Lecture 2

408/508 *Computational Techniques for Linguists*

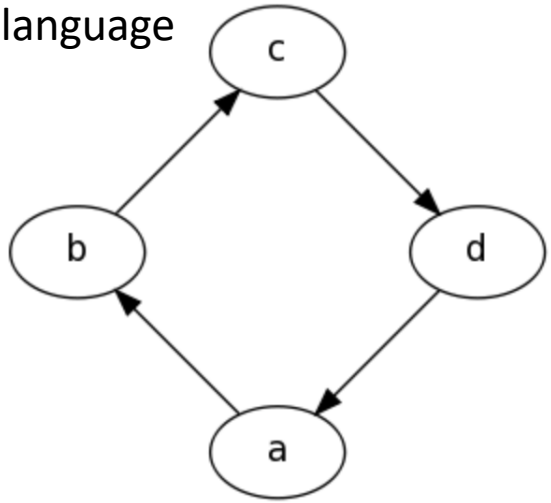
Computer Languages

- Think of two basic kinds:
  - Sequence of instructions
  - Description (data)

```
fh = open(filename)
raw = fh.read()
import nltk
words = nltk.word_tokenize(raw)
print(len(words)/len(raw))
```

graphviz: dot language

```
digraph {
    a -> b;
    b -> c;
    c -> d;
    d -> a;
}
```



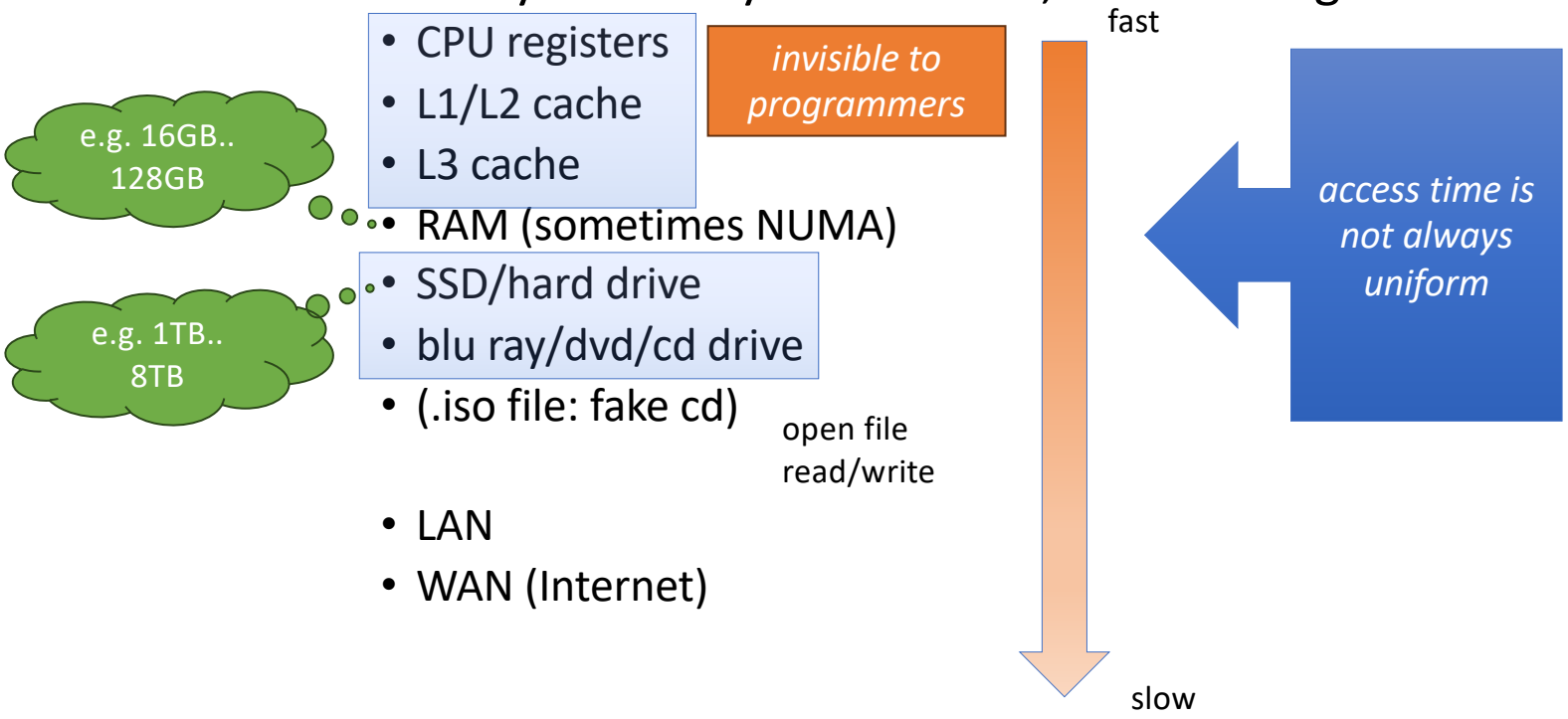
https://graphviz.org/doc/info/lang.html

Introduction

- **Computers**
  - Memory (several kinds)
    - Store programs and data
  - CPU (Central Processing Unit)
    - Interprets primitive machine instructions (*not Turing Machine*)
  - I/O (Input/Output) require drivers
    - keyboard, mouse, microphone, speaker
    - touchpad, (touch) screen, (3D) printer
    - Bluetooth, USB, Thunderbolt, Ethernet, NAS (Network …)
    - WiFi, cellular, satellite …

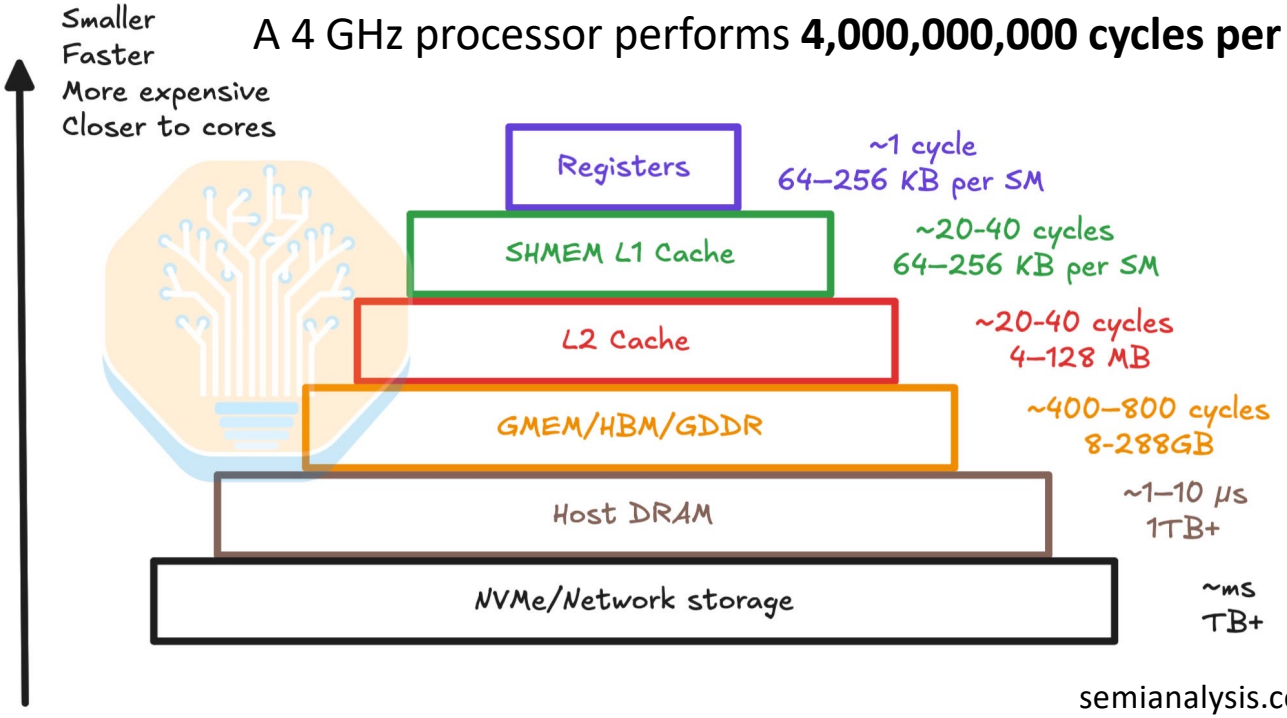
Introduction

- Memory Hierarchy: fast to slow, small to large



Introduction

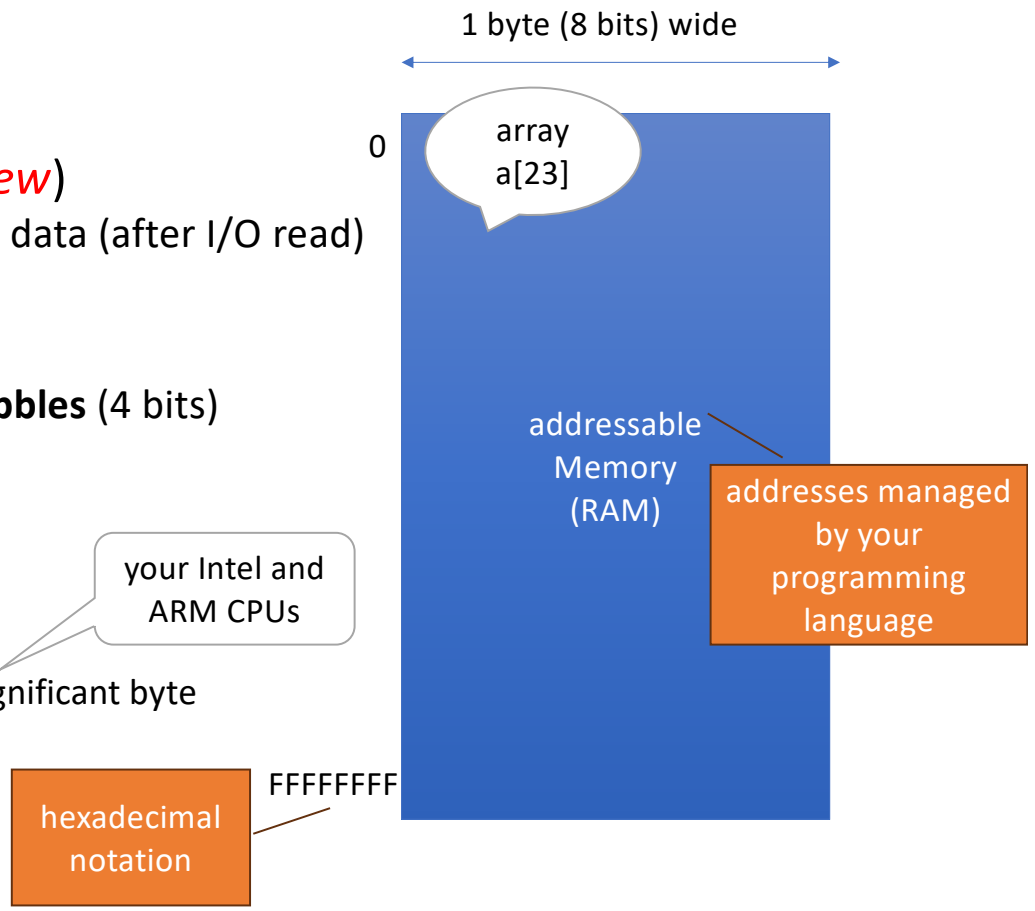
A 4 GHz processor performs **4,000,000,000 cycles per second**



semianalysis.com

Introduction

- RAM memory (*your program's view*)
  - the area to store your program and data (after I/O read)
- Underlying representation
  - binary: zeros and ones (1 bit)
  - organized into **bytes** (8 bits) and **nibbles** (4 bits)
    - memory is byte-addressable
  - **word** (32 bits)
    - e.g. integer
    - (64 bits: floating point number)
  - big-endian/little-endian
    - most significant byte first or least significant byte
    - *matters for communication …*

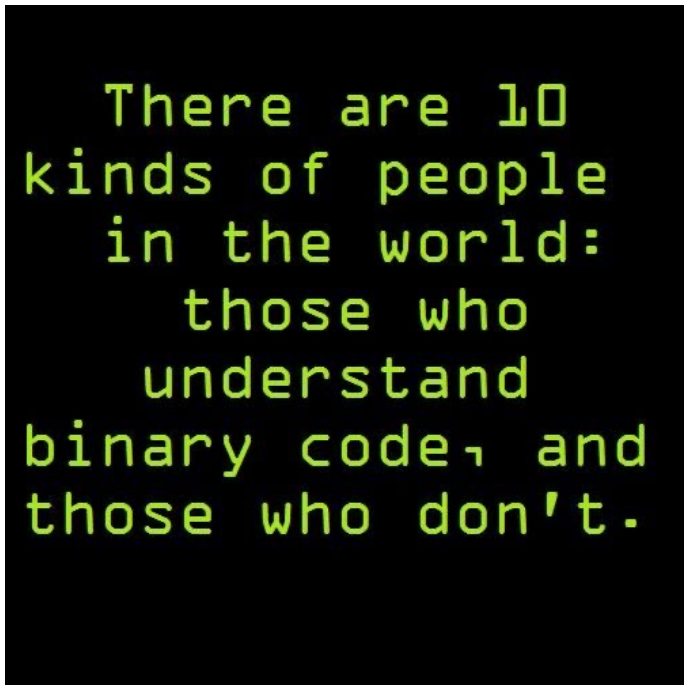


Joke

- Continue with the introduction
  - binary representation (base 2) and arithmetic

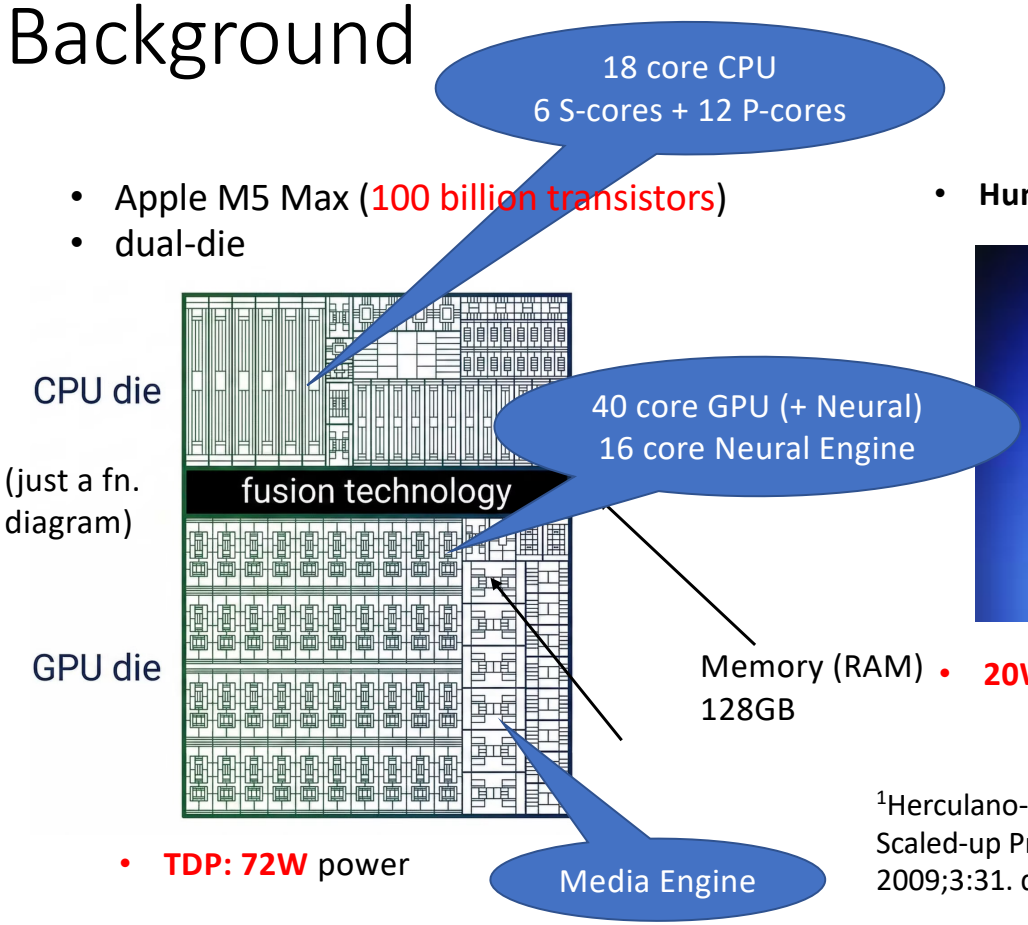
2^1	2^0	Total (decimal)
1	0	2

10^1	10^0	Total
1	0	10



Background

- Apple M5 Max (100 billion transistors)
- dual-die



- **TDP: 72W** power

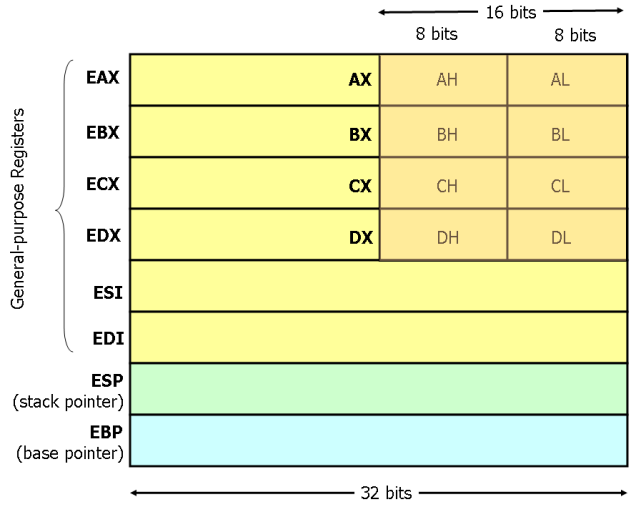
- **Human brain:** 86 billion neurons[1]

- **20W** of power (oft-cited figure)

[1]Herculano-Houzel, S. The Human Brain in Numbers: A Linearly Scaled-up Primate Brain . *Frontiers in Human Neuroscience*. 2009;3:31. doi:10.3389/neuro.09.031.2009.

Introduction

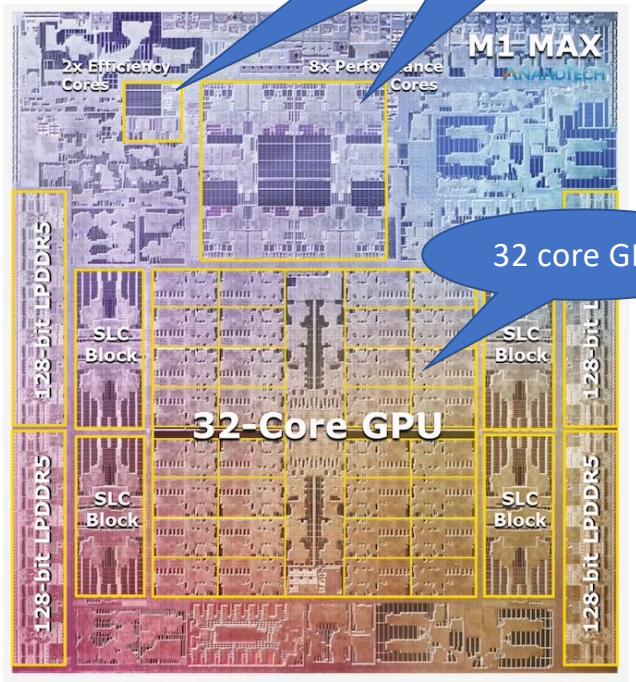
- Machine Language
  - A CPU understands only one language: machine language (Intel/AMD x86)
    - **all other languages** must be translated into machine language
  - Primitive instructions include:
    - MOV
    - PUSH
    - POP
    - ADD / SUB
    - INC / DEC
    - IMUL / IDIV
    - AND / OR / XOR / NOT
    - NEG
    - SHL / SHR
    - JMP
    - CMP
    - JE / JNE / JZ / JG / JGE / JL / JLE
    - CALL / RET



Assembly Language: (this notation)
by definition, nothing built on it is more powerful

http://www.cs.virginia.edu/~evans/cs216/guides/x86.html

Background



Machine Language (ML)

- A CPU understands only **Machine Language** (ARM64)
- **all other languages** must be translated into **ML**
- Each core is an independent CPU itself:
  - 31 general purpose registers X0..X31
  - 32 floating point/vector registers
  - SP
- Primitive instructions include:
  - `ADD X0, X1, X2`
  - `MOV X0, #1`
  - `LDR X0, [<address>]`
  - `STRW X0, [<address>]`
  - `CBZ <Xn> <label>` and `CBNZ <Xn> <label>`
  - `BL <label>` / `RET`

https://developer.arm.com/documentation/ddi0602/2022-12/?lang=en

Fugaku supercomputer

- World's fastest computer (using the ARM instruction set) until May 2022 (*now #7*)
- Power consumption of 30 (to 40) megawatts (#1)
- https://www.fujitsu.com/global/about/innovation/fugaku/

Number of Nodes

Number of Nodes	158,976 nodes

Node

Architecture	Armv8.2-A SVE 512 bit With the following Fujitsu's extensions: Hardware barrier, Sector cache, and Prefetch
Number of computational cores	48 cores

FukugakuNEXT coming
100x faster hybrid AI-HPC

Supercomputers rely on parallelism

- each CPU may have 64 cores each + GPUs

- Not all tasks are easily parallelizable.
  - Can you use 8 million cores?
  - e.g. *analyze 8 million sentences at a time*?

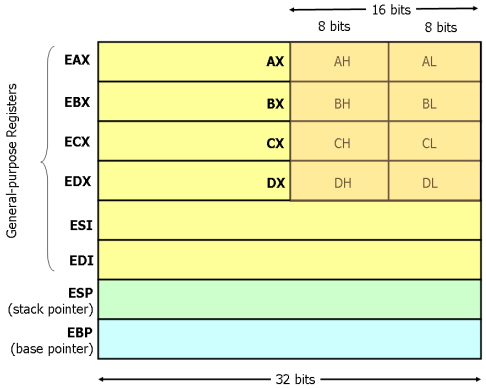
https://www.top500.org

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	**El Capitan** - HPE Cray EX255a, AMD 4th Gen EPYC 24C 1.8GHz, AMD Instinct MI300A, Slingshot-11, TOSS, HPE DOE/NNSA/LLNL United States	11,039,616	1,742.00	2,746.38	29,581
2	**Frontier** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE Cray OS, HPE DOE/SC/Oak Ridge National Laboratory United States	9,066,176	1,353.00	2,055.72	24,607
3	**Aurora** - HPE Cray EX - Intel Exascale Compute Blade, Xeon CPU Max 9470 52C 2.4GHz, Intel Data Center GPU Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States	9,264,128	1,012.00	1,980.01	38,698
4	**JUPITER Booster** - BullSequana XH3000, GH Superchip 72C 3GHz, NVIDIA GH200 Superchip, Quad-Rail NVIDIA InfiniBand NDR200, RedHat Enterprise Linux, EVIDEN EuroHPC/FZJ Germany	4,801,344	793.40	930.00	13,088
5	**Eagle** - Microsoft NDv5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft Azure Microsoft Azure United States	2,073,600	561.20	846.84	

Introduction

- Not all machine instructions are conceptually necessary
  - many provided for speed/efficiency
- Theoretical Computer Science
  - All mechanical computation can be carried out using a TURING MACHINE (a-machine; Turing, 1936)
  - Finite state table + (infinite) tape
  - Tape instructions:
    - at the tape head: Erase, Write, Move (Left/Right/NoMove)
  - Finite state table:
    - Current state x Tape symbol --> new state x New Tape symbol x Move

Assembly Language instructions:
MOV/ADD/JMP/JZ/CALL/RET



Recall the *Busy Beaver* Turing Machine?

1. A 0 (Initially, all 0's, state A)
2. B 10
3. A 11
4. B 011
5. A 0111
6. B 1111
7. H 1111

State

	A	B
0	1RB	1L A
1		

symbol @ tape head

- Halt state

en.wikipedia.org/wiki/Busy_beaver

Values of busy beaver functions

Function	2-state	3-state	4-state	5-state	6-state	7-state
$S(n)$	6[5]	21[5]	107[5]	47 176 870[3][38]	$> 2\uparrow\uparrow\uparrow 5$[36]	$> 2\uparrow^{11}2\uparrow^{11}3$[36]
space(n)	4[37]	7[37]	16[37]	12289[38]	$> 2\uparrow\uparrow\uparrow 5$ space(n) ≥ $\Sigma(n)$	$> 2\uparrow^{11}2\uparrow^{11}3$[36]
$\Sigma(n)$	4[37]	6[37]	13[37]	4098[38][36]	$> 2\uparrow\uparrow\uparrow 5$[36]	$> 2\uparrow^{11}2\uparrow^{11}3$[36]
num(n)	4[37]	6[37]	12[37]	165[39]	?	?

Introduction

- Storage:
  - based on digital logic
  - binary (base 2) – everything is a power of 2
  - Byte: 8 bits
    - 01011011
    - = $2^6+2^4+2^3+2^1+2^0$
    - = 64 + 16 + 8 + 2 + 1
    - = 91 (in decimal)
  - Hexadecimal (base 16)
    - 0-9,A,B,C,D,E,F (need 4 bits)
    - 5B (= 1 byte)
    - = $5*16^1 + 11$
    - = 80 + 11
    - = 91

2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
0	1	0	1	1	0	1	1

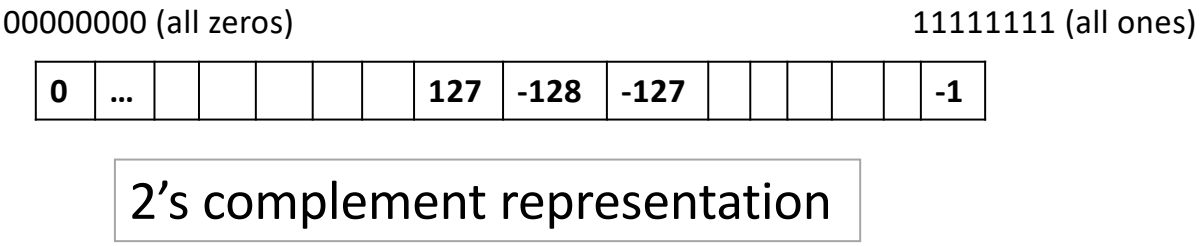
2^3	2^2	2^1	2^0	2^3	2^2	2^1	2^0
0	1	0	1	1	0	1	1

5 B

16^1	16^0
5	B

Introduction: data types

- Integers
  - In one byte (= 8 bits), what's the largest and smallest number, we can represent?
  - 00000000 = 0
  - 01111111 = 127
  - 10000000 = -128
  - 11111111 = -1
  - Number line:



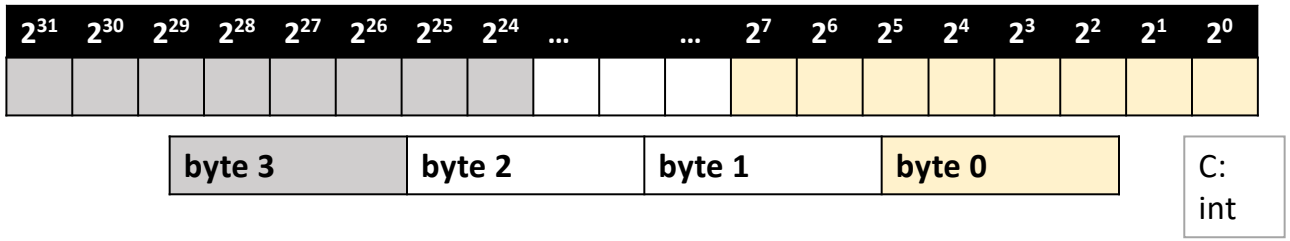
Introduction: data types

- Integers
  - In one byte, what's the largest and smallest number, we can represent?
  - **Answer**: -128 .. 0 .. 127 using the **2's complement representation**
  - Why? super-convenient for arithmetic operations
  - "to convert a positive integer X to its negative counterpart, flip all the bits, and add 1"
  - **Example**:
  - 00001010 = $2^3 + 2^1 = 10$ (decimal)
  - 11110101 + 1 = 11110110 = -10 (decimal)
  - 11110110 flip + 1 = 00001001 + 1 = 00001010

Addition:
-10 + 10
= 11110110
+ 00001010 = 0 (ignore overflow)

Introduction: data types

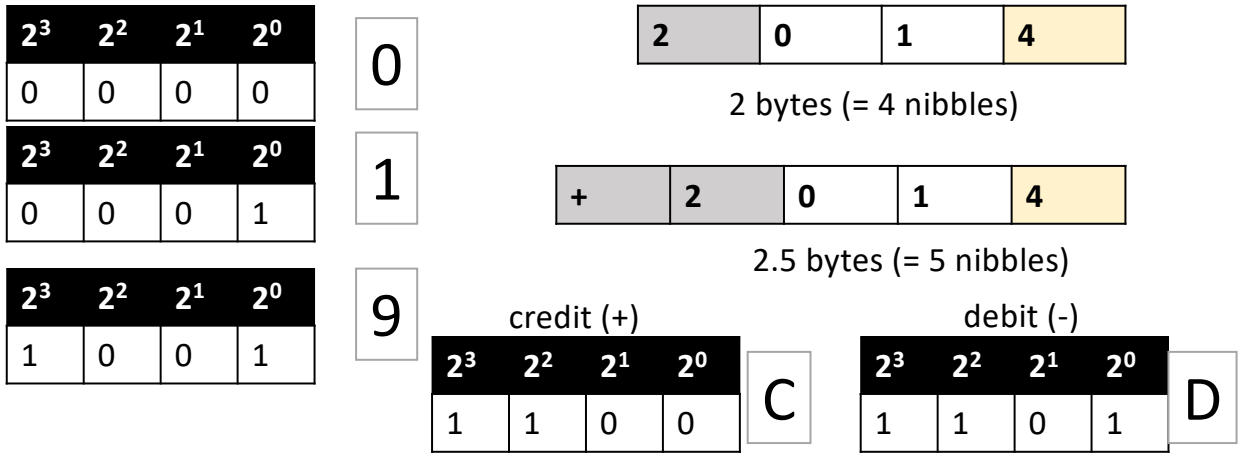
- Typically 32 bits (4 bytes) are used to store an integer
  - range: -2,147,483,648 ($2^{(31-1)}$ -1) to 2,147,483,647 ($2^{(32-1)}$ -1)



- what if you want to store even larger numbers?
  - Binary Coded Decimal (BCD)
  - code each decimal digit separately, use a string (sequence) of decimal digits …

Introduction: data types

- what if you want to store even larger numbers?
  - Binary Coded Decimal (BCD)
  - 1 byte can code two digits (0-9 requires 4 bits)
  - 1 nibble (4 bits) codes the sign (+/-), e.g. hex C/D



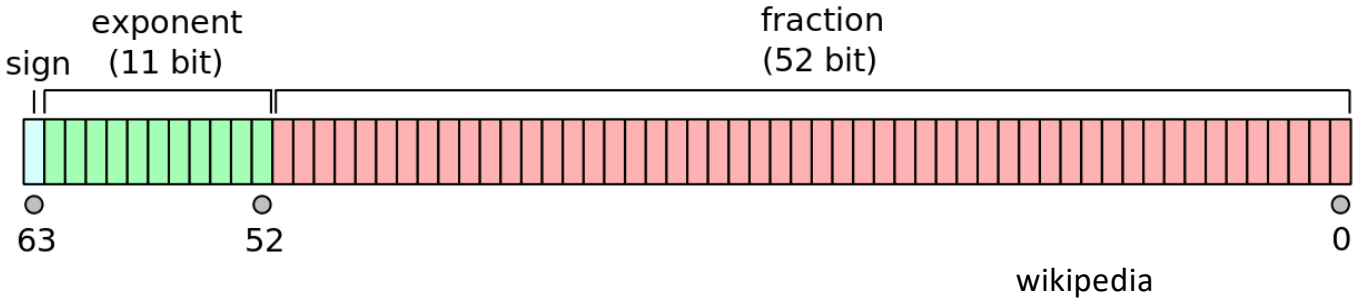
Introduction: data types

e.g. probabilities

- Typically, 64 bits (8 bytes) are used to represent floating point numbers (double precision)
  - c = 2.99792458 x 10^8 (m/s)
  - coefficient: 52 bits (**implied 1**, therefore treat as 53)
  - exponent: 11 bits (usually not 2's complement, unsigned with bias $2^{(10-1)}$-1 = 511)
  - sign: 1 bit (+/-)

C:
float
double

x86 CPUs have a built-in floating point coprocessor (x87)
80 bit long registers



Example 1

- The speed of light:
  - $c = 2.99792458 \times 10^8$ (m/s)

1. Can a 4 byte integer be used to represent *c* exactly?
   - 4 bytes = 32 bits
   - 32 bits in 2's complement format
   - Largest positive number is
   - $2^{31}-1 = 2{,}147{,}483{,}647$
   - *c* = 299,792,458

Example 2

- Recall the speed of light:
  - $c = 2.99792458 \times 10^8$ (m/s)

2. How much memory would you need to encode *c* using BCD notation as an integer?
   - 9 digits
   - each digit requires 4 bits (a nibble)
   - BCD notation includes a sign nibble
   - total is 5 bytes

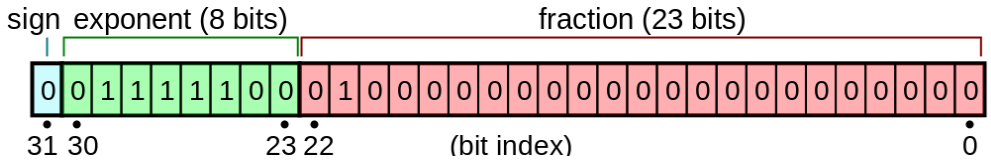
Example 3

- Recall the speed of light:
  - $c = 2.99792458 \times 10^8$ (m/s)

3. Can the 64 bit floating point representation (`double`) encode *c* without loss of precision?
   - Recall significand precision: 53 bits (52 explicitly stored)
   - $2^{53}-1 = 9{,}007{,}199{,}254{,}740{,}991$
   - almost 16 digits
   - (we only need 9 digits of precision)

Example 4

- Recall the speed of light:
  - $c = 2.99792458 \times 10^8$ (m/s)
- The 32 bit floating point representation (`float`) – sometimes called single precision - is composed of 1 bit sign, 8 bits exponent (unsigned with bias $2^{(8-1)}-1$), and 23 bits coefficient (24 bits effective).



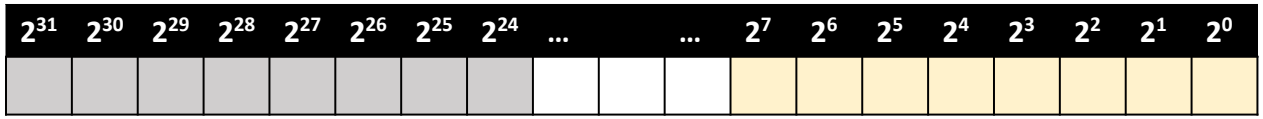
- Can it represent *c* without loss of precision?
  - $2^{24}-1 = 16{,}777{,}215$
  - Nope (7 digits of precision)

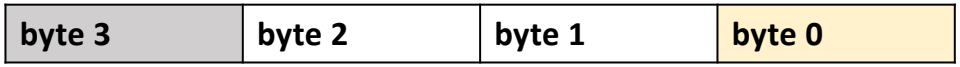
Example 5

- Atomic clocks use the caesium standard. Frequency is exactly **9 192 631 770** Hz.
- Does the 32 bit binary integer representation have enough bits to represent this frequency?
- Relevant integer is:
  - 9 192 631 770 (Hz)
  - Largest possible integer using 2's complement is:
  - $2^{31} - 1 = 2\ 147\ 483\ 648$ (too small)
  - Largest possible integer even if we use *unsigned* representation is:
  - $2^{32} - 1 = 4\ 294\ 967\ 296$ (still too small)

Homework 1: Binary Exercise

- 2,147,483,659 is a prime number.
- Does the 32 bit binary integer representation have enough bits to represent this prime? Explain.





Instructions

- Email to sandiway@arizona.edu
- By Sunday midnight
- SUBJECT: 408/508 Homework 1: **YOUR NAME**
- Send me the binary bit pattern!
- Either Plain Text or PDF accepted
  - no MS Word .doc/.docx files please