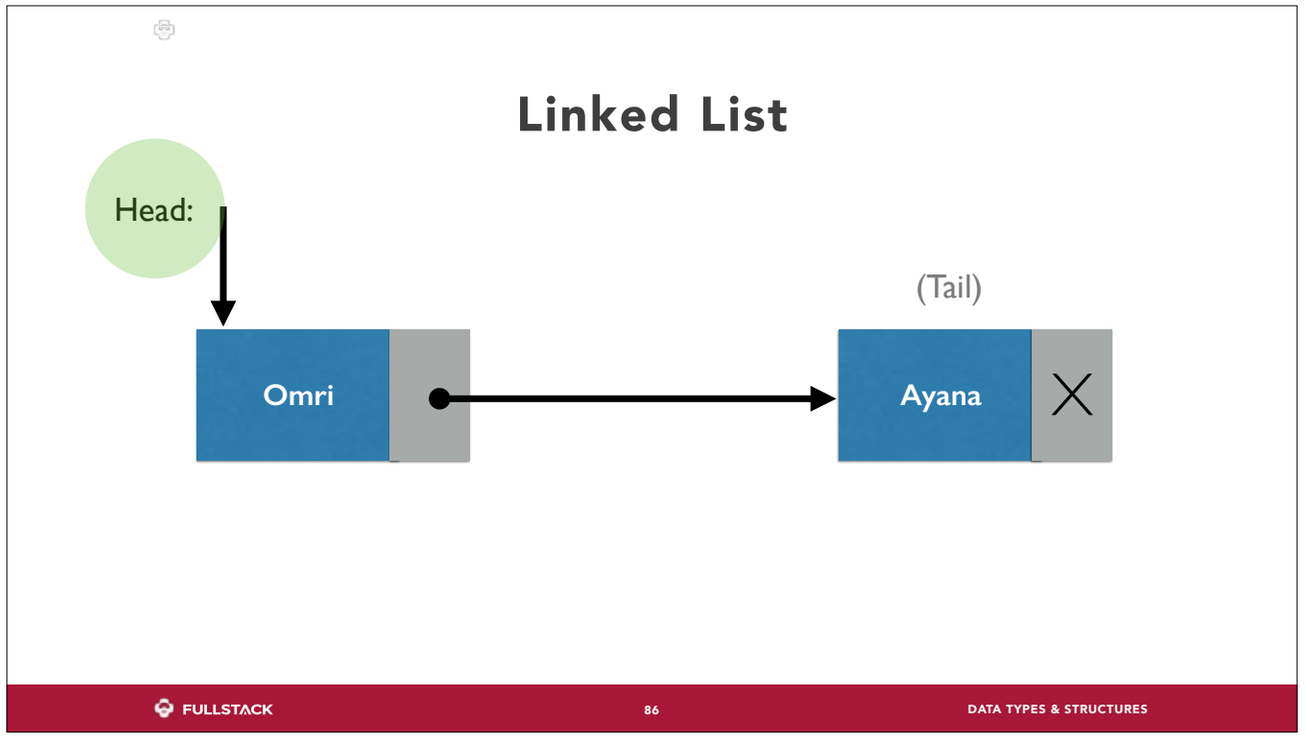
When it comes to implementations, the LinkedList is often considered synonymous with its handle or handles (in this case just an empty "head" reference).



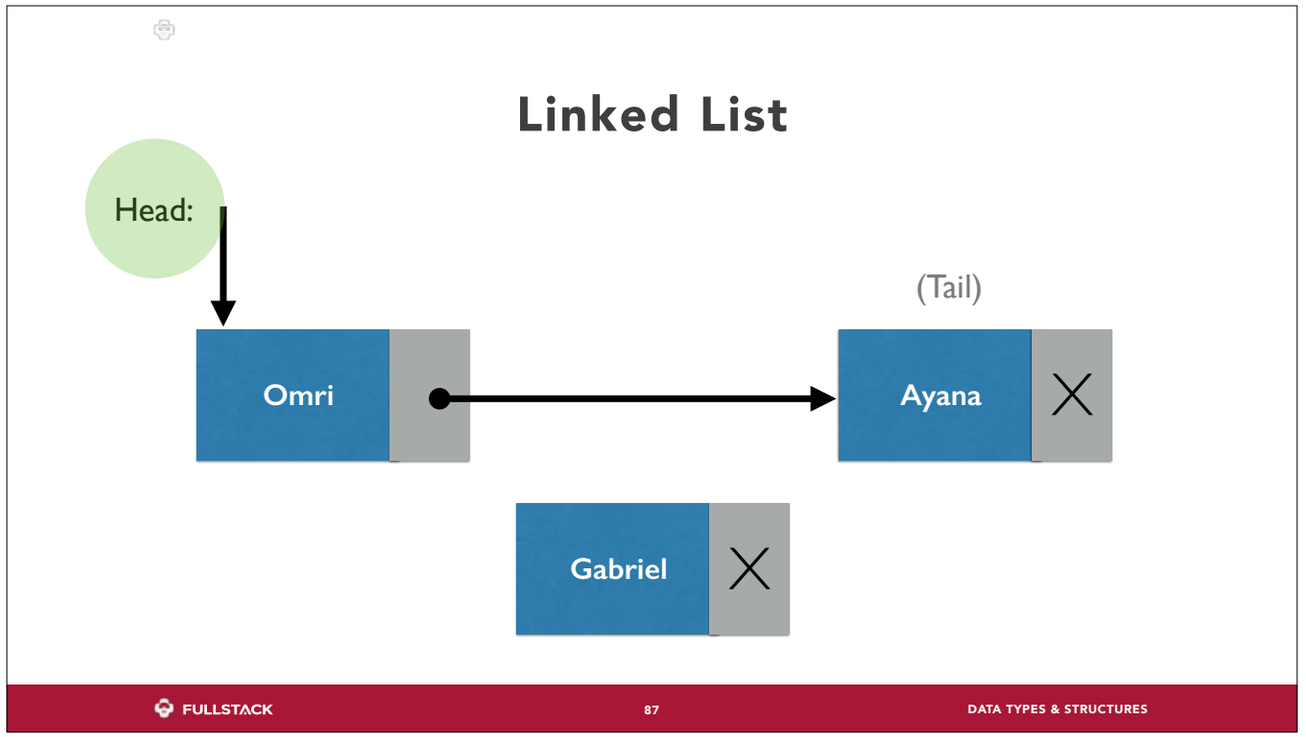
This is a Linked List containing one node. The node has a value (Omri) and an empty `next` pointer. In this case it only has one pointer (no `previous`) so this is going to be a singly-linked list.



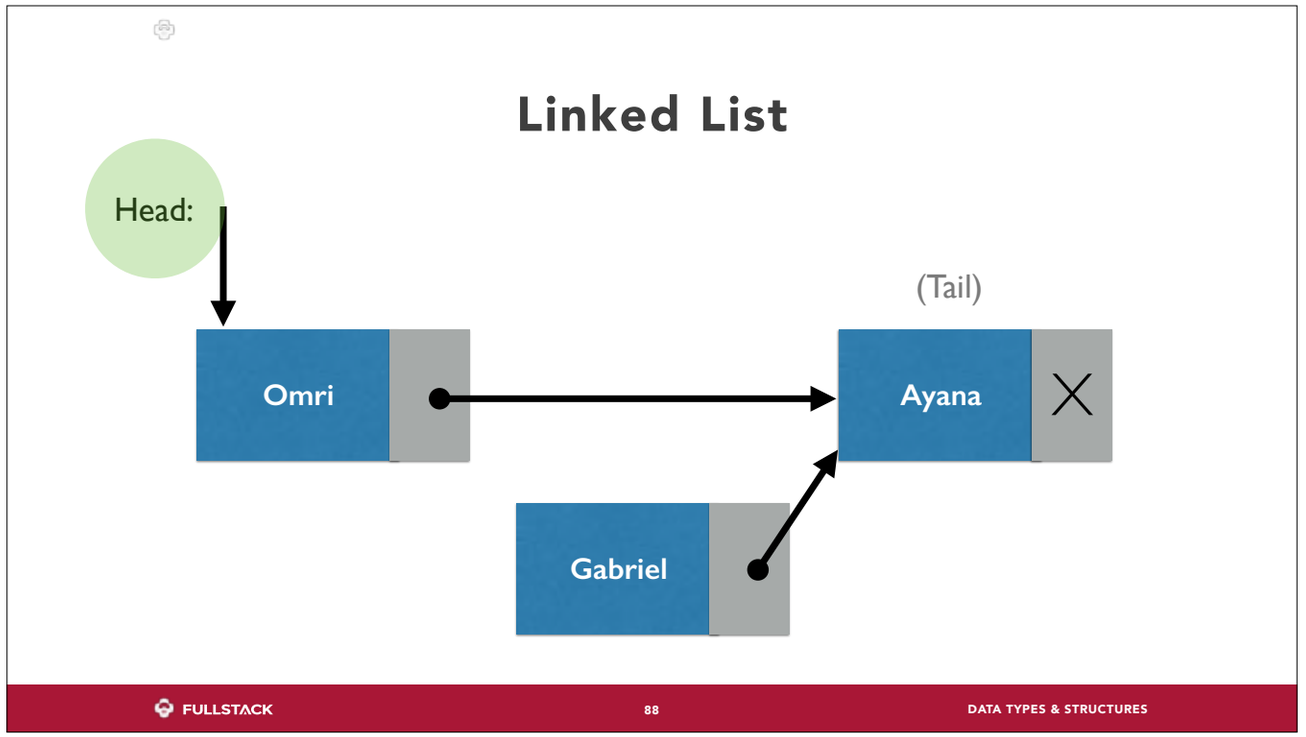
Partway through adding to the tail — we have created a new Ayana node, but it isn't connected to our list yet.



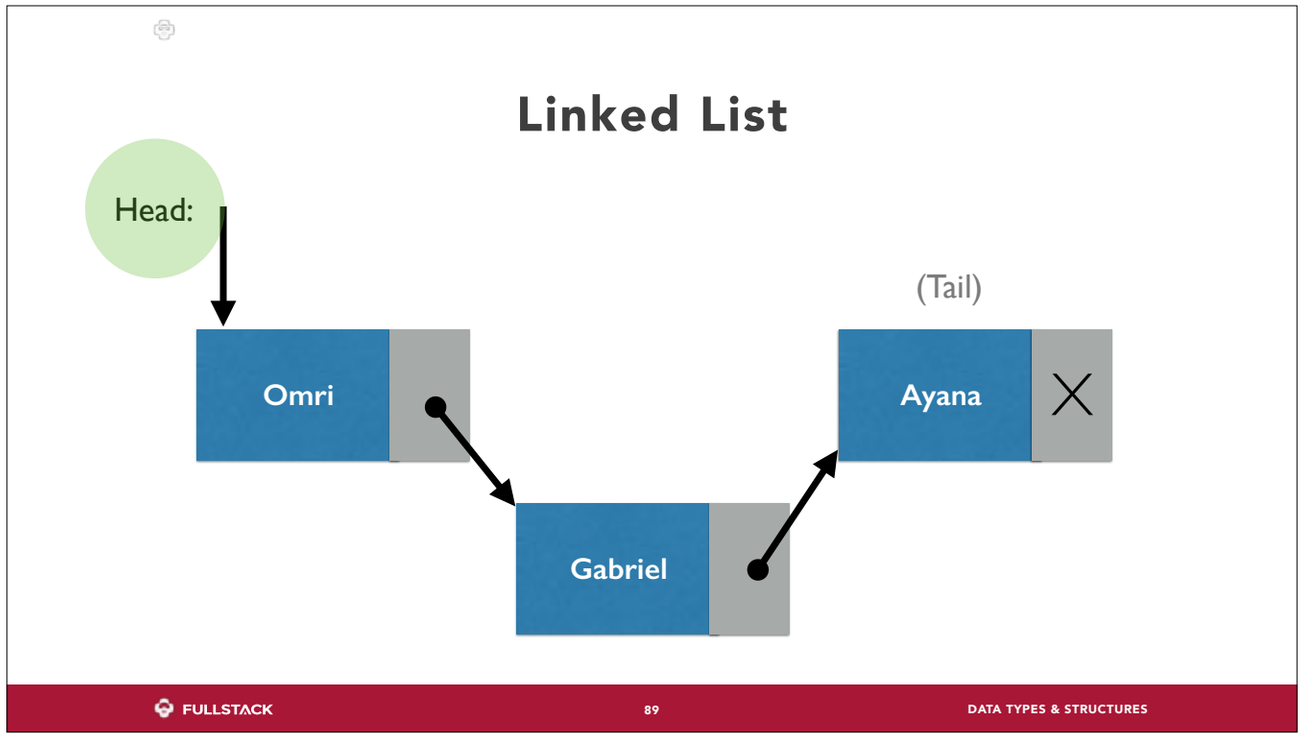
Set the Omri node's `next` pointer to the Ayana node, and we would say that Ayana is the new tail node. Can I get to Omri from Ayana? If I want to reach Ayana, I have to start at `head` and then follow `next`.



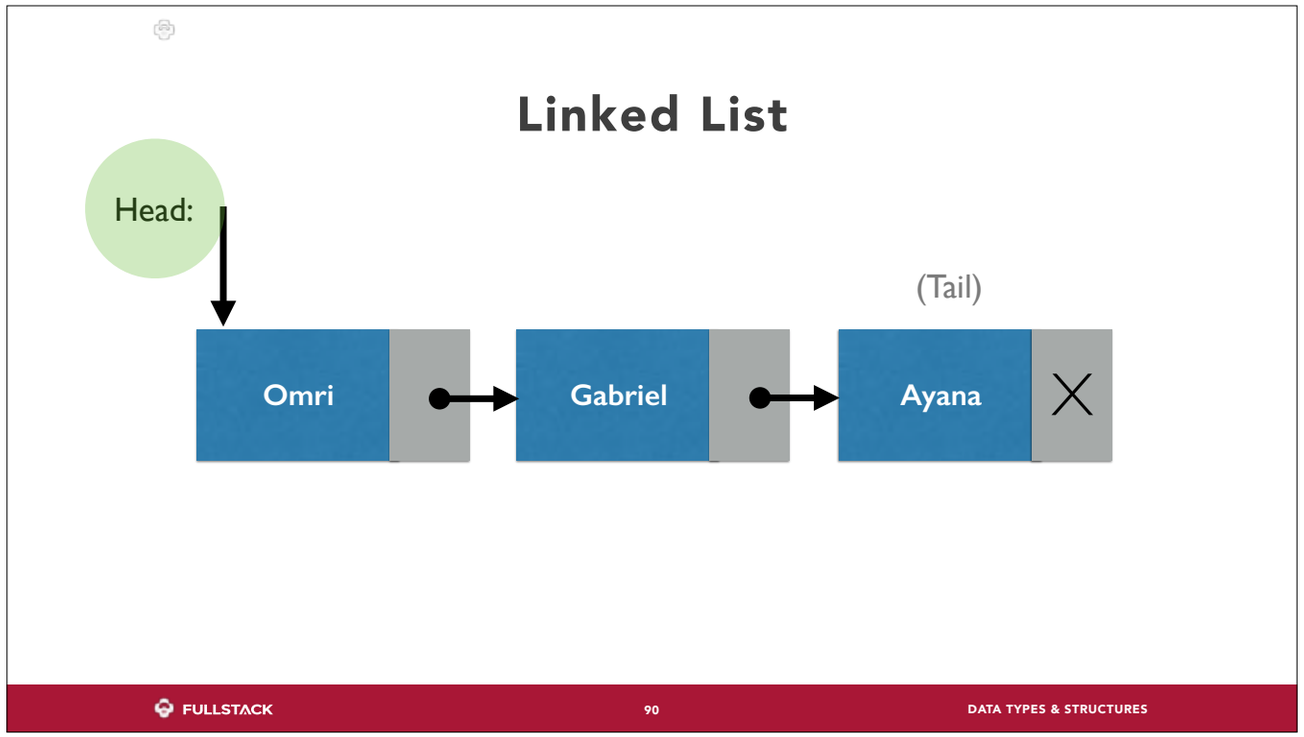
What if I want to add something in the middle of the list?



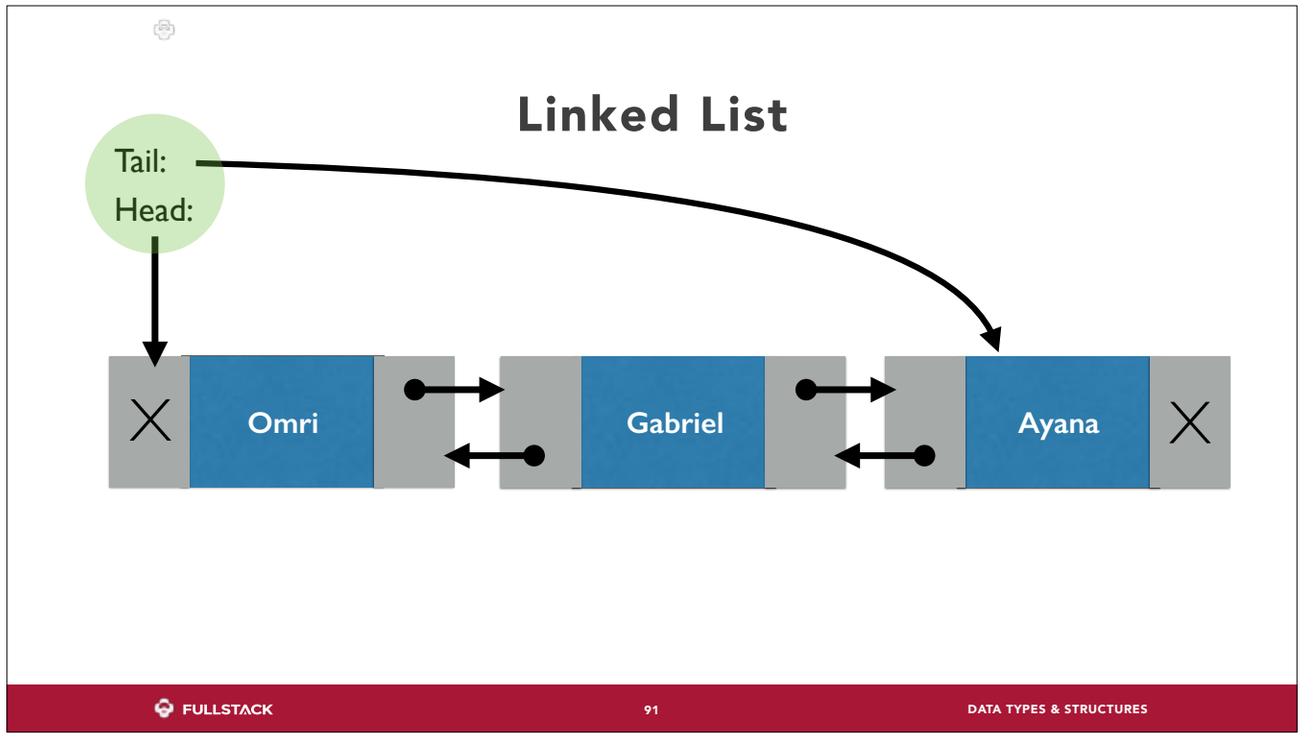
The best thing about Linked Lists is that *insertion* (adding in the middle) always takes the same number of steps, regardless of how big the list is. Again, we call that "constant time." First, point the new node's `next` to the old later node.



Then, change the previous node's `next` to point to the new node.


Linked List
Head:
(Tail)
Omri
Gabriel
Ayana
FULLSTACK
90
DATA TYPES & STRUCTURES

That's it!



Here is an example of a doubly-linked list with head and tail pointers. Think about the pros and cons of this approach.

(some) pros/cons: Linked Lists vs Arrays

Operation	Linked List	Typed Array
Reach element in middle	Must crawl though nodes	Constant time
Insert in middle or start	Constant time (if we have ref).	Must move all following elements
Add element to end	With handle, constant time	Constant time
Space per element	Container + element + pointer(s)	Just element!
Total space	Grows as needed	Pre-reserved & limited*
Physical locality	Not likely	Best possible

**Dynamic* arrays keep track of their limit, and if it is exceeded, the array is copied into a new bigger array (which is expensive but hopefully happens infrequently).

Part 1 of the workshop! Do Queues & Linked Lists. The next two specs — Hash Tables and Binary Search Trees — are part of the next phase, which we'll be doing tomorrow.