Lecture 6: Inside the processor, continued

- 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

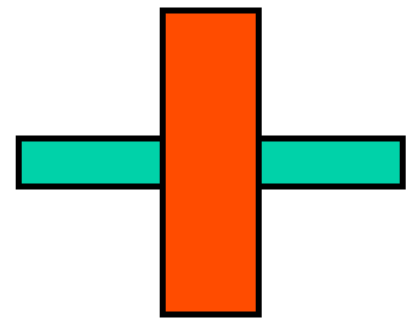
- computer architecture: real machines
- caching: making things seem faster than they are
- how chips are made
- Moore's Law
- von Neumann architecture
- Turing machines

Technology evolution (dates approximate)

- **1920-1960: vacuum tubes**
  - expensive, poor reliability, fragile, bulky, power hungry
- **1947 first transistor (Bell Labs)**
  - low power, mechanically robust, tiny
- **1960 discrete transistors**
  - basically switches: voltage on one lead controls current through others
- **1960 ... integrated circuits**
  - grow an entire circuit on a silicon surface
  - continuously increasing density of individual components

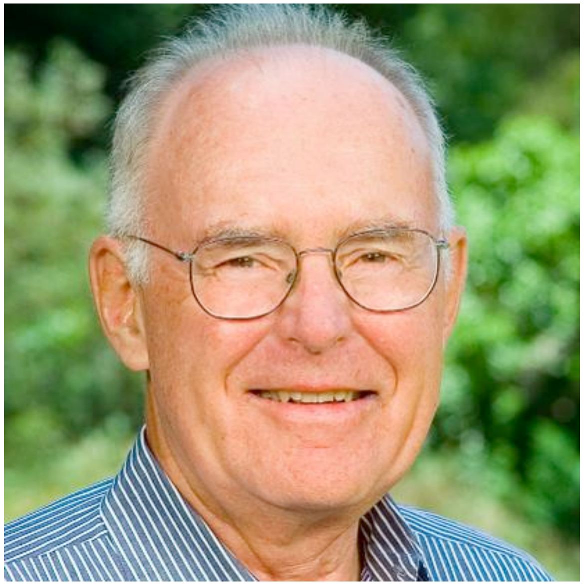
Fabrication: making chips

- **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

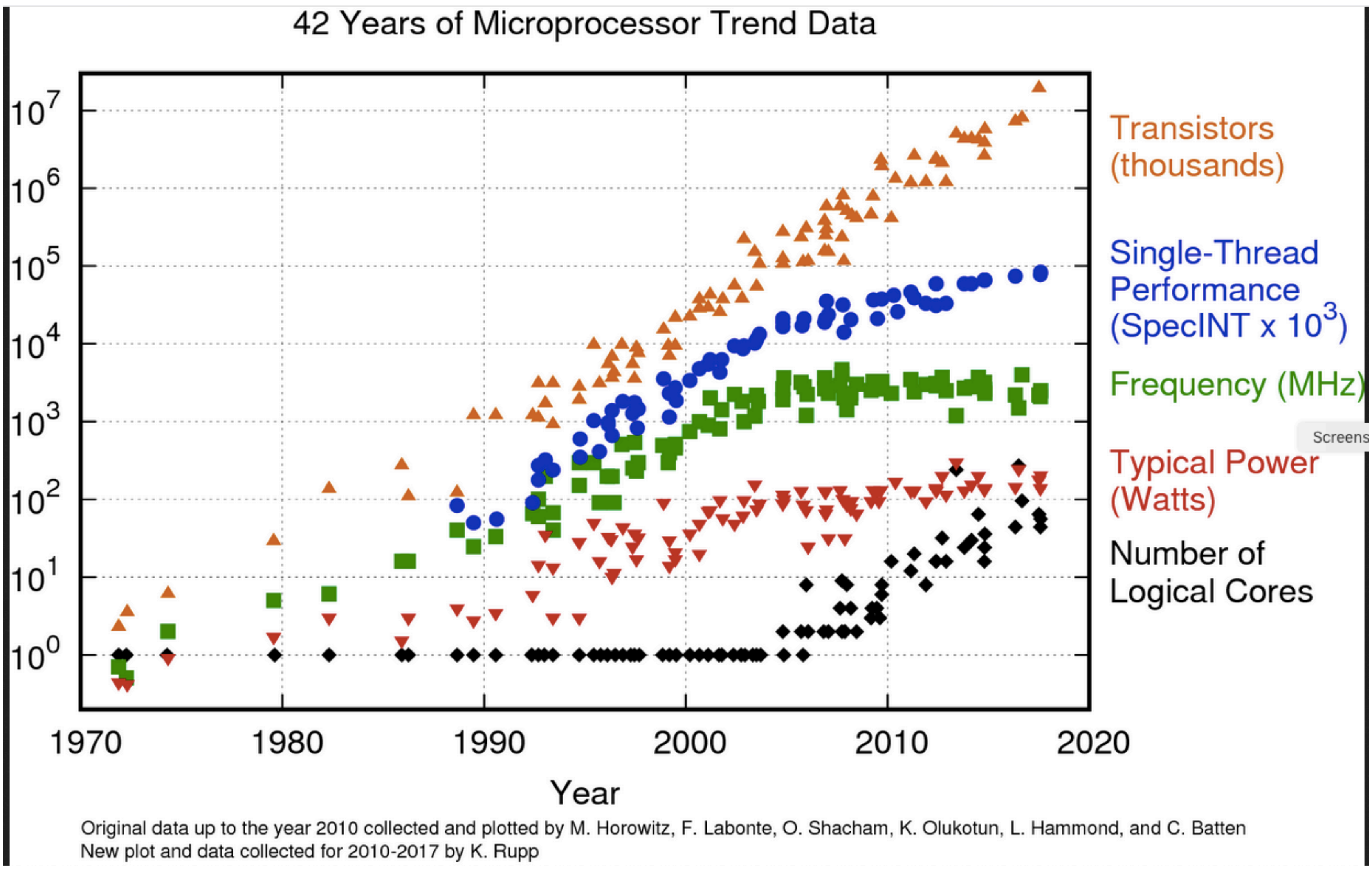
Moore's Law (1965, Gordon Moore, founder & former CEO of Intel)



1929-2023

- 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

Transistor counts and Moore's Law



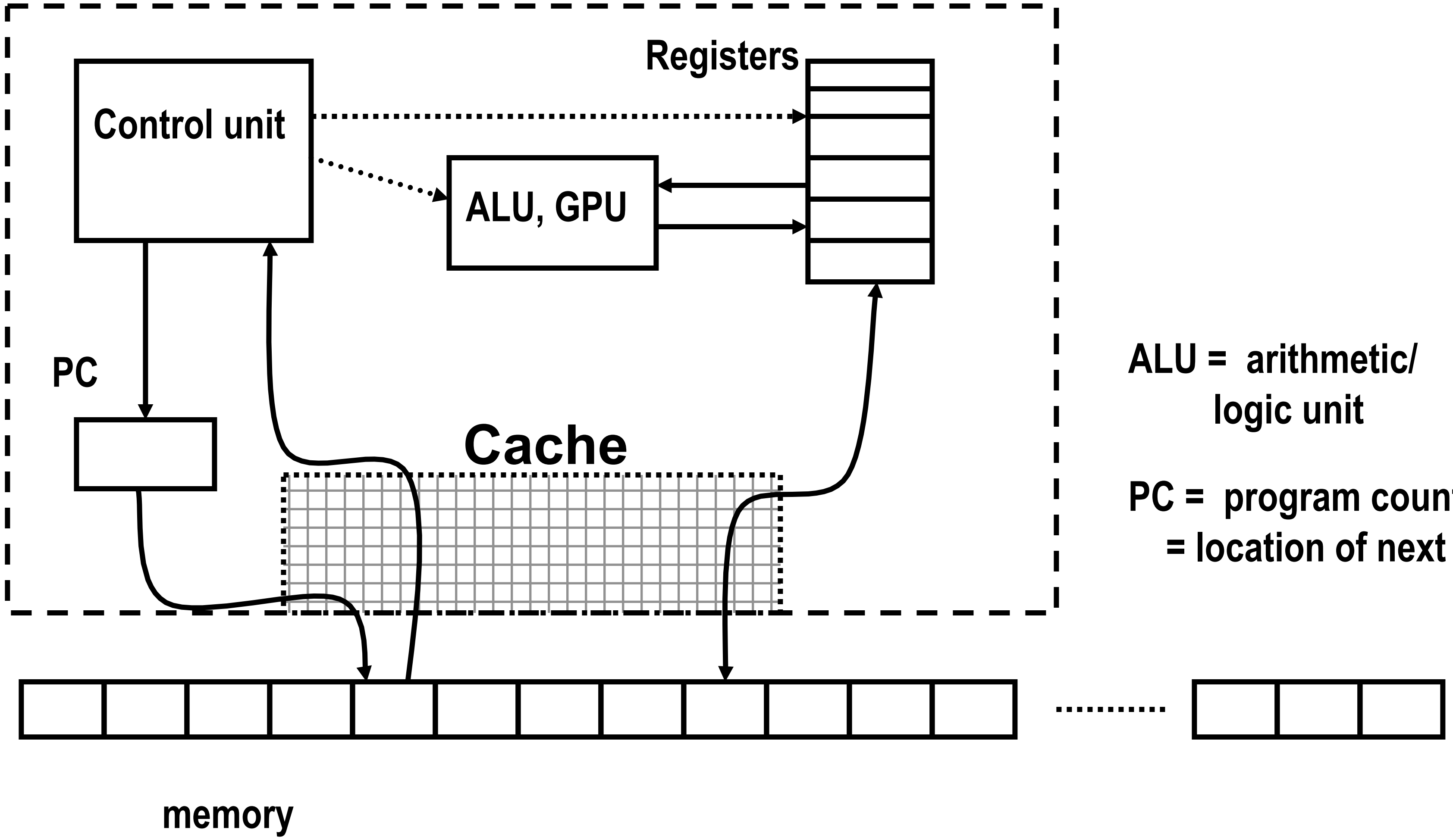
Computer architecture

- **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 or recently used information is accessible to CPU without going to RAM
- **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
  - GPUs to do some computations in parallel at high speed
- **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

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 Macs or PCs

- "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, ...
- GPU (graphics processing unit)
  - specialized processor for 3-d graphics, other streaming computations

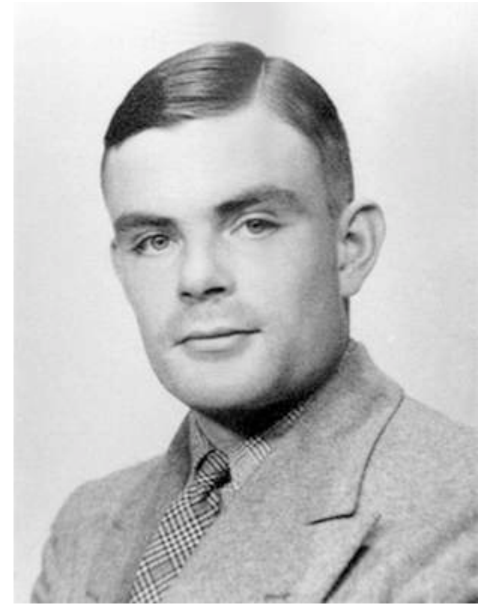
- each represents some set of tradeoffs among cost, computing power, size, speed, reliability, ...

Turing machines

- 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

    https://www.youtube.com/watch?v=E3keLeMwfHY

- see also
  - Turing Test
  - Turing Award
  - Enigma



Alan Turing *38
1912-1954

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