Inside the CPU

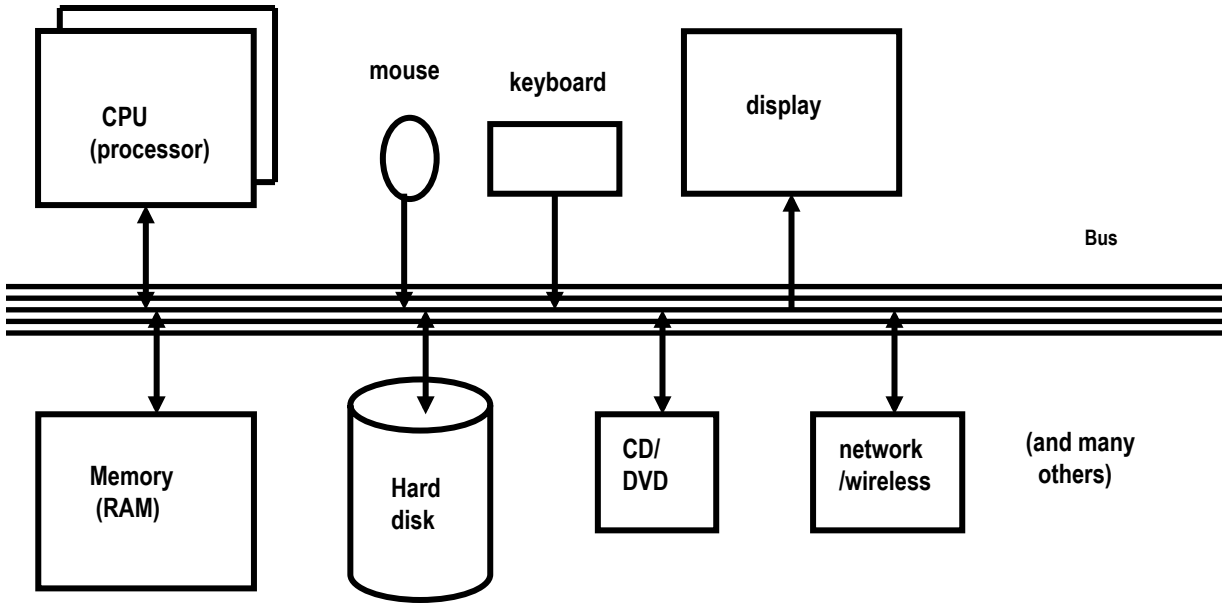
- **how does the CPU work?**
  - what operations can it perform?
  - how does it perform them? on what kind of data?
  - where are instructions and data stored?
- **some short, boring programs to illustrate the basics**
- **a toy machine to try the programs**
  - a program that simulates the toy machine
  - so we can run programs written for the toy machine

- **computer architecture: real machines**
- **caching: making things seem faster than they are**
- **how chips are made**
- **Moore's law**

- **equivalence of all computers**
  - von Neumann, Turing

Block diagram of computer

- **CPU can perform a small set of basic operations**
  - arithmetic: add, subtract, multiply, divide, …
  - memory access: fetch data from memory, store results back in memory
  - decision making: compare numbers, letters, …, and decide what to do next according to result
  - control the rest of the machine

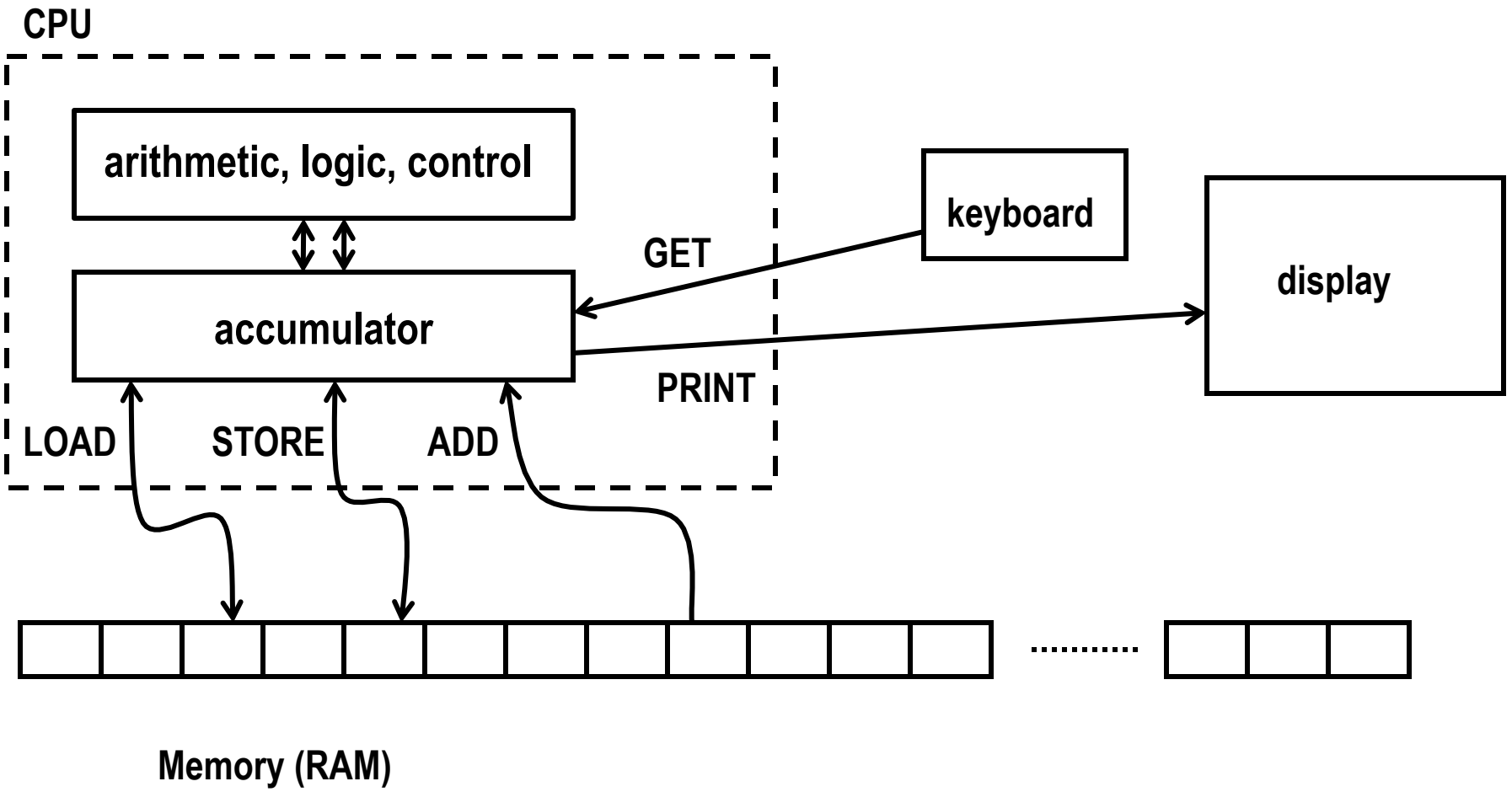


- **operates by performing sequences of very simple operations *very* fast**

A simple "toy" computer (a "paper" design)

- **repertoire ("instruction set"): a handful of instructions, including**
  - **GET** a number from keyboard and put it into the accumulator
  - **PRINT** number that's in the accumulator (accumulator contents don't change)
  - **STORE** the number that's in the accumulator into a specific RAM location (accumulator doesn't change)
  - **LOAD** the number from a particular RAM location into the accumulator (original RAM contents don't change)
  - **ADD** the number from a particular RAM location to the accumulator value, put the result back in the accumulator (original RAM contents don't change)
- **each RAM location holds one number or one instruction**
- **CPU has one "accumulator" for arithmetic and input & output**
  - a place to store one value temporarily
- **execution: CPU operates by a simple cycle**
  - FETCH: get the next instruction from RAM
  - DECODE: figure out what it does
  - EXECUTE: do the operation
  - go back to FETCH
- **programming: writing instructions to put into RAM and execute**

Toy computer block diagram (non-artist's conception)



A program to print a number

```
GET       get a number from keyboard into accumulator
PRINT     print the number that's in the accumulator
STOP
```

- convert these instructions into numbers
- put them into RAM starting at first location
- tell CPU to start processing instructions at first location

- CPU fetches GET, decodes it, executes it
- CPU fetches PRINT, decodes it, executes it
- CPU fetches STOP, decodes it, executes it

A program to add any two numbers

```
    GET             get first number from keyboard into accumulator
    STORE  NUM      save value in RAM location labeled "NUM"
    GET             get second number from keyboard into accumulator
    ADD  NUM        add value from NUM (1st number) to accumulator
    PRINT           print the result (from accumulator)
    STOP
NUM   ---           a place to save the first number
```

- **questions:**
  - how would you extend this to adding three numbers?
  - how would you extend this to adding 1000 numbers?
  - how would you extend this to adding as many numbers as there were?

Looping and testing and branching

- **we need a way to re-use instructions**
- **add a new instruction to CPU's repertoire:**
  - **GOTO** take next instruction from a specified RAM location instead of just using next location
- **this lets us repeat a sequence of instructions indefinitely**

- **how do we stop the repetition?**
- **add another new instruction to CPU's repertoire:**
  - **IFZERO** if accumulator value is zero, go to specified location instead of using next location

- **these two instructions let us write programs that repeat instructions until a specified condition becomes true**
- **the CPU can change the course of a computation according to the results of previous computations**

Add up a lot of numbers and print the sum

```
Start   GET             get a number from keyboard
        IFZERO Show     if number was zero, go to "Show"
        ADD Sum         add Sum so far to new number
        STORE Sum       store it back in Sum so far
        GOTO Start      go back to "Start" to get the next number
Show    LOAD Sum        load sum into accumulator
        PRINT           print result
        STOP
Sum     0           initial value set to 0 before program runs (by assembler)
```

Assembly languages and assemblers

- **assembly language: instructions specific to a particular machine**
  - X86 (PC) family; PowerPC (older Macs); ARM (cellphones); ...

- **assembler: a program that converts a program into numbers for loading into RAM**
- **handles clerical tasks**
  - replaces instruction names (ADD) with corresponding numeric value
  - replaces labels (names for memory locations) with corresponding numeric values: location "Start" becomes 1 or whatever
  - loads initial values into specified locations

- **terminology is archaic but still used**

- **each CPU architecture has its own instruction format and one (or more) assemblers**

A simulator for the toy computer

- simulator (a program) reads a program written for the toy computer
- simulates what the toy computer would do
- toy machine's instruction repertoire:

`get`	read a number from the keyboard into accumulator
`print`	print contents of accumulator
`load Val`	load accumulator with Val (which is unchanged)
`store Lab`	store contents of accumulator into location labeled Lab
`add Val`	add Val to accumulator
`sub Val`	subtract Val from accumulator
`goto Lab`	go to instruction labeled Lab
`ifpos Lab`	go to instruction labeled Lab if accumulator positive (>= 0)
`ifzero Lab`	go to instruction labeled Lab if accumulator is zero
`stop`	stop execution
`Num`	initialize this memory location to numeric value Num (once, before simulation starts)

if Val is a name like Sum, it refers to a memory location with that label;
if Val is a number like 17, that value is used literally

Summary

- **each memory location holds an instruction or a data value (or part)**
- **instructions are encoded numerically (so they look the same as data)**
  - e.g., GET = 1, PRINT = 2, LOAD = 3, STORE = 4, …
- **can't tell whether a specific memory location holds an instruction or a data value (except by context)**
  - everything looks like numbers

- **CPU operates by a simple cycle**
  - FETCH: get the next instruction from memory
  - DECODE: figure out what it does
  - EXECUTE: do the operation

    move operands between memory and accumulator, do arithmetic, etc.
  - go back to FETCH

Real processors

- **multiple accumulators (called "registers")**
- **more instructions, though basically the same kinds**
  - arithmetic of various kinds and sizes (e.g., 8, 16, 32, 64-bit integers):
    add, subtract, etc., usually operating on registers
  - move data of various kinds and sizes
    load a register from value stored in memory
    store register value into memory
  - comparison, branching: select next instruction based on results of computation
    changes the normal sequential flow of instructions
    normally CPU just steps through instructions in successive memory locations
  - control rest of computer
- **typical CPU has dozens to few hundreds of instructions in its repertoire**
- **instructions and data usually occupy multiple memory locations**
  - typically 2 - 8 bytes
- **modern processors have several "cores" that are all CPUs on the same chip**

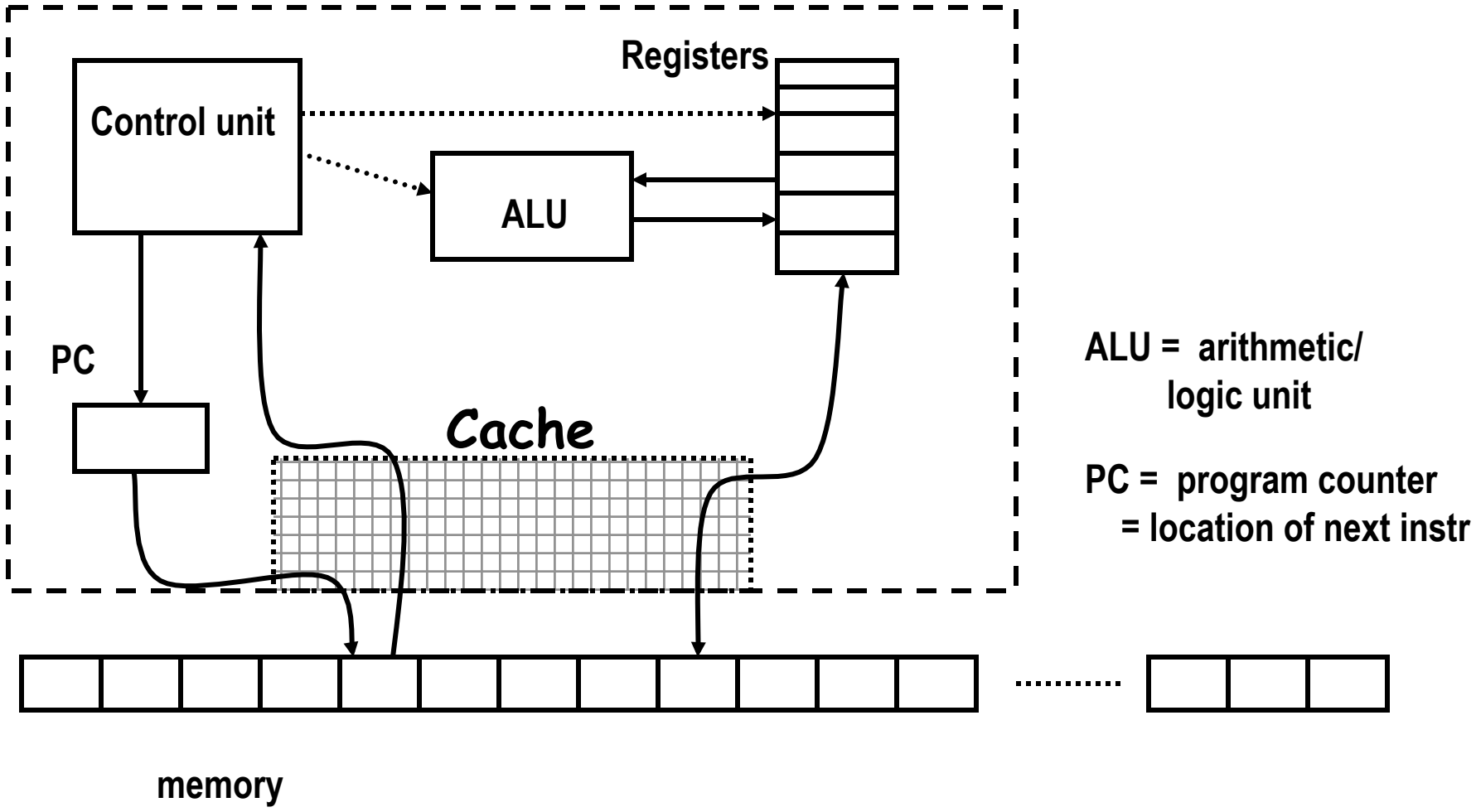
Computer architecture

- **what instructions does the CPU provide?**
  - CPU design involves complicated tradeoffs among functionality, speed, complexity, programmability, power consumption, …
  - Intel and ARM are unrelated, totally incompatible
    - Intel: lot more instructions, many of which do complex operations
      - e.g., add two memory locations and store result in a third
    - ARM: fewer instructions that do simpler things, but faster
      - e.g., load, add, store to achieve same result
- **how is the CPU connected to the RAM and rest of machine?**
  - memory is the real bottleneck; RAM is slow (25-50 nsec to fetch)
    - modern computers use a hierarchy of memories (caches) so that frequently used information is accessible to CPU without going to memory
- **what tricks do designers play to make it go faster?**
  - overlap fetch, decode, and execute so several instructions are in various stages of completion (pipeline)
  - do several instructions in parallel
  - do instructions out of order to avoid waiting
  - multiple "cores" (CPUs) in one package to compute in parallel
- **speed comparisons are hard, not very meaningful**

Caching: making things seem faster than they are

- **cache: a small very fast memory for recently-used information**
  - loads a block of info around the requested info
- **CPU looks in the cache first, before looking in main memory**
  - separate caches for instructions and data
- **CPU chip usually includes multiple levels of cache**
  - faster caches are smaller
- **caching works because recently-used info is more likely to be used again soon**
  - therefore more likely to be in the cache already
- **cache usually loads nearby information at the same time**
  - nearby information is more likely to be used soon
  - therefore more likely to be in the cache when needed
- **this kind of caching is invisible to users**
  - except that machine runs faster than it would without caching

CPU block diagram (non-artist's conception)



ALU = arithmetic/
logic unit

PC = program counter
= location of next instr

Caching is a much more general idea

- **things work more efficiently if what we need is close**
- **if we use something now**
  - we will likely use it again soon (time locality)
  - or we will likely use something nearby soon (space locality)
- **other caches in computers:**
  - CPU registers
  - cache(s) in CPU
  - RAM as a cache for disk or network or …
  - disk as a cache for network
  - network caches as a cache for faraway networks
  - caches at servers

- **some are automatic (in hardware), some are controlled by software, some you have some control over**

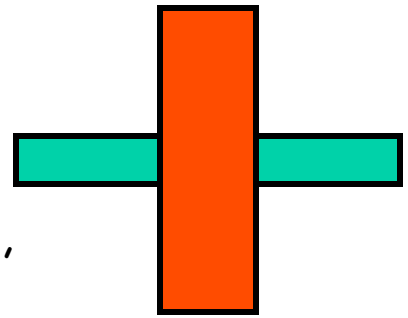
Other kinds of computers

- **not all computers are PCs or Macs**
- **"supercomputers"**
  - usually large number of fairly standard processors
  - extra instructions for well-structured data
- **"distributed" computing**
  - sharing computers and computation by network
  - e.g., web servers
- **embedded computers**
  - phones, games, music players, ...
  - cars, planes, weapons, ...

- **each represents some set of tradeoffs among cost, computing power, size, speed, reliability, ...**

Fabrication: making chips

- **grow layers of conducting and insulating materials on a thin wafer of very pure silicon**
- **each layer has intricate pattern of connections**
  - created by complex sequence of chemical and photographic processes
- **dice wafer into individual chips, put into packages**
  - yield is less than 100%, especially in early stages
- **how does this make a computer?**
  - when conductor on one layer crosses one on lower layer, voltage on upper layer controls current on lower layer
  - this creates a transistor that acts as off-on switch that can control what happens at another transistor
- **wire widths keep getting smaller: more components in given area**
  - today ~0.022 micron = 22 nanometers; next is 14 nm
    1 micron == 1/1000 of a millimeter (human hair is about 100 microns)
  - eventually this will stop
  - has been "10 years from now" for a long time, but seems closer now



Moore's Law (1965, Gordon Moore, founder & former CEO of Intel)

- **computing power (roughly, number of transistors on a chip)**
  - doubles about every 18 months
  - and has done so since ~1961
- **consequences**
  - cheaper, faster, smaller, less power consumption per unit
  - ubiquitous computers and computing
- **limits to growth**
  - fabrication plants now cost $2-4B; most are outside US
  - line widths are nearing fundamental limits
  - complexity is increasing
- **maybe some other technology will come along**
  - atomic level; quantum computing
  - optical
  - biological: DNA computing

Turing machines

- **Alan Turing *38**
- **showed that a simple model of a computer was universal**
  - now called a Turing machine
- **all computers have the same computational power**
  - i.e., they can compute the same things
  - though they may vary enormously in speed, memory, etc.
- **equivalence proven / demonstrated by simulation**
  - any machine can simulate any other
  - a "universal Turing machine" can simulate any other Turing machine

- **see also**
  - Turing test
  - Turing award

Fundamental ideas

- **a computer is a general-purpose machine**
  - executes very simple instructions very quickly
  - controls its own operation according to computed results
- **"von Neumann architecture"**
  - change what it does by putting new instructions in memory
  - instructions and data stored in the same memory
  - indistinguishable except by context

    attributed to von Neumann (1946)

    (and Charles Babbage, in the Analytical Engine (1830's))
  - logical structure largely unchanged for 60+ years
  - physical structures changing very rapdily
- **Turing machines**
  - all computers have exactly the same computational power:

    they can compute exactly the same things; differ only in performance
  - one computer can simulate another computer

    a program can simulate a computer

Important Hardware Ideas

- **programmable computer: a single general-purpose machine can be programmed to do an infinite variety of tasks**
- **simple instructions that do arithmetic, compare items, select next instruction based on results**
- **all machines have the same logical capabilities (Turing)**
  - architecture is mostly unchanged since 1940's (von Neumann)
  - physical properties evolve rapidly
- **bits at the bottom**
  - everything ultimately reduced to representation in bits (binary numbers)
  - groups of bits represent larger entities: numbers of various sizes, letters in various character sets, instructions, memory addresses
  - interpretation of bits depends on context

    one person's instructions are another's data
- **there are many things that we do not know how to represent as bits, nor how to process by computer**