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
- von Neumann architecture
- Turing machines

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)
  - STOP running: don't execute any more instructions
- **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**

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

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 is 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; ARM (cellphones); Toys (COS 109, COS 126), ...

- **assembler: a program that converts a program written in assembly language into numbers for loading into RAM**

- **handles clerical tasks**
  - replaces instruction names (e.g., ADD) with corresponding numeric values
  - replaces labels (names for memory locations) with corresponding numeric values: location "Start" becomes 1, "Show" becomes 6, etc.
  - loads initial values into specified locations ("Sum" set to 0)

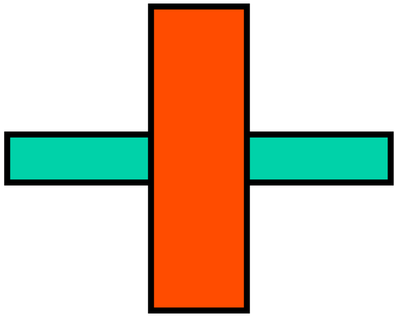
- **each CPU architecture has its own instruction format and one (or more) assemblers**

Real processors

- multiple accumulators (called "registers")
- many 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 repertoire: dozens to a few hundreds of instructions
- instructions and data usually occupy multiple memory locations
  - typically 2 - 8 bytes
- modern processors have multiple "cores" that are all CPUs on the same chip

Fabrication: making chips

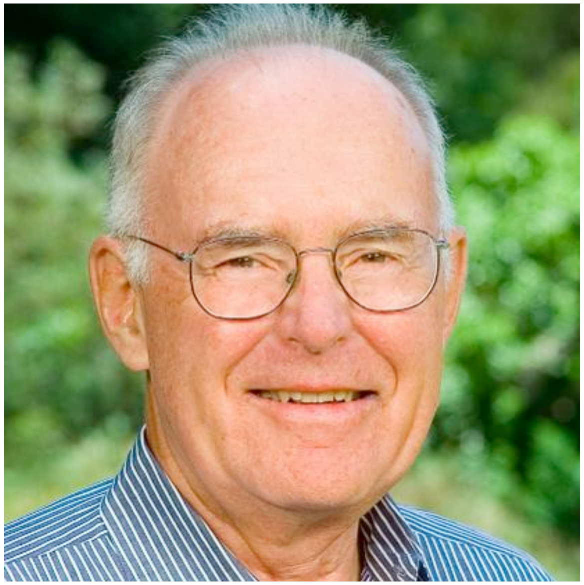
- grow layers of conducting and insulating materials on a thin wafer of very pure silicon
- each layer has intricate pattern of connections
  - created by complex sequence of chemical and photographic processes
- dice wafer into individual chips, put into packages
  - yield is less than 100%, especially 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 ~0.01 micron = 10 nanometers

    1 micron == 1/1000 of a millimeter (human hair is about 100 microns)
  - eventually this will stop

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



- number of transistors on a chip doubles about every 18 months
  - and has done so since ~1961
- consequences
  - cheaper, faster, smaller, less power use 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
  - processors don't run faster
  - speed of light limitations across chip area
- maybe some other technology will come along
  - atomic level; quantum computing
  - optical
  - biological: DNA computing

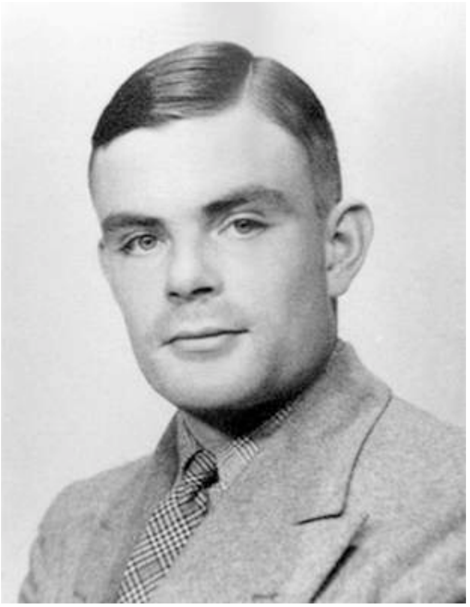
Computer architecture

- **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 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

Turing machines



Alan Turing *38

- in 1936, Turing showed that a simple model of a computer is 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
  - Enigma