CS 110 Computer Architecture Lecture 17: *Performance & Numbers*

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https://robotics.shanghaitech.edu.cn/courses/ca/20s/

School of Information Science and Technology SIST

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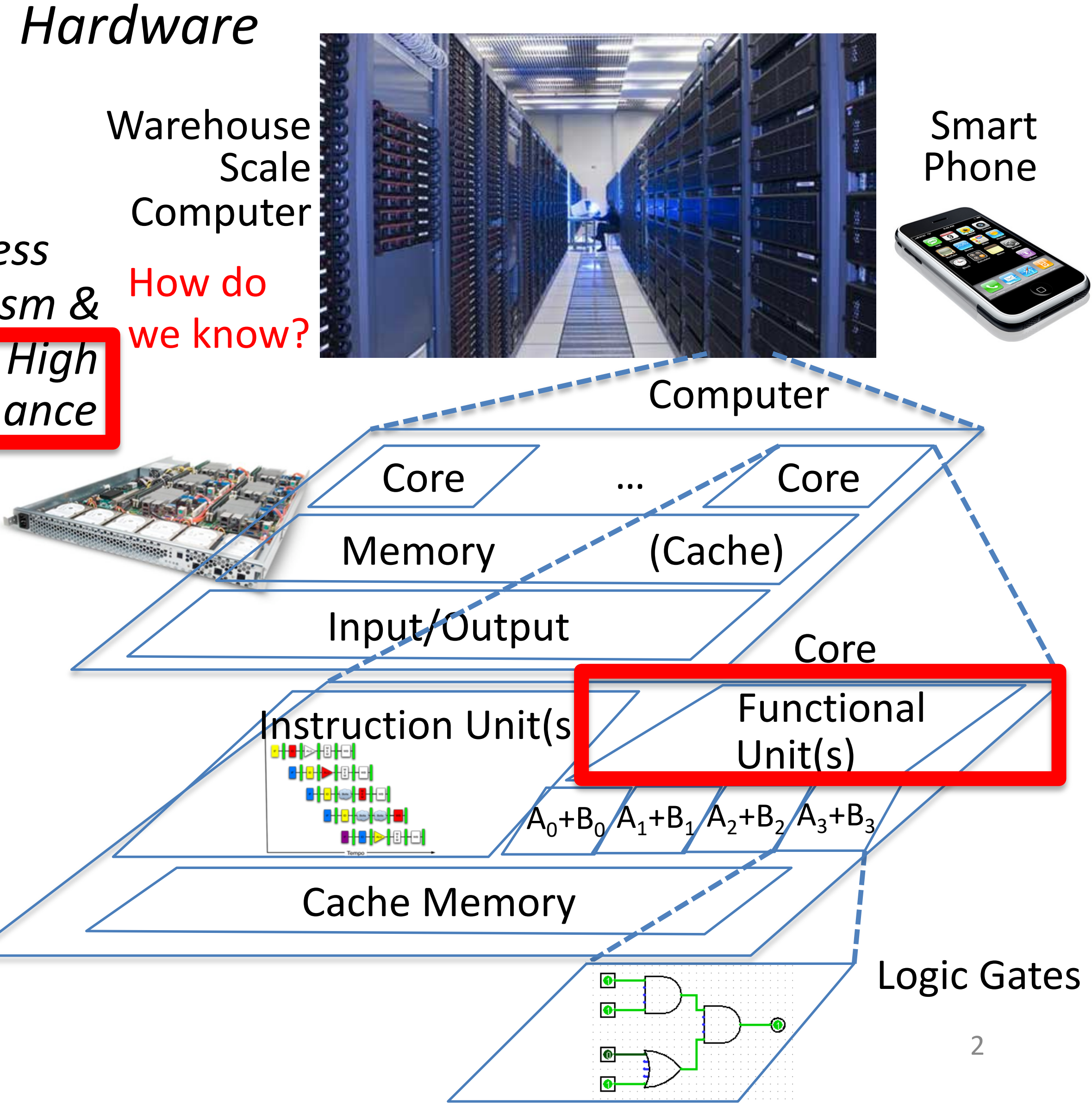
Slides based on UC Berkley's CS61C

New-School Machine Structures (It's a bit more complicated!)

Software | *Hardware*

- Parallel Requests
  Assigned to computer
  e.g., Search "Katz"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates @ one time
- Programming Languages

Harness Parallelism & Achieve High Performance



What is Performance?

- *Latency* (or *response time* or *execution time*)
  - Time to complete one task
- *Bandwidth* (or *throughput*)
  - Tasks completed per unit time

Transportation Analogy

	Sports Car	Bus
Passenger Capacity	2	50
Travel Speed	250 km/h	100 km/h
Fuel consumption	20 l/100km	20 l/100km

Schwerin => Berlin trip: 200 km

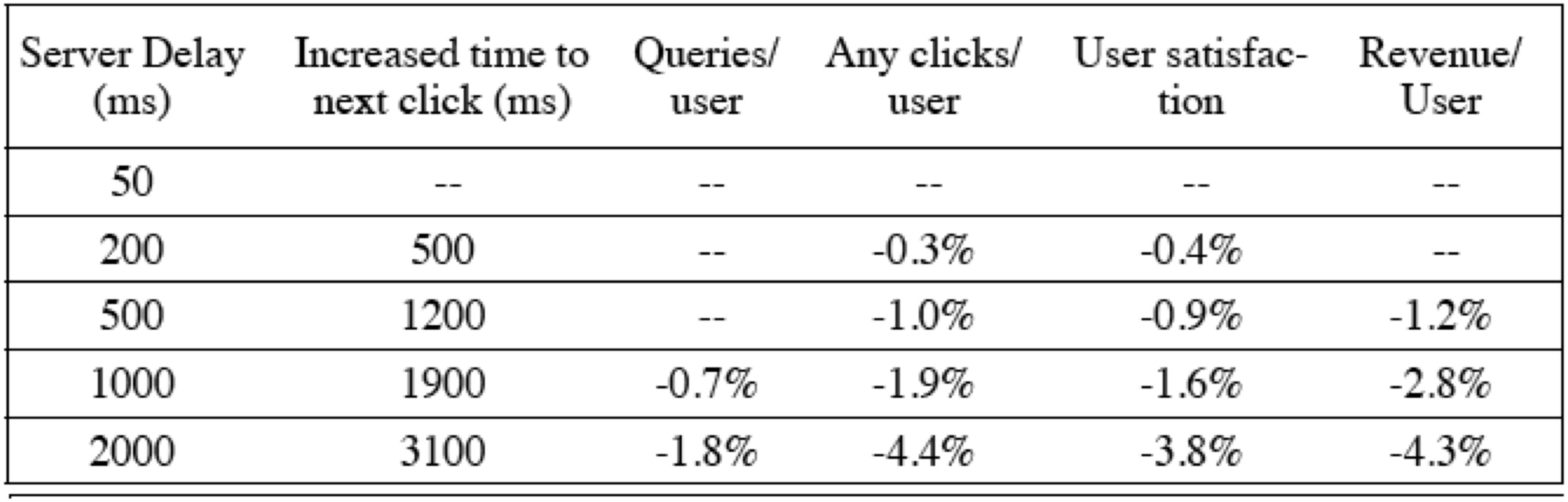
	Sports Car	Bus
Travel Time	48 min	120 min
Time for 100 passengers	40 h	4 h
Fuel per passenger	2000 l	80 l

Latency & Throughput

Transportation	Computer
Travel Time	Program execution time (**latency**) e.g. time to update display
Time for 100 passengers	**Throughput**: e.g. number of server requests handled per hour
Fuel per passenger	Energy per task*: e.g.: - how many movies can you watch per battery charge - energy bill for datacenter

* Note: power is not a good measure, since low-power CPU might run for a long time to complete one task consuming more energy than faster computer running at higher power for a shorter time

Cloud Performance: Why Application Latency Matters



Server Delay (ms)	Increased time to next click (ms)	Queries/ user	Any clicks/ user	User satisfac-tion	Revenue/ User
50	--	--	--	--	--
200	500	--	-0.3%	-0.4%	--
500	1200	--	-1.0%	-0.9%	-1.2%
1000	1900	-0.7%	-1.9%	-1.6%	-2.8%
2000	3100	-1.8%	-4.4%	-3.8%	-4.3%

Figure 6.10 Negative impact of delays at Bing search server on user behavior [Brutlag and Schurman 2009].

- Key figure of merit: application responsiveness
  - Longer the delay, the fewer the user clicks, the less the user happiness, and the lower the revenue per user

Defining Relative CPU Performance

- $\text{Performance}_X = 1/\text{Program Execution Time}_X$
- $\text{Performance}_X > \text{Performance}_Y \Rightarrow$
  $1/\text{Execution Time}_X > 1/\text{Execution Time}_y \Rightarrow$
  $\text{Execution Time}_Y > \text{Execution Time}_X$
- Computer X is N times faster than Computer Y
  $\text{Performance}_X / \text{Performance}_Y = N$ or
  $\text{Execution Time}_Y / \text{Execution Time}_X = N$

Measuring CPU Performance

- Computers use a clock to determine when events takes place within hardware
- *Clock cycles:* discrete time intervals
  - aka clocks, cycles, clock periods, clock ticks
- *Clock rate* or *clock frequency:* clock cycles per second (inverse of clock cycle time)
- 3 GigaHertz clock rate
  => clock cycle time = $1/(3\times10^9)$ seconds
  clock cycle time = 333 picoseconds (ps)

CPU Performance Factors

- To distinguish between processor time and I/O, *CPU time* is time spent in processor

-
  ```
  CPU Time/Program
        = Clock Cycles/Program
          x Clock Cycle Time
  ```
- Or
  ```
  CPU Time/Program
    = Clock Cycles/Program ÷ Clock Rate
  ```

Iron Law of Performance

- A program executes instructions
- `CPU Time/Program`
```
   = Clock Cycles/Program x Clock Cycle Time
   = Instructions/Program
     x Average Clock Cycles/Instruction
     x Clock Cycle Time
```
- 1st term called *Instruction Count*
- 2nd term abbreviated *CPI* for average ***C**lock Cycles **P**er **I**nstruction*
- 3rd term is 1 / Clock rate

Restating Performance Equation

- $$\text{Time} = \frac{\text{Seconds}}{\text{Program}}$$

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock Cycle}}$$

What Affects Each Component? Instruction Count, CPI, Clock Rate

	Affects What?
Algorithm	
Programming Language	
Compiler	
Instruction Set Architecture	

What Affects Each Component? Instruction Count, CPI, Clock Rate

	Affects What?
Algorithm	Instruction Count, CPI
Programming Language	Instruction Count, CPI
Compiler	Instruction Count, CPI
Instruction Set Architecture	Instruction Count, Clock Rate, CPI

Question

Computer	Clock frequency	Clock cycles per instruction	#instructions per program	
A	1GHz	2	1000	[redacted]
B	2GHz	5	800	[redacted]
C	500MHz	1.25	400	[redacted]
D	5GHz	10	2000	[redacted]

- Which computer has the highest performance for a given program?

Question

Computer	Clock frequency	Clock cycles per instruction	#instructions per program	Calculation
A	1GHz	2	1000	1ns * 2 * 1000 = 2µs
B	2GHz	5	800	0.5ns 5 *800 = 2µs
C	500MHz	1.25	400	2ns 1.25 * 400 = 1µs
D	5GHz	10	2000	0.2ns * 10 * 2000 = 4µs

- Which computer has the highest performance for a given program?

Workload and Benchmark

- *Workload:* Set of programs run on a computer
  - Actual collection of applications run or made from real programs to approximate such a mix
  - Specifies programs, inputs, and relative frequencies
- *Benchmark:* Program selected for use in comparing computer performance
  - Benchmarks form a workload
  - Usually standardized so that many use them

SPEC (System Performance Evaluation Cooperative)

- Computer Vendor cooperative for benchmarks, started in 1989
- SPECCPU2006
  - 12 Integer Programs
  - 17 Floating-Point Programs
- Often turn into number where bigger is faster
- *SPECratio*: reference execution time on old reference computer divide by execution time on new computer to get an effective speed-up

SPEC CPU 2017

SPECrate 2017 Integer	SPECspeed 2017 Integer	Language[1]	KLOC[2]	Application Area
500.perlbench_r	600.perlbench_s	C	362	Perl interpreter
502.gcc_r	602.gcc_s	C	1,304	GNU C compiler
505.mcf_r	605.mcf_s	C	3	Route planning
520.omnetpp_r	620.omnetpp_s	C++	134	Discrete Event simulation - computer network
523.xalancbmk_r	623.xalancbmk_s	C++	520	XML to HTML conversion via XSLT
525.x264_r	625.x264_s	C	96	Video compression
531.deepsjeng_r	631.deepsjeng_s	C++	10	Artificial Intelligence: alpha-beta tree search (Chess)
541.leela_r	641.leela_s	C++	21	Artificial Intelligence: Monte Carlo tree search (Go)
548.exchange2_r	648.exchange2_s	Fortran	1	Artificial Intelligence: recursive solution generator (Sudoku)
557.xz_r	657.xz_s	C	33	General data compression

SPECrate 2017 Floating Point	SPECspeed 2017 Floating Point	Language[1]	KLOC[2]	Application Area
503.bwaves_r	603.bwaves_s	Fortran	1	Explosion modeling
507.cactuBSSN_r	607.cactuBSSN_s	C++, C, Fortran	257	Physics: relativity
508.namd_r		C++	8	Molecular dynamics
510.parest_r		C++	427	Biomedical imaging: optical tomography with finite elements
511.povray_r		C++, C	170	Ray tracing
519.lbm_r	619.lbm_s	C	1	Fluid dynamics
521.wrf_r	621.wrf_s	Fortran, C	991	Weather forecasting
526.blender_r		C++, C	1,577	3D rendering and animation
527.cam4_r	627.cam4_s	Fortran, C	407	Atmosphere modeling
	628.pop2_s	Fortran, C	338	Wide-scale ocean modeling (climate level)
538.imagick_r	638.imagick_s	C	259	Image manipulation
544.nab_r	644.nab_s	C	24	Molecular dynamics
549.fotonik3d_r	649.fotonik3d_s	Fortran	14	Computational Electromagnetics
554.roms_r	654.roms_s	Fortran	210	Regional ocean modeling

[1] For multi-language benchmarks, the first one listed determines library and link options (details)

[2] KLOC = line count (including comments/whitespace) for source files used in a build / 1000

SPECINT2006 on AMD Barcelona

Description	Instruction Count (B)	CPI	Clock cycle time (ps)	Execution Time (s)	Reference Time (s)	SPEC-ratio
Interpreted string processing	2,118	0.75	400	637	9,770	15.3
Block-sorting compression	2,389	0.85	400	817	9,650	11.8
GNU C compiler	1,050	1.72	400	724	8,050	11.1
Combinatorial optimization	336	10.0	400	1,345	9,120	6.8
Go game	1,658	1.09	400	721	10,490	14.6
Search gene sequence	2,783	0.80	400	890	9,330	10.5
Chess game	2,176	0.96	400	837	12,100	14.5
Quantum computer simulation	1,623	1.61	400	1,047	20,720	19.8
Video compression	3,102	0.80	400	993	22,130	22.3
Discrete event simulation library	587	2.94	400	690	6,250	9.1
Games/path finding	1,082	1.79	400	773	7,020	9.1
XML parsing	1,058	2.70	400	1,143	6,900	6.0

Summarizing Performance …

System	Rate (Task 1)	Rate (Task 2)
A	10	20
B	20	10

Clickers: Which system is faster?

A: System A

B: System B

C: Same performance

D: Unanswerable question!

… Depends Who's Selling

System	Rate (Task 1)	Rate (Task 2)	Average
A	10	20	15
B	20	10	15

Average throughput

System	Rate (Task 1)	Rate (Task 2)	Average
A	0.50	2.00	1.25
B	1.00	1.00	1.00

Throughput relative to B

System	Rate (Task 1)	Rate (Task 2)	Average
A	1.00	1.00	1.00
B	2.00	0.50	1.25

Throughput relative to A

Summarizing SPEC Performance

- Varies from 6x to 22x faster than reference computer
- *Geometric mean* of ratios: N-th root of product of N ratios

$$\sqrt[n]{\prod_{i=1}^{n} \text{Execution time ratio}_i}$$

  - Geometric Mean gives same relative answer no matter what computer is used as reference
- Geometric Mean for Barcelona is 11.7

TA Discussion

Jinrui Wang

Q & A

Quiz

Quiz

Piazza: "Online Lecture 17 Benchmarks"

Reply to the post and describe with your own (English) words:

1) Why benchmarking is important (1-2 sentences)
2) Provide a list of items/ concepts that you think influence the measured speed w.r.t. to CPU architecture (5-8 items).
3) Provide a list of items/ concepts that you think influence the measured speed w.r.t. to the software (5-8 items).

CS 110
Computer Architecture
Lecture 17:
Performance & Numbers
Video 2: Multiplication and Division

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Integer Multiplication (1/3)

- Paper and pencil example (unsigned):

```
Multiplicand      1000     8
Multiplier       x1001     9
                 -----
                  1000
                 0000
                0000
             +1000
             --------
             01001000      72
```

- m bits x n bits = m + n bit product

Integer Multiplication (2/3)

- In RISC-V, we multiply registers, so:
  - 32-bit value x 32-bit value = 64-bit value
- Multiplication is ***not*** part of standard RISC-V…
  - Instead it is an ***optional*** extra:
    The compiler needs to produce a series of shifts and adds if the multiplier isn't present
- Syntax of Multiplication (signed):
  - **`mul rd, rs1, rs2`**
  - **`mulh rd, rs1, rs2`**
  - Multiplies 32-bit values in those registers and returns either the lower or upper 32b result
    - If you do mulh/mul back to back, the architecture can fuse them
  - Also unsigned versions of the above

Integer Multiplication (3/3)

- Example:
  - in C: **`a = b * c;`**
    - **`int64_t a; int32_t b, c;`**
    - Aside, these types are defined in C99, in stdint.h
- in RISC-V:
  - let b be **s2**; let c be **s3**; and let a be **s0** and **s1** (since it may be up to 64 bits)

  -
    ```
    mulh s1, s2, s3
    mul s0, s2, s3
    ```

Integer Division (1/2)

- Paper and pencil example (unsigned):
  - Quotient = `1001010 / 1000`
  - Remainder = `1001010 % 1000`

```
                  1001     Quotient
Divisor 1000|1001010       Dividend
           -1000
               10
               101
               1010
              -1000
                 10 Remainder
               (or Modulo result)
```

- Dividend = Quotient x Divisor + Remainder

Integer Division (2/2)

- Syntax of Division (signed):
  - **`div rd, rs1, rs2`**
    `rem rd, rs1, rs2`
  - Divides 32-bit rs1 by 32-bit rs2, returns the quotient (/) for div, remainder (%) for rem
  - Again, can fuse two adjacent instructions
- Example in C: a = c / d; b = c % d;
- RISC-V:
    - a↔s0; b↔s1; c↔s2; d↔s3
  - **`div s0, s2, s3`**
    `rem s1, s2, s3`

Note Optimization...

- A recommended convention

  -
    ```
    mulh s1 s2 s3
    mul s0 s2 s3
    ```

  -
    ```
    div s0 s2 s3
    rem s1 s2 s3
    ```
- Not a ***requirement but***...
  - RISC-V says "if you do it this way, ***and*** the microarchitecture supports it, it can fuse the two operations into one"
  - Same logic behind much of the 16b ISA design:
    If you follow the convention you can get significant optimizations

CS 110 Computer Architecture Lecture 17: *Performance & Numbers* *Video 3: Floating Point Numbers*

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Review of Integer Numbers

- Computers are made to deal with numbers
- What can we represent in N bits?
  - 2^N things, and no more! They could be…
  - Unsigned integers:

    0 to $2^N - 1$

    (for N=32, $2^N – 1 = 4{,}294{,}967{,}295$)
  - Signed Integers (Two's Complement)

    $-2^{(N-1)}$ to $2^{(N-1)} - 1$

    (for N=32, $2^{(N-1)} = 2{,}147{,}483{,}648$)

What about other numbers?

1. Very large numbers? (seconds/millennium)
   => $31{,}556{,}926{,}000_{10}$ ($3.1556926_{10} \times 10^{10}$)
2. Very small numbers? (Bohr radius)
   => 0.000000000052917_{10}m ($5.29177_{10} \times 10^{-11}$)
3. Numbers with <u>both</u> integer & fractional parts?
   => 1.5

First consider #3.

…our solution will also help with #1 and #2.

Representation of Fractions

“Binary Point” like decimal point signifies boundary between integer and fractional parts:

Example 6-bit representation:

$$\underset{2^1}{\mathrm{x}}\,\underset{2^0}{\mathrm{x}}\,.\,\underset{2^{-1}}{\mathrm{y}}\,\underset{2^{-2}}{\mathrm{y}}\,\underset{2^{-3}}{\mathrm{y}}\,\underset{2^{-4}}{\mathrm{y}}$$

$$\mathbf{10.1010_{two} = 1x2^{1} + 1x2^{-1} + 1x2^{-3} = 2.625_{ten}}$$

If we assume “fixed binary point”, range of 6-bit representations with this format:

0 to 3.9375 (almost 4)

Fractional Powers of 2

i	2^{-i}	
0	1.0	1
1	0.5	1/2
2	0.25	1/4
3	0.125	1/8
4	0.0625	1/16
5	0.03125	1/32
6	0.015625	
7	0.0078125	
8	0.00390625	
9	0.001953125	
10	0.0009765625	
11	0.00048828125	
12	0.000244140625	
13	0.0001220703125	
14	0.00006103515625	
15	0.000030517578125	

Representation of Fractions with Fixed Pt.

What about addition and multiplication?

Addition is straightforward:

```
  01.100   1.5ten
+ 00.100   0.5ten
  ------
  10.000   2.0ten
```

Multiplication a bit more complex:

```
       01.100   1.5ten
       00.100   0.5ten
       ------
       00 000
      000 00
     0110 0
    00000
   00000
   ---------
  0000110000
```

Where's the answer, `0.11`? (need to remember where point is)

Representation of Fractions

So far, in our examples we used a "fixed" binary point. What we really want is to "float" the binary point. Why?

Floating binary point most effective use of our limited bits (and thus more accuracy in our number representation):

example: put 0.1640625_{ten} into binary. Represent with 5-bits choosing where to put the binary point.

$$\ldots\ 000000.00\underbrace{10101}00000\ldots$$

Store these bits and keep track of the binary point 2 places to the left of the MSB

Any other solution would lose accuracy!

With floating-point rep., each numeral carries an exponent field recording the whereabouts of its binary point.

The binary point can be outside the stored bits, so very large and small numbers can be represented.

Scientific Notation (in Decimal)

mantissa **exponent**

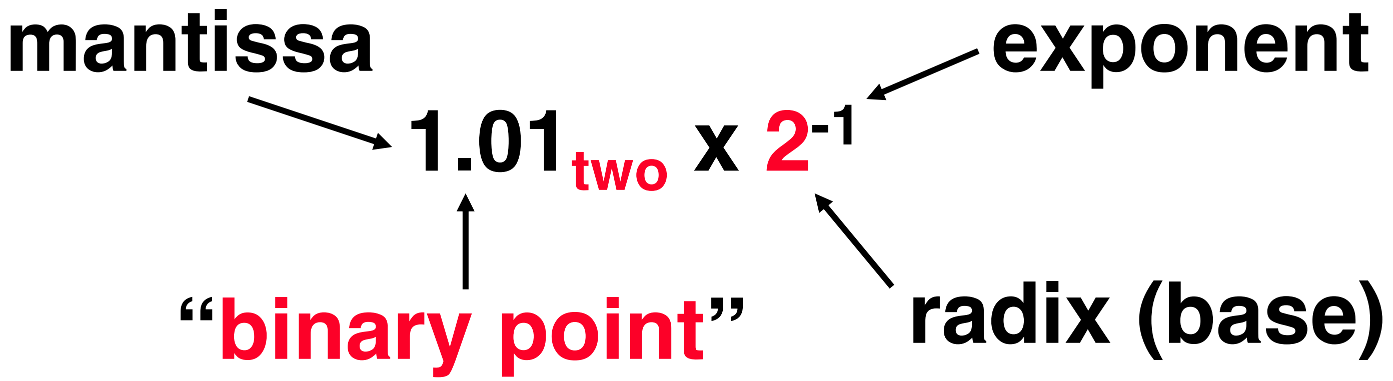
$$6.02_{\text{ten}} \times 10^{23}$$

decimal point **radix (base)**

- Normalized form: no leadings 0s
  (exactly one digit to left of decimal point)

- Alternatives to representing 1/1,000,000,000
  - Normalized: 1.0×10^{-9}
  - Not normalized: $0.1 \times 10^{-8}, 10.0 \times 10^{-10}$

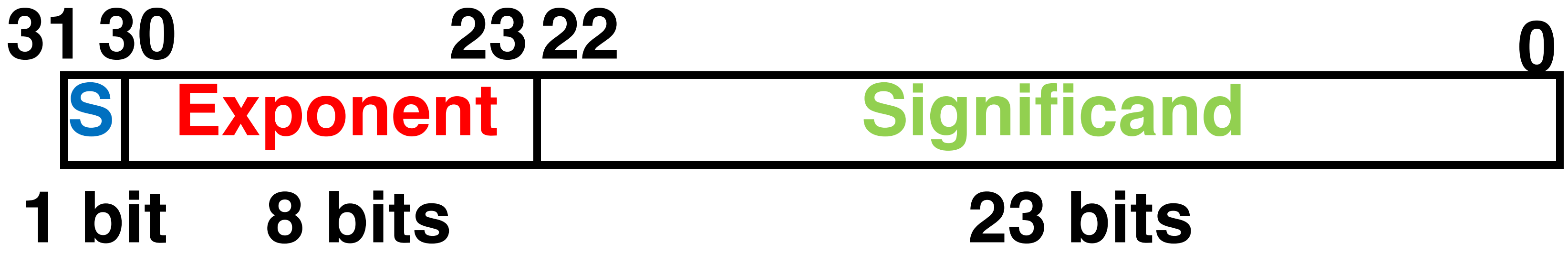
Scientific Notation (in Binary)



- Computer arithmetic that supports it called floating point, because it represents numbers where the binary point is not fixed, as it is for integers
  - Declare such variable in C as `float`
    - `double` for double precision.

Floating-Point Representation (1/2)

- Normal format: $+1.\text{xxx...x}_{\text{two}} * 2^{\text{yyy...y}_{\text{two}}}$
- Multiple of Word Size (32 bits)



- S represents Sign
  Exponent represents y's
  Significand represents x's

- Represent numbers as small as $2.0_{\text{ten}} \times 2^{-126}$ to as large as $2.0_{\text{ten}} \times 2^{127}$

- $2^{126} = 8.507059173023462\text{ e}37 \approx 10^{38}$

Floating-Point Representation (2/2)

- What if result too large?

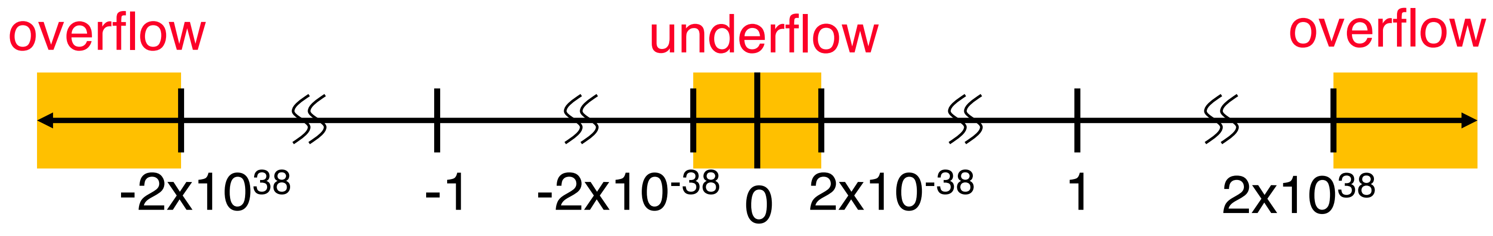
  ($> 2.0\text{x}10^{38}$, $< -2.0\text{x}10^{38}$)

  – **Overflow!** => Exponent larger than represented in 8-bit Exponent field

- What if result too small?

  (>0 & $< 2.0\text{x}10^{-38}$, <0 & $> -2.0\text{x}10^{-38}$)

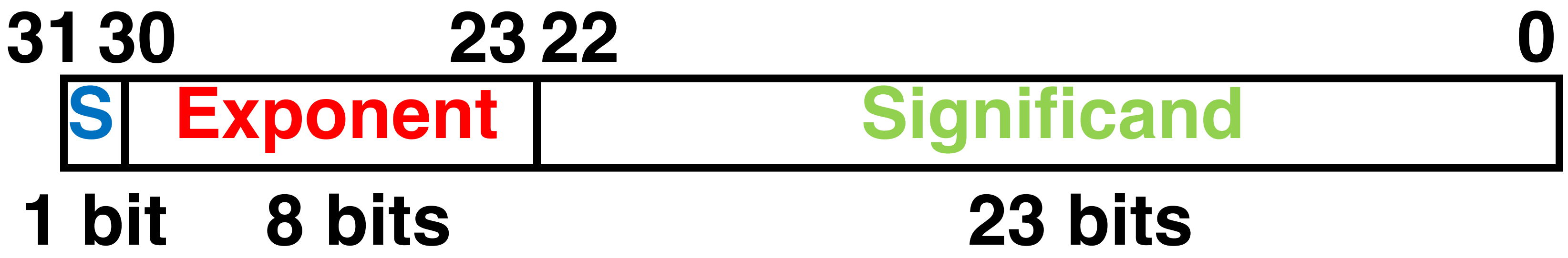
  – **Underflow!** => Negative **exponent** larger than represented in 8-bit Exponent field



- What would help reduce chances of overflow and/or underflow?

IEEE 754 Floating Point Standard (1/3)

Single Precision (Double Precision similar):



- Sign bit: 1 means negative 0 means positive
- Significand in *sign-magnitude* format (not 2's complement)
  - To pack more bits, leading 1 implicit for normalized numbers
  - 1 + 23 bits single, 1 + 52 bits double
  - always true: 0 < Significand < 1 (for normalized numbers)
- Note: 0 has no leading 1, so reserve exponent value 0 just for number 0

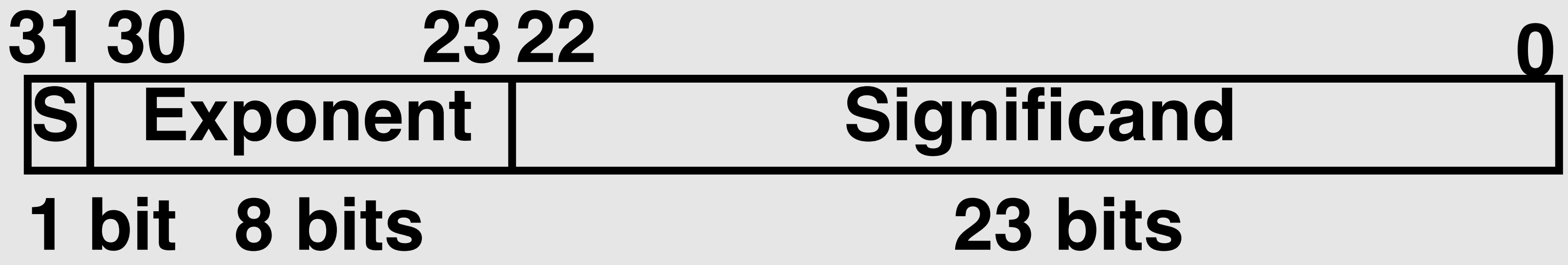
IEEE 754 Floating Point Standard (2/3)

- IEEE 754 uses "biased exponent" representation
  - Designers wanted FP numbers to be used even if no FP hardware; e.g., sort records with FP numbers using integer compares
  - Wanted bigger (integer) exponent field to represent bigger numbers
  - 2's complement poses a problem (because negative numbers look bigger)
    - Use just magnitude and offset by half the range

IEEE 754 Floating Point Standard (3/3)

- Called Biased Notation, where bias is number subtracted to get final number
  - IEEE 754 uses bias of 127 for single prec.
  - Subtract 127 from Exponent field to get actual value for exponent

- **Summary (single precision):**



- **$(-1)^S$ x (1 + Significand) x $2^{(\text{Exponent}-127)}$**

  - Double precision identical, except with exponent bias of 1023 (half, quad similar)

Question

- Guess this Floating Point number:

1 1000 0000 1000 0000 0000 0000 0000 000

A: $-1\text{x } 2^{128}$

B: $+1\text{x } 2^{-128}$

C: $-1\text{x } 2^{1}$

D: $+1.5\text{x } 2^{-1}$

E: $-1.5\text{x } 2^{1}$

Representation for ± ∞

- In FP, divide by 0 should produce ± ∞, not overflow.
- Why?
  - OK to do further computations with ∞
    E.g., X/0 > Y may be a valid comparison

- IEEE 754 represents ± ∞
  - Most positive exponent reserved for ∞
  - Significands all zeroes

Representation for 0

- Represent 0?
  - exponent all zeroes
  - significand all zeroes
  - What about sign? Both cases valid

```
+0: 0 00000000 00000000000000000000000
-0: 1 00000000 00000000000000000000000
```

Special Numbers

- **What have we defined so far? (Single Precision)**

Exponent	Significand	Object
0	0	0
0	nonzero	???
1-254	anything	+/- fl. pt. #
255	0	+/- ∞
255	nonzero	???

- **Clever idea:**
  - Use exp=0,255 & Sig!=0

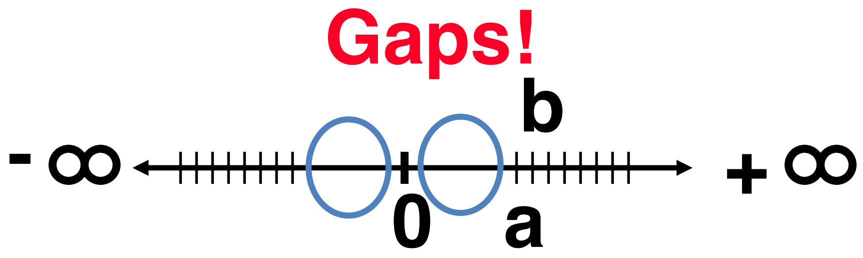
Representation for Not a Number

- What do I get if I calculate
  `sqrt(-4.0)` or `0/0`?
  - If ∞ not an error, these shouldn't be either
  - Called Not a Number (NaN)
  - Exponent = 255, Significand nonzero
- Why is this useful?
  - Hope NaNs help with debugging?
  - They contaminate: op(NaN, X) = NaN
  - Can use the significand to identify which!

Representation for Denorms (1/2)

- Problem: There's a gap among representable FP numbers around 0
  - Smallest representable pos num:
    - a = 1.0… 2 * 2-126 = 2-126
  - Second smallest representable pos num:
    - b = 1.000……1 2 * 2-126
      = (1 + 0.00…12) * 2-126
      = (1 + 2-23) * 2-126
      = 2-126 + 2-149
  - a - 0 = 2-126
  - b - a = 2-149

Normalization and implicit 1 is to blame!

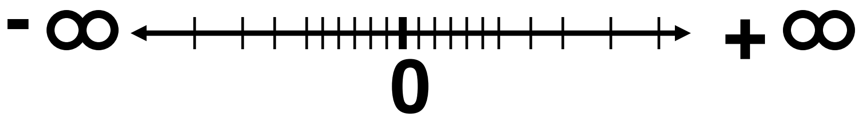


Representation for Denorms (2/2)

- **Solution:**
  - **We still haven't used Exponent = 0, Significand nonzero**
  - **DEnormalized number: no (implied) leading 1, implicit exponent = -126.**
  - **Smallest representable pos num:**

    a = 2^{-149}
  - **Second smallest representable pos num:**

    b = 2^{-148}



Special Numbers Summary

- **Reserve exponents, significands:**

Exponent	**Significand**	**Object**
0	**0**	**0**
0	**nonzero**	**Denorm**
1-254	**anything**	**+/- fl. pt. #**
255	**0**	**+/- ∞**
255	**nonzero**	**NaN**

Conclusion

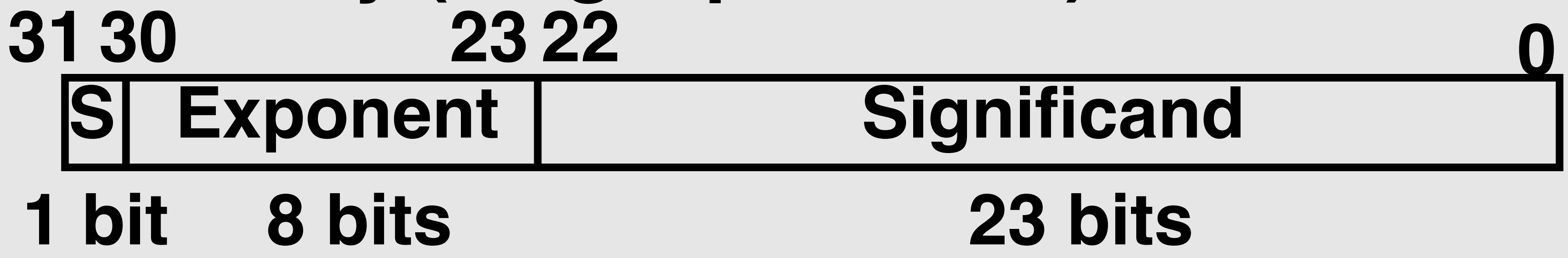
Exponent tells Significand how much (2^i) to count by (…, 1/4, 1/2, 1, 2, …)

- Floating Point lets us:
  - Represent numbers containing both integer and fractional parts; makes efficient use of available bits.
  - Store approximate values for very large and very small #s.

Can store NaN, ± ∞

- IEEE 754 Floating-Point Standard is most widely accepted attempt to standardize interpretation of such numbers (Every desktop or server computer sold since ~1997 follows these conventions)

- Summary (single precision):



- $(-1)^S \times (1 + \text{Significand}) \times 2^{(\text{Exponent}-127)}$

- Double precision identical, except with exponent bias of 1023 (half, quad similar)

And In Conclusion, …

- Time (seconds/program) is measure of performance

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock Cycle}}$$

- Integer Multiplication and Division:
  need 2 result registers!

- Floating-point representations hold approximations of real numbers in a finite number of bits

Question

`Piazza: "Video Lecture 17 Poll"`

- Select the statements that are TRUE regarding IEEE754 floating point numbers:

A. We have a positive and negative 0.
B. Denormalized floats help with overflow.
C. Denormalized floats help with underflow.
D. For NaN the significant has no meaning.