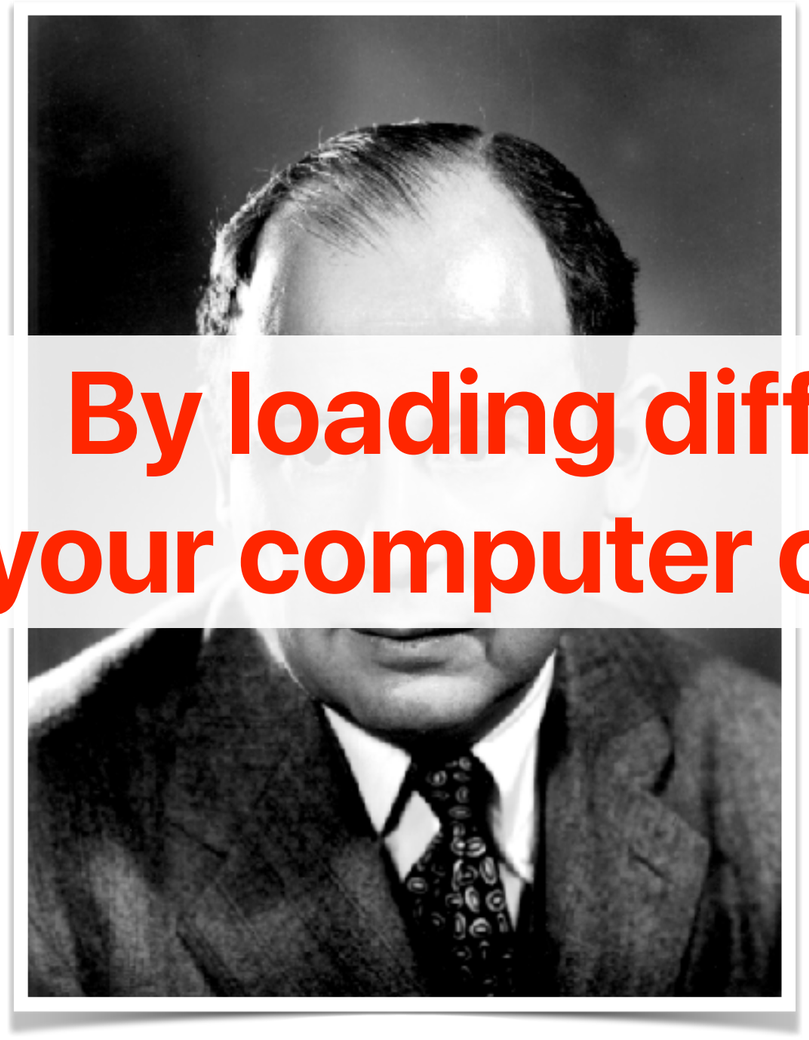
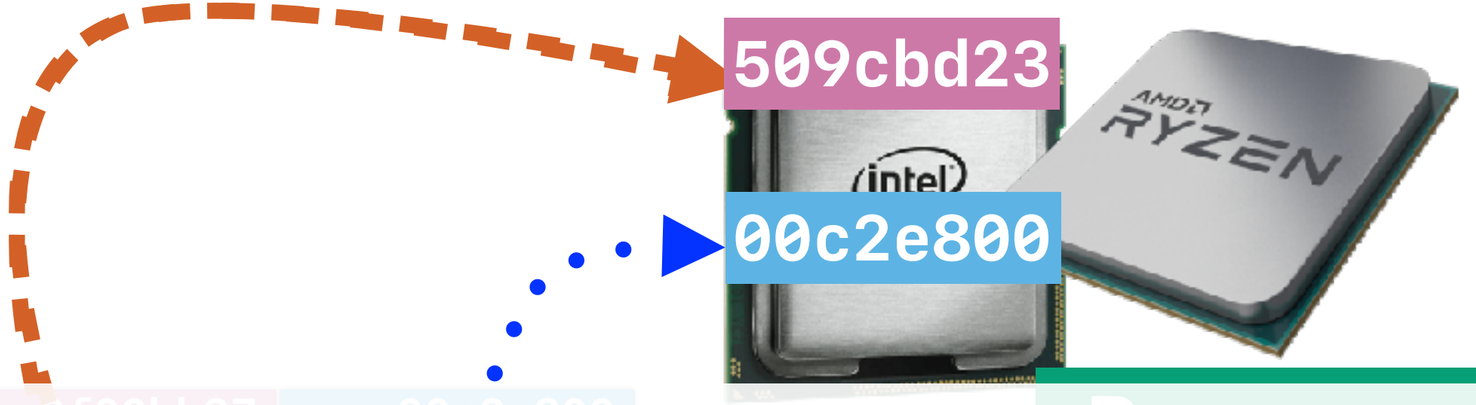
Performance (2): What is better?

Hung-Wei Tseng

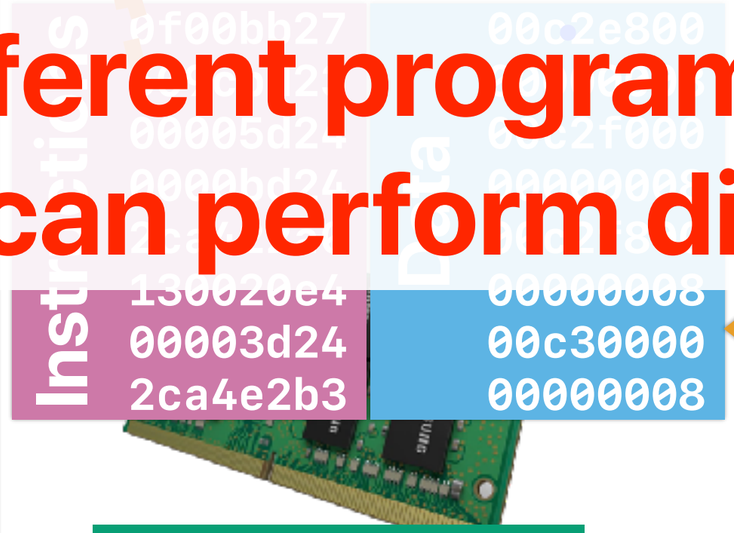
Recap: von Neumman Architecture





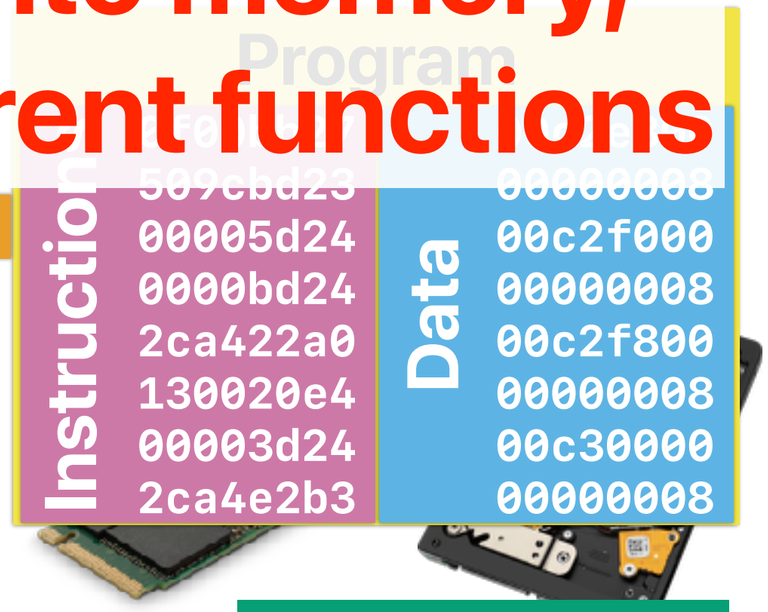
Processor

By loading different programs into memory, your computer can perform different functions



Memory

Program



Storage

Recap: CPU Performance Equation

$$Performance = \frac{1}{Execution\ Time}$$

$$Execution\ Time = \frac{Instructions}{Program} \times \frac{Cycles}{Instruction} \times \frac{Seconds}{Cycle}$$

$$ET = IC \times CPI \times CT$$

$$1GHz = 10^9 Hz = \frac{1}{10^9} sec\ per\ cycle = 1\ ns\ per\ cycle$$

$$\frac{1}{Frequency(i.e., clock\ rate)}$$

Recap: Important performance metrics

- End-to-end latency — how much **time** the program/operation takes from the beginning to the end
- Response time — how much **time** the user starts to feel the program is running/finishing
- Throughput/bandwidth — the average amount of work/data can the program/system deliver within the execution **time**
- Energy consumption — the aggregated power during the execution **time**
- Cost of operation — the amount of money necessary for finishing an operation (related to **time**)
- Quality of results — the human perception of the execution result
- Power consumption — the heat generation produced by the circuit

Recap — programmer & performance

A

```
for(i = 0; i < ARRAY_SIZE; i++)
{
  for(j = 0; j < ARRAY_SIZE; j++)
  {
    c[i][j] = a[i][j]+b[i][j];
  }
}
```

B

```
for(j = 0; j < ARRAY_SIZE; j++)
{
  for(i = 0; i < ARRAY_SIZE; i++)
  {
    c[i][j] = a[i][j]+b[i][j];
  }
}
```

$O(n^2)$	Complexity	$O(n^2)$
Same	Instruction Count?	Same
Same	Clock Rate	Same
Better	CPI	Worse

Recap: Programmer's impact

- By adding the "sort" in the following code snippet, what the programmer changes in the performance equation to achieve **better** performance?

```
std::sort(data, data + arraySize);

for (unsigned c = 0; c < arraySize*1000; ++c) {
        if (data[c%arraySize] >= INT_MAX/2)
            sum ++;
    }
}
```

A. CPI

B. IC ← **programmer changes IC as well, but not in the positive direction**

C. CT

D. IC & CPI

E. CPI & CT

Recap: What matters?

- Execution time is the most essential performance metric
- The following three factors define the execution time of a program
  - Instruction count
  - Cycles per instruction
  - Cycle time
- Programmers can control all factors that affect performance

Outline

- What affects each factor in “Performance Equation” (cont.)
- The definition of “Speedup”
- Amdahl’s law and its implications

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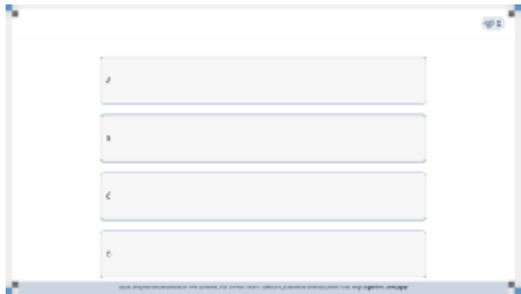
How programming languages affect performance

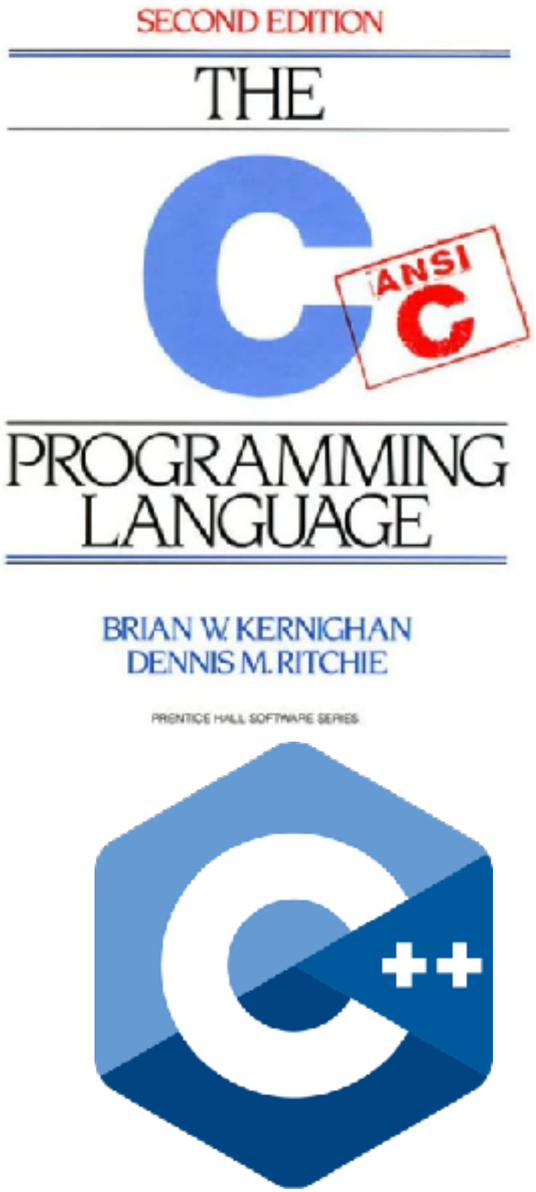
- Performance equation consists of the following three factors
  ① IC
  ② CPI
  ③ CT

  How many can the **programming language** affect?

  A. 0
  B. 1
  C. 2
  D. 3



Programming languages



"Black Perl" [edit]

```
BEFOREHAND: close door, each window & exit; wait until time.
    open spellbook, study, read (scan, select, tell us);
write it, print the hex while each watches,
    reverse its length, write again;
    kill spiders, pop them, chop, split, kill them.
        unlink arms, shift, wait & listen (listening, wait),
sort the flock (then, warn the "goats" & kill the "sheep");
    kill them, dump qualms, shift moralities,
    values aside, each one;
        die sheep! die to reverse the system
        you accept (reject, respect);
next step,
    kill the next sacrifice, each sacrifice,
    wait, redo ritual until "all the spirits are pleased";
    do it ("as they say").
do it(*everyone***must***participate***in***forbidden**s*e*x*).
return last victim; package body;
    exit crypt (time, times & "half a time") & close it,
    select (quickly) & warn your next victim;
AFTERWORDS: tell nobody.
    wait, wait until time;
    wait until next year, next decade;
        sleep, sleep, die yourself,
        die at last
```

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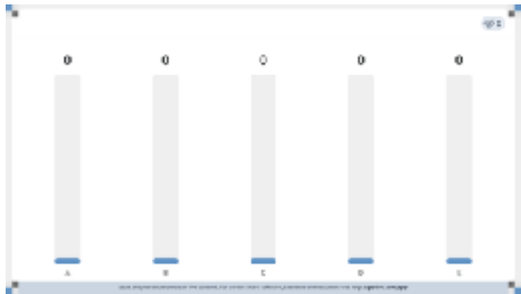
Programming languages

- Which of the following programming language needs to highest instruction count to print “Hello, world!” on screen?
  A. C
  B. C++
  C. Java
  D. Perl
  E. Python



Programming languages

- How many instructions are there in “Hello, world!”

	Instruction count	LOC	Ranking
C	600k	6	1
C++	3M	6	2
Java	~145M	8	5
Perl	~12M	4	3
Python	~33M	1	4
GO (Interpreter)	~1200M	1	6
GO (Compiled)	~1.7M	1	
Rust	~1.4M	1	

Programming languages

- Which of the following programming language needs to highest instruction count to print “Hello, world!” on screen?
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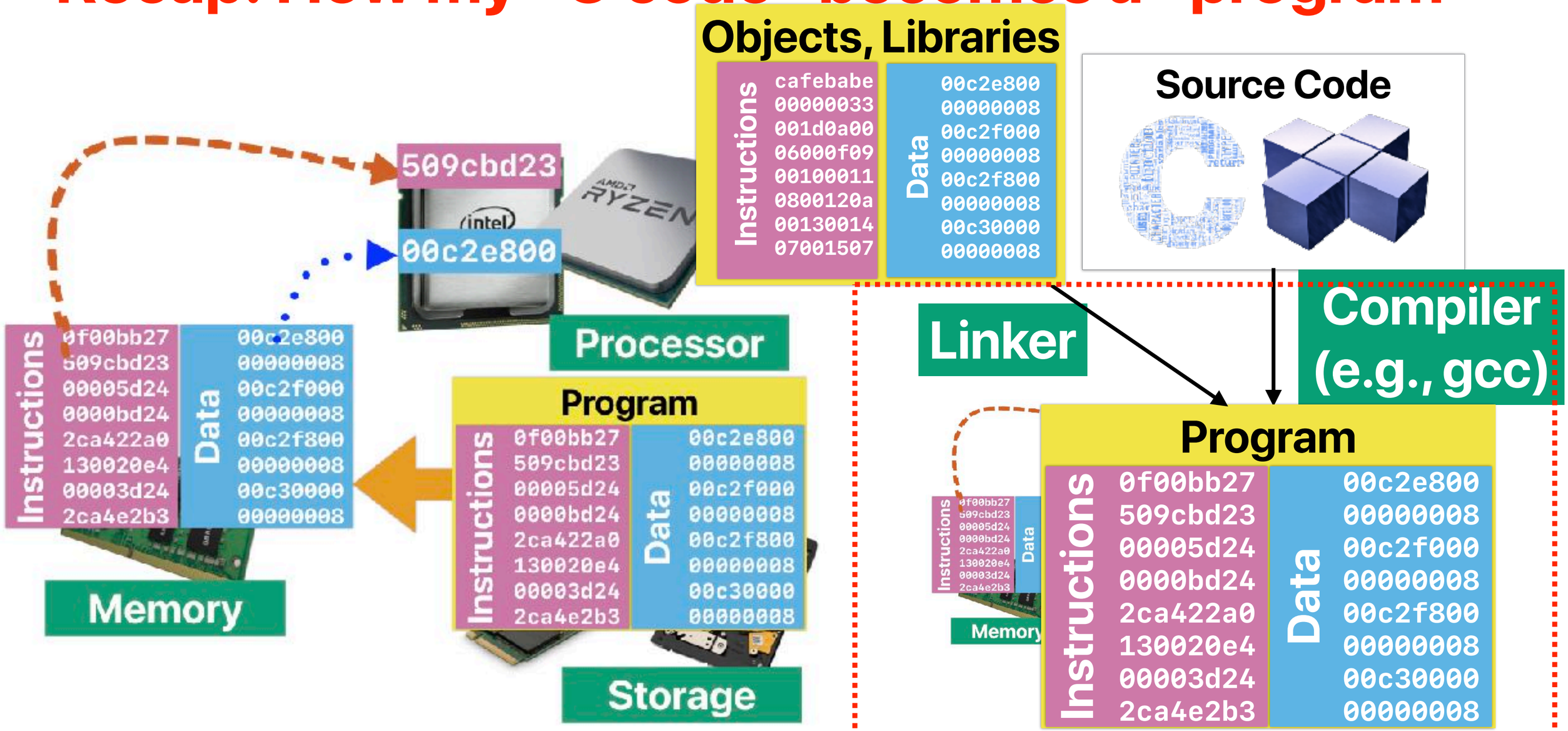
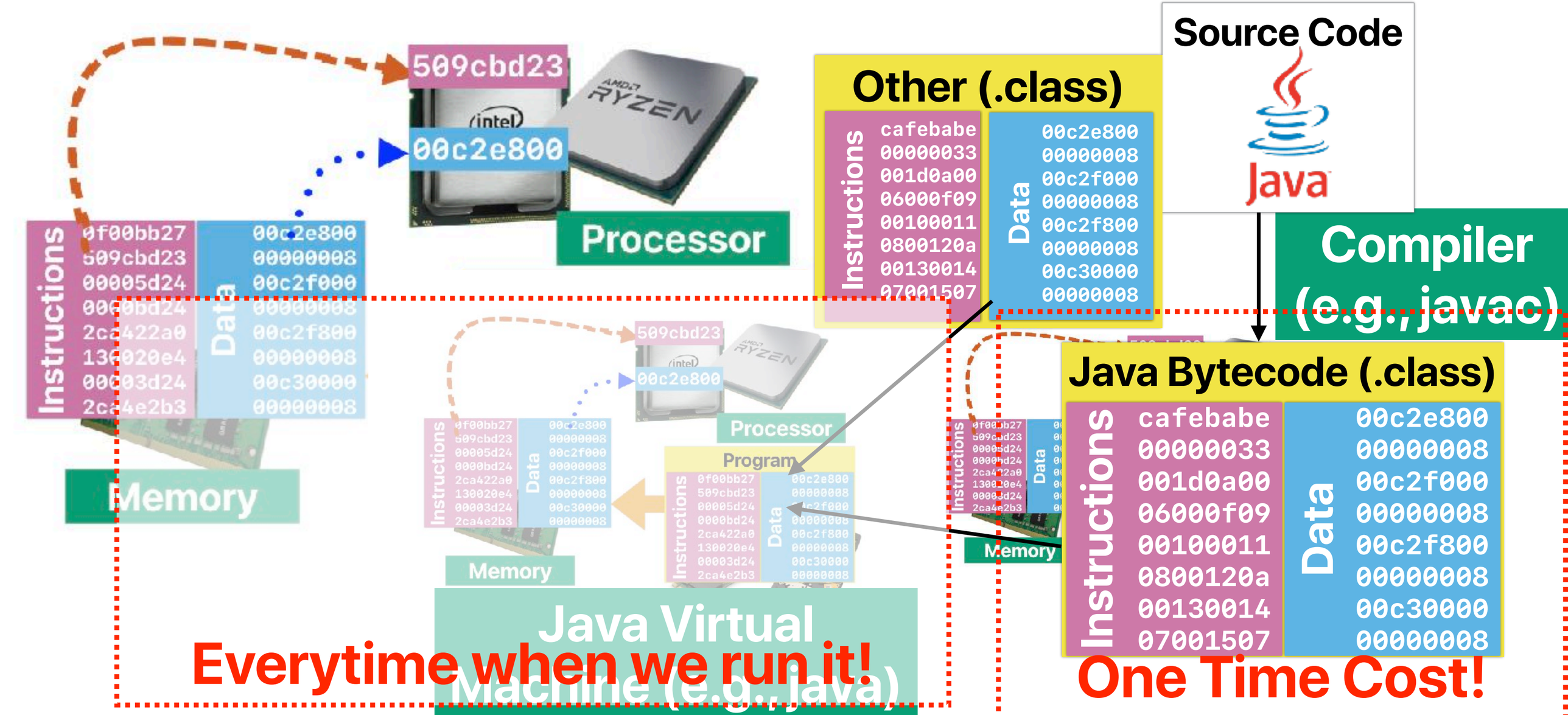
  B. C++
  C. Java
  D. Perl
  E. Python

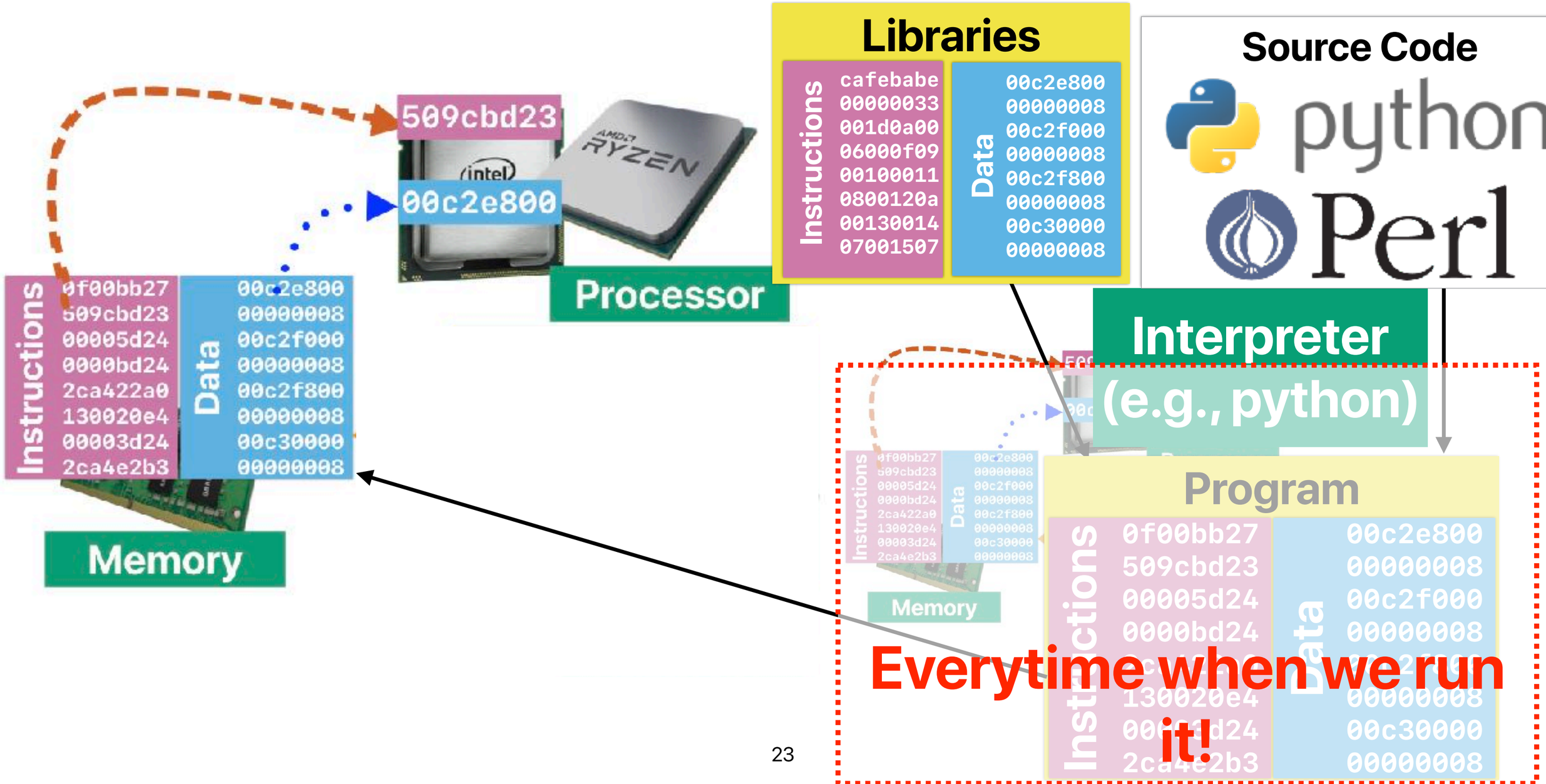
Recap: How my "C code" becomes a "program"



Recap: How my "Java code" becomes a "program"



Recap: How my "Python code" becomes a "program"



How programming languages affect performance

- Performance equation consists of the following three factors
  1. IC
  2. CPI
  3. CT ← **Programmer uses programming languages to create library/ programs that changes the CT, not the programming language itself makes the change**

How many can the **programming language** affect?

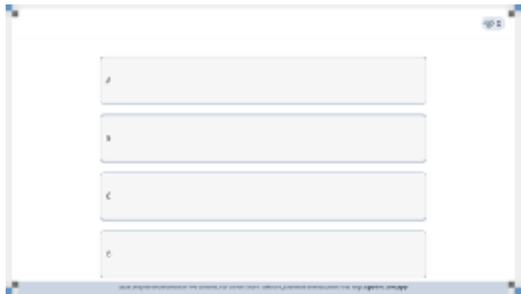
A. 0
B. 1
C. 2
D. 3

How compilers affect performance

- Performance equation consists of the following three factors
  ① IC
  ② CPI
  ③ CT

  How many can the **compiler** affect?

  A. 0
  B. 1
  C. 2
  D. 3



How compilers affect performance

- Performance equation consists of the following three factors
  1. IC
  2. CPI
  3. CT

Compiler is less effective than programmer if the programmer wisely tweaked the code based on architecture!

How many can the **compiler** affect?

A. 0
B. 1
C. 2
D. 3

Revisited the demo with compiler optimizations!

- gcc has different optimization levels.
  - -O0 — no optimizations
  - -O3 — typically the best-performing optimization

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for(i = 0; i < ARRAY_SIZE; i++)
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```
for(j = 0; j < ARRAY_SIZE; j++)
{
  for(i = 0; i < ARRAY_SIZE; i++)
  {
    c[i][j] = a[i][j]+b[i][j];
  }
}
```

- Compiler has limited effect if the programmer did not do it right

Takeaways: What matters?

- Execution time is the most essential performance metric
- The following three factors define the execution time of a program
  - Instruction count
  - Cycles per instruction
  - Cycle time
- Programmers can control all factors that affect performance
- Different programming languages can generate machine operations with different orders of magnitude performance — programmers need to make wise choice of that!
- Compiler optimization can help — but programmers need to write code in a way facilitate optimizations!

How about complexity?

How about “computational complexity”

- Algorithm complexity provides a good estimate on the performance if —
  - Every instruction takes exactly the same amount of time
  - Every operation takes exactly the same amount of instructions

These are unlikely to be true

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Speedup of Y over X

- Consider the same program on the following two machines, X and Y. By how much Y is faster than X?

	Clock Rate	Dynamic Instruction Count	Percentage of Type-A	CPI of Type-A	Percentage of Type-B	CPI of Type-B	Percentage of Type-C	CPI of Type-C
Machine X	4 GHz	5000000000	20%	4	20%	3	60%	1
Machine Y	6 GHz	5000000000	20%	6	20%	4	60%	1

A. 0.2
B. 0.25
C. 0.8
D. 1.25
E. No changes

Speedup

- The relative performance between two machines, X and Y. Y is n times faster than X, or say the speedup of Y over X

$$Speedup = n = \frac{Execution\ Time_X}{Execution\ Time_Y}$$

Speedup of Y over X

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Machine Y	6 GHz	5000000000	20%	6	20%	4	60%	1

A. 0.2
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D. 1.25
E. No changes

$$ET_X = (5 \times 10^9) \times (20\% \times 4 + 20\% \times 3 + 60\% \times 1) \times \frac{1}{4 \times 10^9}\ sec = 2.5\ sec$$

$$ET_Y = (5 \times 10^9) \times (20\% \times 6 + 20\% \times 3 + 60\% \times 1) \times \frac{1}{6 \times 10^9}\ secs = 2\ secs$$

$$Speedup = \frac{Execution\ Time_X}{Execution\ Time_Y}$$

$$= \frac{2.5}{2} = 1.25$$

Takeaways: Are we there yet?

- Definition of "Speedup of Y over X" or say Y is n times faster than X: $speedup_{Y\_over\_X} = n = \frac{Execution\ Time_X}{Execution\ Time_Y}$
-

Amdahl's Law — and It's Implication in the Multicore Era

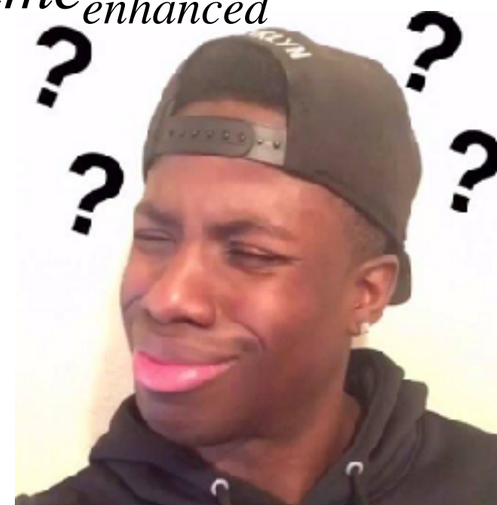
Amdahl's Law

$$Speedup_{enhanced}(f, s) = \frac{1}{(1 - f) + \frac{f}{s}}$$

f — The fraction of time in the original program

s — The speedup we can achieve on f

$$Speedup_{enhanced} = \frac{Execution\ Time_{baseline}}{Execution\ Time_{enhanced}}$$



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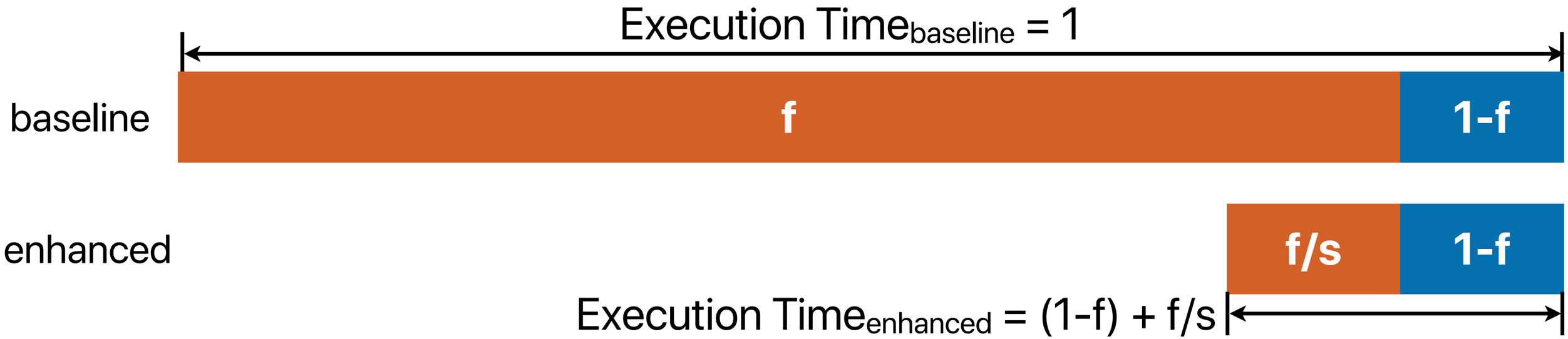

$$Speedup_{enhanced} = \frac{Execution\ Time_{baseline}}{Execution\ Time_{enhanced}} = \frac{1}{(1 - f) + \frac{f}{s}}$$

Takeaways: Are we there yet?

- Definition of "Speedup of Y over X" or say Y is n times faster than X: $speedup_{Y\_over\_X} = n = \frac{Execution\ Time_X}{Execution\ Time_Y}$
- Amdahl's Law — $Speedup_{enhanced}(f, s) = \frac{1}{(1-f) + \frac{f}{s}}$

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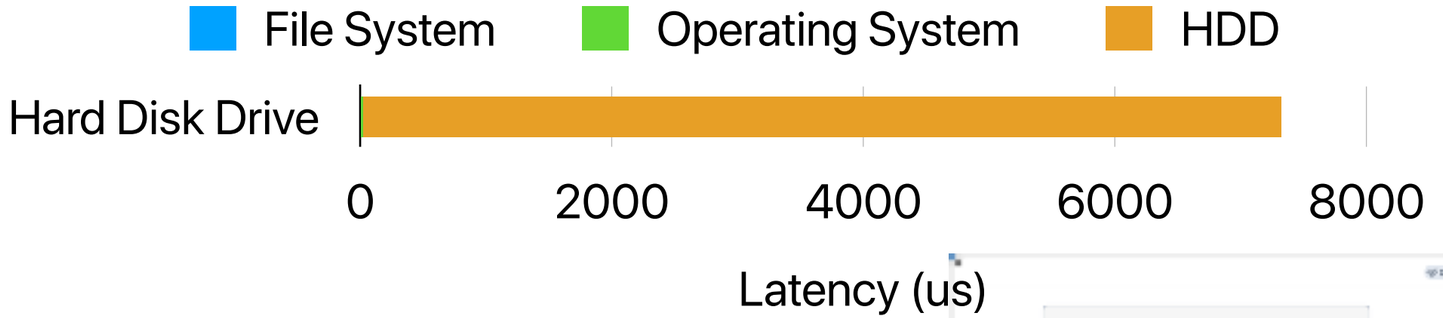
Practicing Amdahl's Law

- Final Fantasy XV spends lots of time loading a map — within which period that 95% of the time on the accessing the H.D.D., the rest in the operating system, file system and the I/O protocol. If we replace the H.D.D. with a flash drive, which provides 100x faster access time. By how much can we speed up the map loading process?
  - A. ~7x
  - B. ~10x
  - C. ~17x
  - D. ~29x
  - E. ~100x



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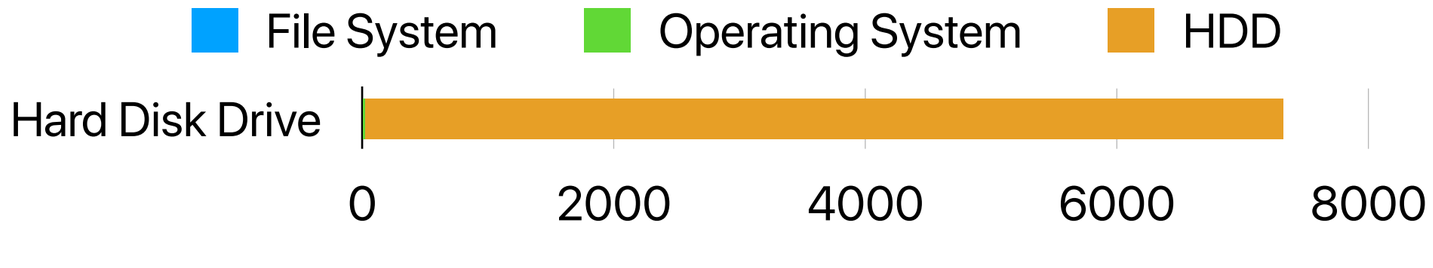

$$Speedup_{enhanced}(95\%, 100) = \frac{1}{(1 - 95\%) + \frac{95\%}{100}} = 16.81\times$$

Amdahl's Law on Multiple Optimizations

- We can apply Amdahl's law for multiple optimizations
- These optimizations must be dis-joint!
  - If optimization #1 and optimization #2 are dis-joint:

$$Speedup_{enhanced}(f_{Opt1}, f_{Opt2}, s_{Opt1}, s_{Opt2}) = \frac{1}{(1 - f_{Opt1} - f_{Opt2}) + \frac{f\_Opt1}{s\_Opt1} + \frac{f\_Opt2}{s\_Opt2}}$$

  - If optimization #1 and optimization #2 are not dis-joint:

$$Speedup_{enhanced}(f_{OnlyOpt1}, f_{OnlyOpt2}, f_{BothOpt1Opt2}, s_{OnlyOpt1}, s_{OnlyOpt2}, s_{BothOpt1Opt2}) = \frac{1}{(1 - f_{OnlyOpt1} - f_{OnlyOpt2} - f_{BothOpt1Opt2}) + + \frac{f\_BothOpt1Opt2}{s\_BothOpt1Opt2} + \frac{f\_OnlyOpt1}{s\_OnlyOpt1} + \frac{f\_OnlyOpt2}{s\_OnlyOpt2}}$$

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Practicing Amdahl's Law (2)

- Final Fantasy XV spends lots of time loading a map — within which period that 95% of the time on the accessing the H.D.D., the rest in the operating system, file system and the I/O protocol. If we replace the H.D.D. with a flash drive, which provides 100x faster access time and a better processor to accelerate the software overhead by 2x. By how much can we speed up the map loading process?

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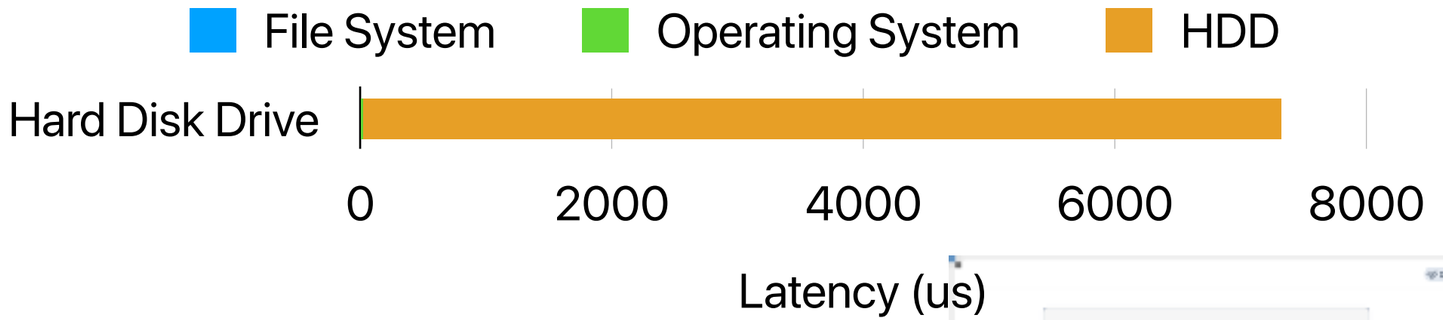
  B. ~10x
  C. ~17x
  D. ~29x
  E. ~100x



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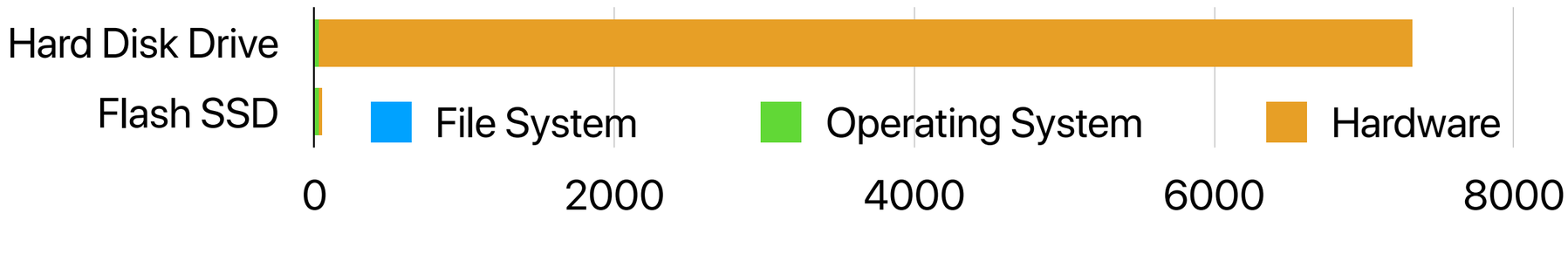
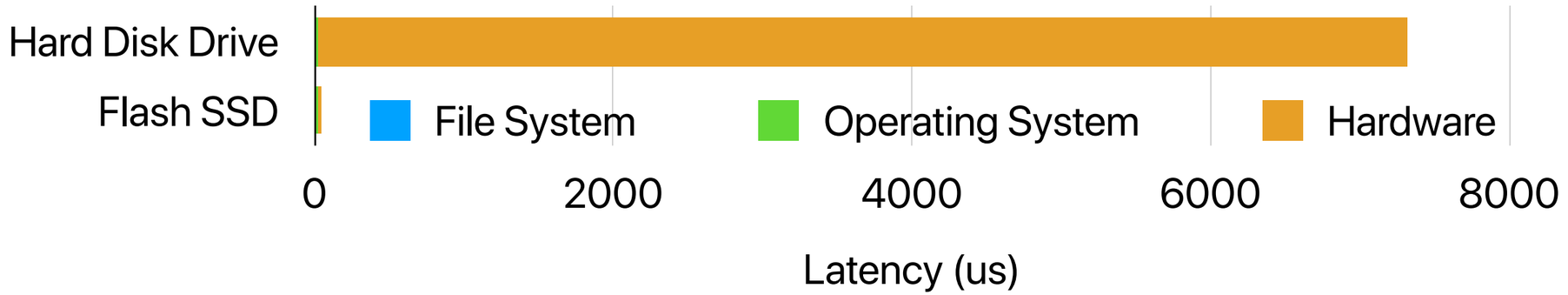


$$Speedup_{enhanced}(95\%, 5\%, 100, 2) = \frac{1}{(1 - 95\% - 5\%) + \frac{95\%}{100} + \frac{5\%}{2}} = 28.98\times$$

Speedup further!

- With the latest flash memory technologies, the system spends 16% of time on accessing the flash, and the software overhead is now 84%. If your company ask you and your team to invent a new memory technology that replaces flash to achieve 2x speedup on loading maps, how much faster the new technology needs to be?

A. ~5x
B. ~10x
C. ~20x
D. ~100x
E. None of the above



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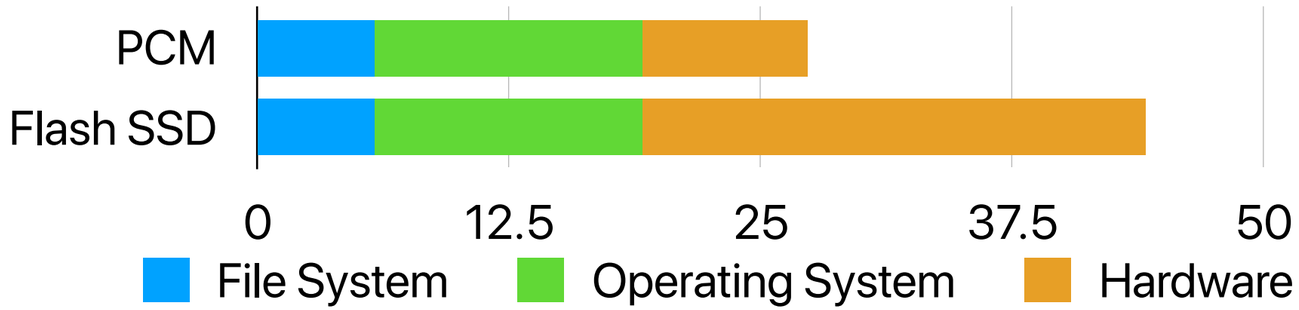

$$Speedup_{enhanced}(16\,\%\,, x) = \frac{1}{(1 - 16\%) + \frac{16\,\%}{x}} = 2$$

$$x = 0.47$$

Does this make sense?

Amdahl's Law Corollary #1

- The maximum speedup of an optimization is bounded by

$$Speedup_{max}(f, \infty) = \frac{1}{(1-f) + \frac{f}{\infty}}$$

$$Speedup_{max}(f, \infty) = \frac{1}{(1-f)}$$

Takeaways: Are we there yet?

- Definition of "Speedup of Y over X" or say Y is n times faster than X: $speedup_{Y\_over\_X} = n = \frac{Execution\ Time_X}{Execution\ Time_Y}$
- Amdahl's Law — $Speedup_{enhanced}(f, s) = \frac{1}{(1-f) + \frac{f}{s}}$ $Speedup_{max}(f, \infty) = \frac{1}{(1-f)}$
  - Corollary 1 — each optimization has an upper bound

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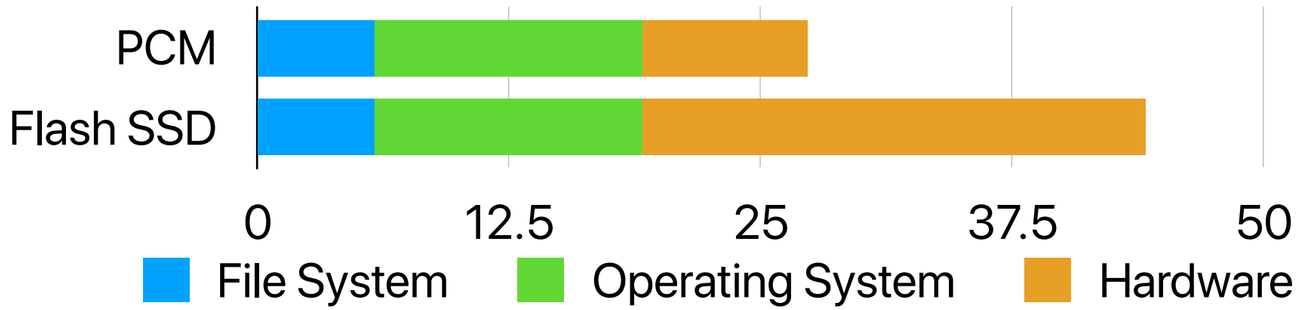

$$Speedup_{max}(16\,\%\,, \infty) = \frac{1}{(1 - 16\%)} = 1.19$$

2x is not possible

NEWS

Intel kills the remnants of Optane memory

The speed-boosting storage tech was already on the ropes.

By Michael Crider
Staff Writer, PCWorld | JUL 29, 2022 6:59 AM PDT

Image: Intel

Announcement

- Assignment #1 due this Thursday
  - We never allow late submission and we will never have deadline extension
  - We autograde everything in your assignment + unlimited submissions before the deadline = start early, receive feedback early, and get good grades
  - No regrading — please make sure your submission can be parsed by the grader correctly
- Assignment #2 due on 4/18
- Check our
  - **website** for slides/grades/schedules
  - **gradescope** for quizzes/assignments
  - **piazza** for discussions
  - **escalab.org/datahub** as the place to work on your assignments
  - there is **no** eLearn for this class
- Youtube channel for lecture recordings: https://www.youtube.com/c/ProfUsagi/playlists

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