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)
- **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**

Assembly languages and assemblers

- **assembly language: instructions specific to a particular machine**
  - X86 (PC) family; ARM (cellphones); Toy (COS 109), ...

- **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)

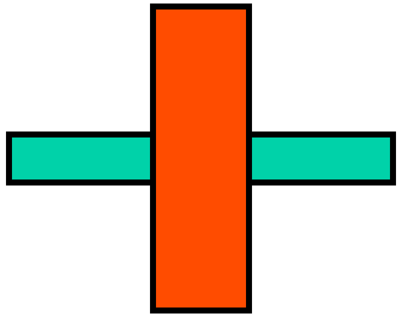
- **each CPU architecture has its own instruction format and one (or more) assemblers**

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

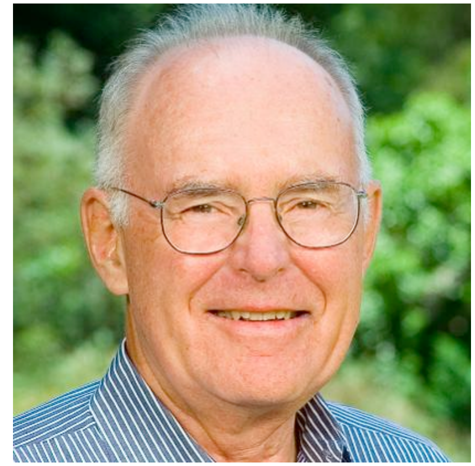
- **grow layers of conducting and insulating materials on a thin wafer of very pure silicon**
- **each layer has intricate pattern of connections**
  – created by complex sequence of chemical and photographic processes
- **dice wafer into individual chips, put into packages**
  – yield is less than 100%,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

- **computing power (roughly, the 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

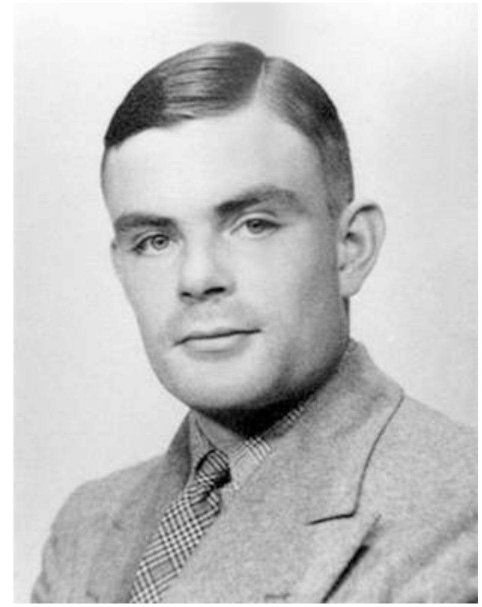
Computer architecture

- **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, 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

Fundamental ideas

- **programmable, general-purpose computers**
  - simple instructions for arithmetic, moving data, comparison of values
  - select next instruction based on results
  - controls its own operation according to computed results
- **von Neumann architecture**
  - change what it does by putting new instructions in memory
  - instructions & data stored in same memory, indistinguishable except by context

    attributed to von Neumann, 1946 (and Charles Babbage, Analytical Engine, 1830's)
  - logical structure largely unchanged for 60+ years, evolving now
  - physical structures changing very rapidly
- **Turing machines**
  - all computers have exactly the same logical power:

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

    a program can simulate a computer
- **everything is ultimately represented 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 person's data