Lecture 5: Inside the processor

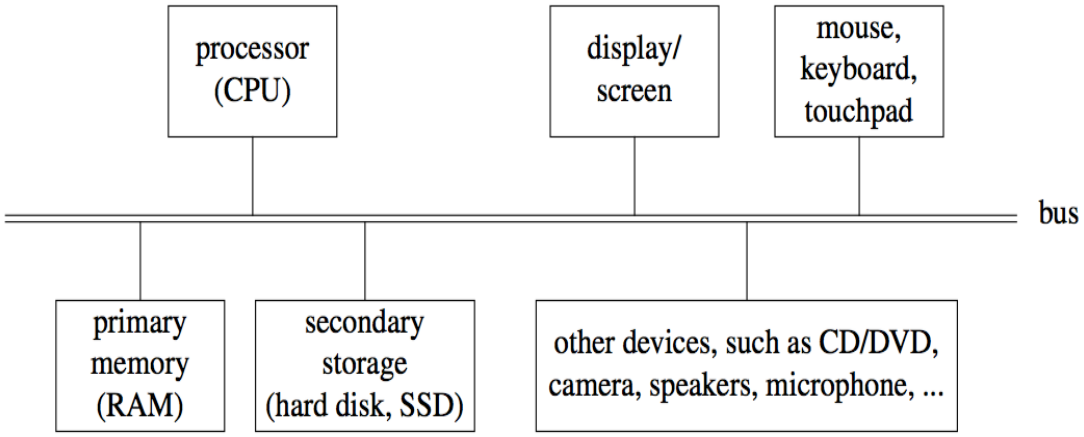
- how does the CPU work?
  - what operations can it perform?
  - how does it perform them? on what kind of data?
  - where are instructions and data stored?
- some short, boring programs to illustrate the basics
- a toy machine to try the programs
  - a program that simulates the toy machine
  - so we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

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

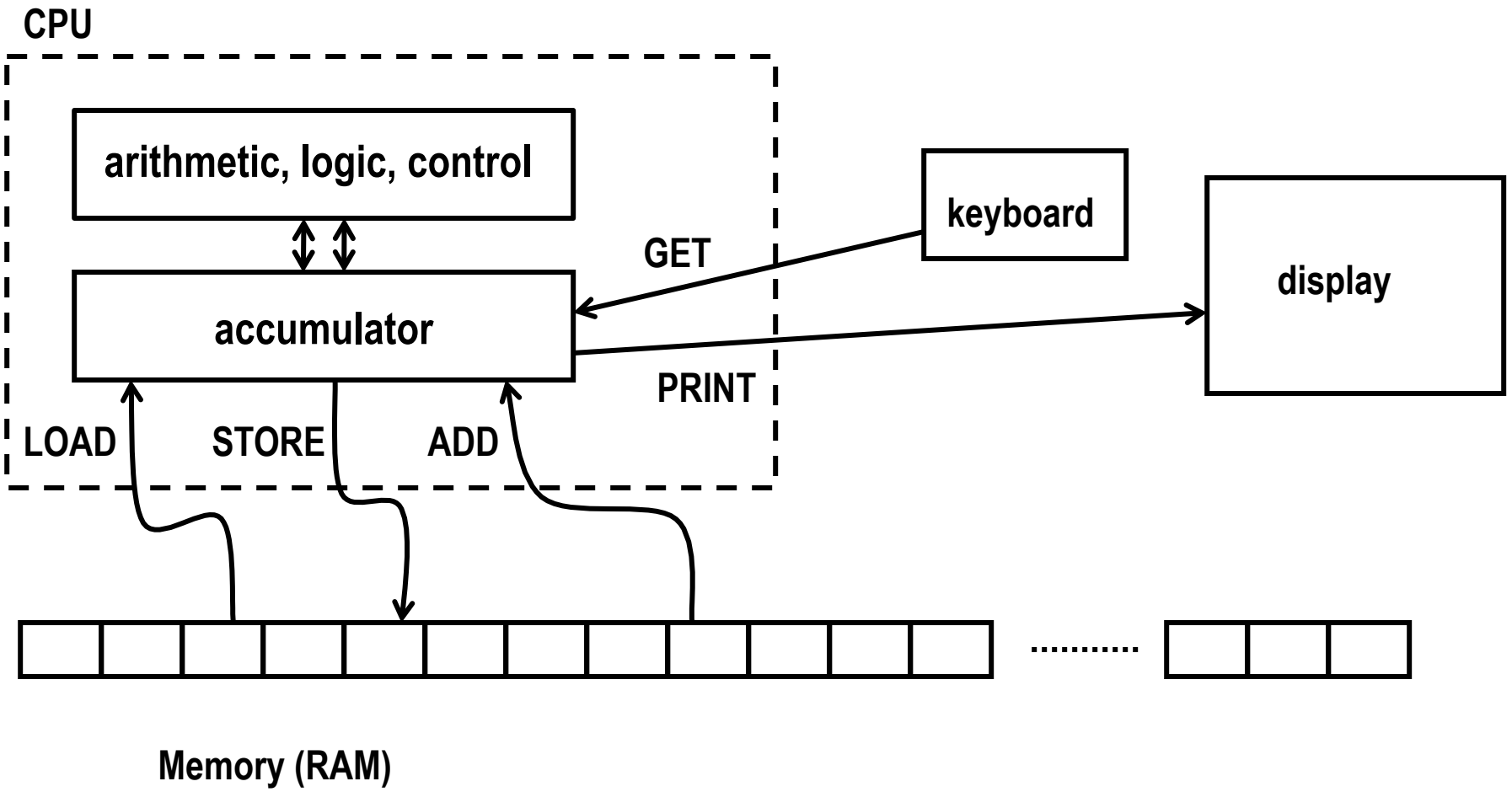


John von Neumann
1903-1957

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

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     0               a place to save the first number (set it to zero)
```

- 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 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 (phones, newer Macs); 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

A simulator for the toy computer (toysim.html)

- 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

`M Num`	before program runs, set this memory location to Num

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 of how CPU operates

- 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")
- 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
  - plus GPUs, caches, ...