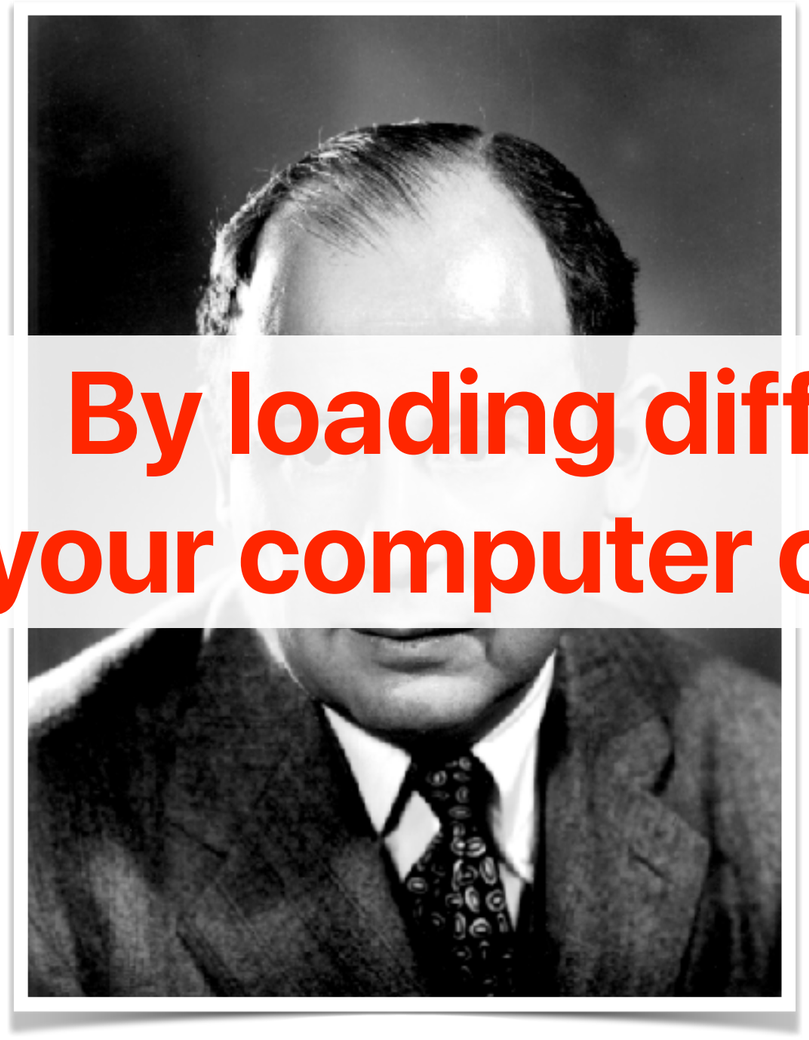
Performance (1): How Good Is "Good"?

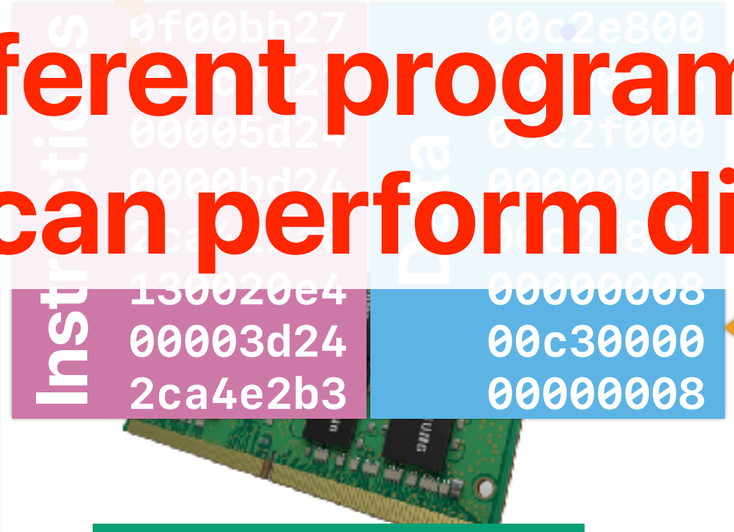
Hung-Wei Tseng

Recap: von Neumman Architecture

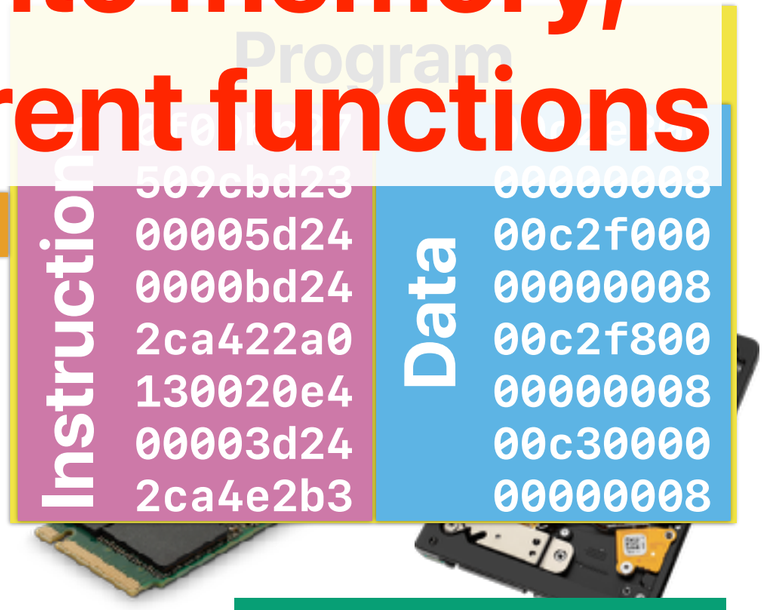


Processor

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



Memory



Storage

Recap: Start with this simple program in C

```
int A[] =
{1,2,3,4,5,6,7,8,9,10,1,2,3,4
,5,6,7,8,9,10};
```

Compiler

```
Contents of section .data:
 0000 01000000 02000000 03000000 04000000
 0010 05000000 06000000 07000000 08000000
 0020 09000000 0a000000 01000000 02000000
 0030 03000000 04000000 05000000 06000000
 0040 07000000 08000000 09000000 0a000000
```

Data

```
int main()
{
    int i=0, sum=0;
    for(i = 0; i < 20; i++)
    {
        sum += A[i];
    }
    return 0;
}
```

control flow operations

logical operations

memory access

arithmetic operations

```
main:
.LFB0:
    endbr64
    pushq   %rbp
    movq    %rsp, %rbp
    movl    $0, -8(%rbp)
    movl    $0, -4(%rbp)
    movl    $0, -8(%rbp)
    jmp .L2
.L3:
    movl    -8(%rbp), %eax
    cltq
    leaq    0(,%rax,4), %rdx
    leaq    A(%rip), %rax
    movl    (%rdx,%rax),
%eax
    addl    %eax, -4(%rbp)
    addl    $1, -8(%rbp)
.L2:
    cmpl    $19, -8(%rbp)
    jle .L3
    movl    $0, %eax
    popq    %rbp
    ret
```

Compiler

```
Contents of section .text:
 0000 f30f1efa 554889e5 c745f800 000000c7
 0010 45fc0000 0000c745 f8000000 00eb1e8b
 0020 45f84898 488d1425 00000000 488d0500
 0030 0000008b 04020145 fc8345f8 01837df8
 0040 137edcb8 00000000 5dc3
```

Instructions

Recap: Demo

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

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

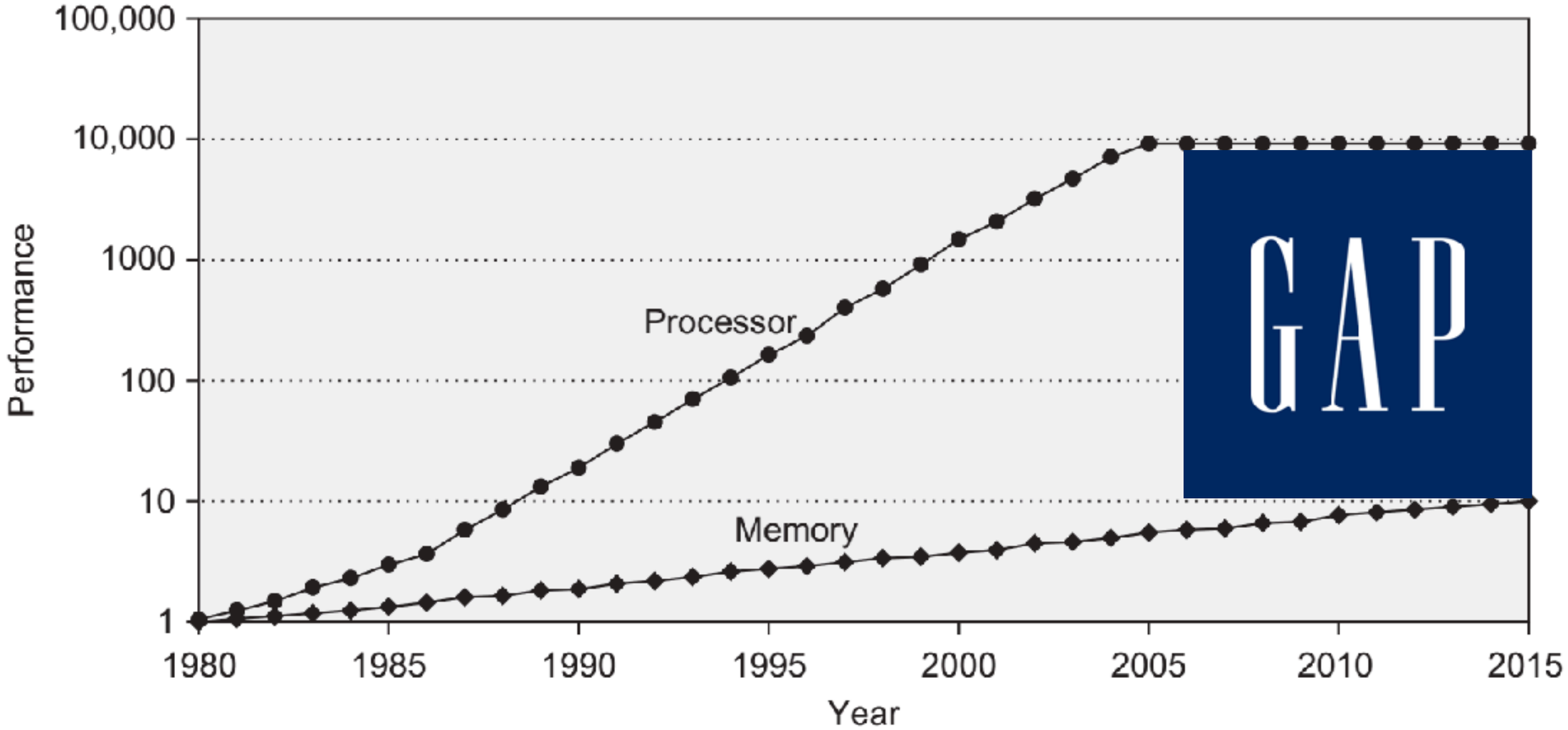
$O(nlog_2n)$

$O(n)$

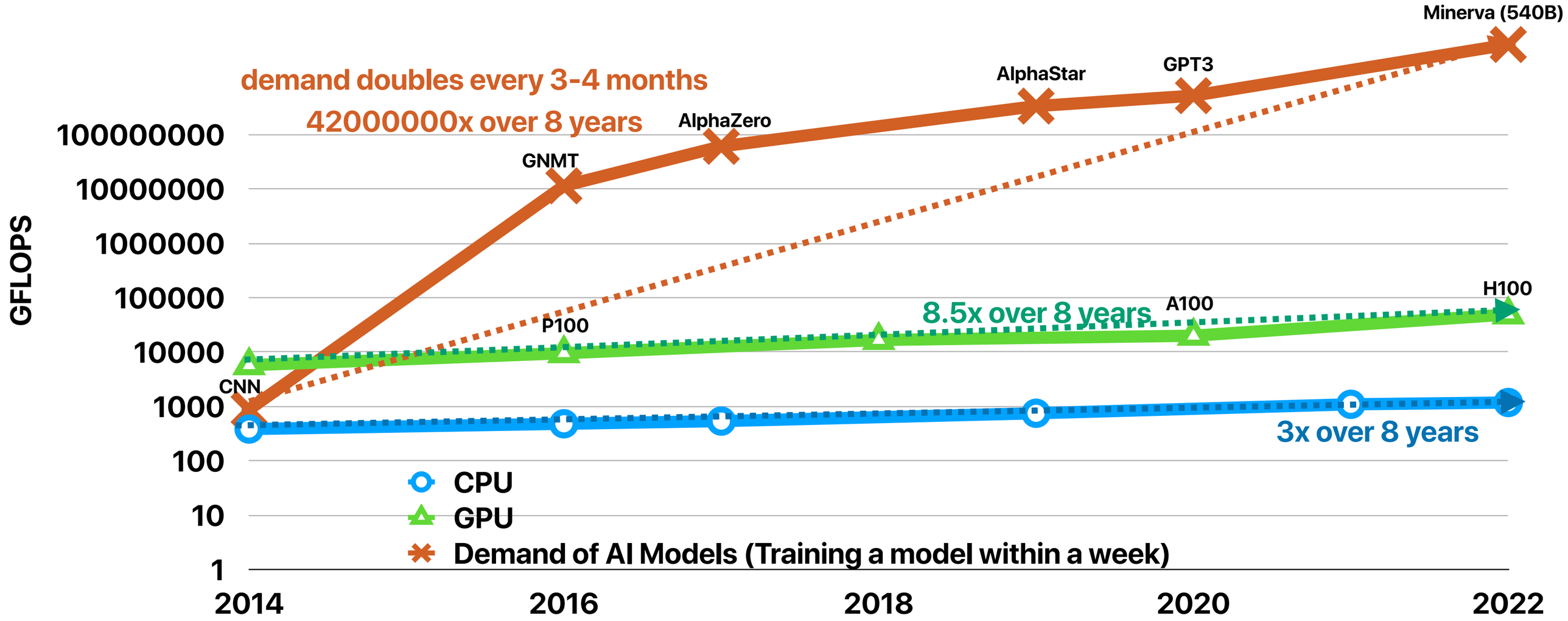
if option is set to 1: $O(nlog_2n)$

otherwise, O(n): $O(n)$

Recap: Performance gap between Processor/Memory



Recap: Mis-matching AI/ML demand and general-purpose processing



https://ourworldindata.org/grapher/artificial-intelligence-training-computation

Outline

- Definition of “Performance”
- The performance equation
- What affects each factor in “Performance Equation”

Best Nation

Schools in the National Univers
a full range of undergraduate r
producing groundbreaking res

To unlock full rankings, SAT/A

SUMMARY

443

Scho

Loca

Rank

Nat

Best Compute

Best Computer Science Schools

Ranked in 2022, part of Best Science S

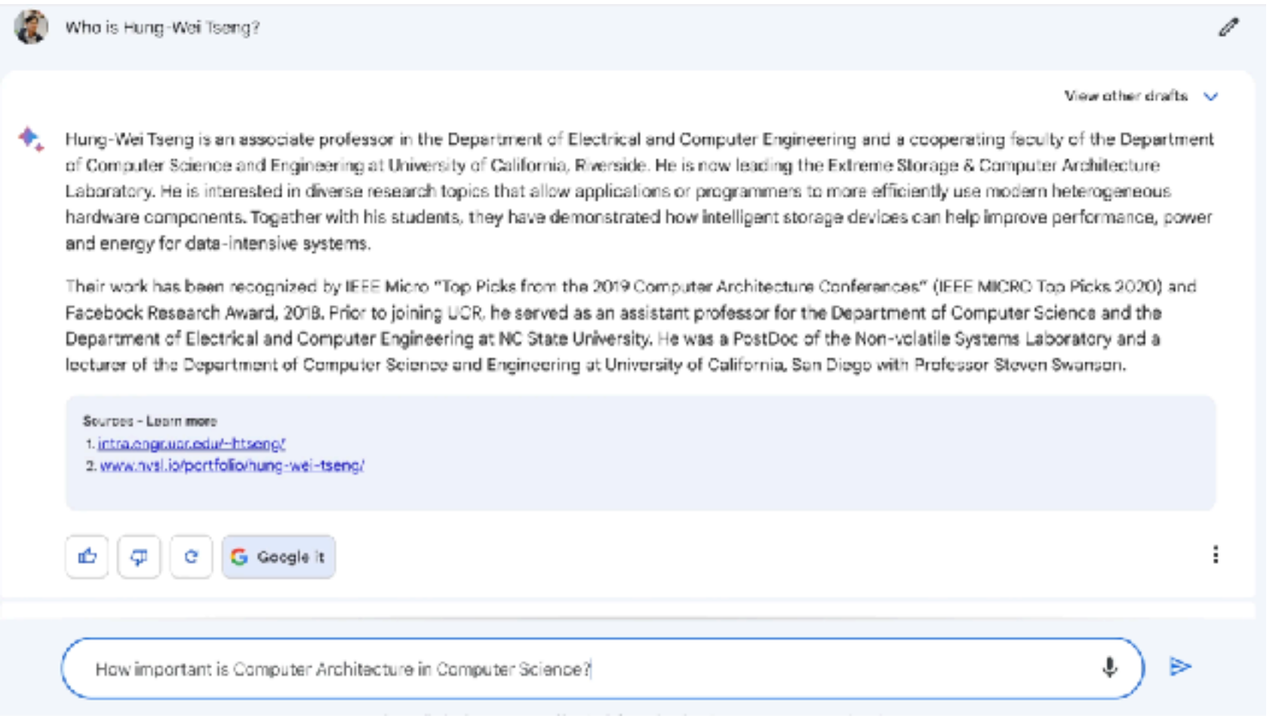
Earning a graduate degree in computer
technology companies and colleges ar
reflects its average rating on a scale fr
institutions. Read the methodology »

UC San Diego Ranked No. 1 Public University by Washington Monthly

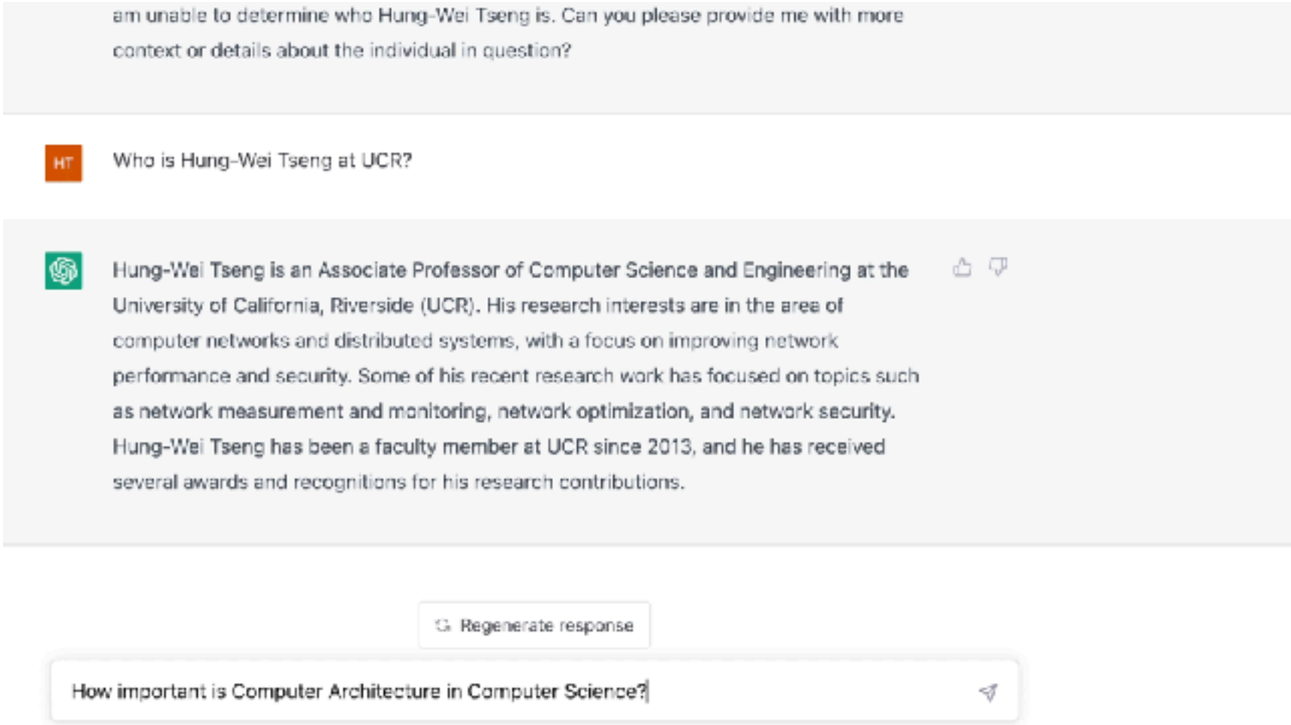
Campus celebrated as a leader in social mobility, research and public

What does it really mean by “better” performance

Bard



182 words/6 secs



170 words/18 secs

Peer instruction

- Before the lecture — You need to complete the required **reading**
- During the lecture — I'll bring in activities to ENGAGE you in exploring your understanding of the material
  - Popup questions
  - Individual **thinking** — use polls in Zoom to express your opinion
  - Group **discussion**
    - Breakout rooms based on your residential colleges!
    - Use polls in Zoom to express your group's opinion
  - Whole-classroom **discussion** — we would like to hear from you

Read **Think** **Discuss**

Now, make sure you login to Poll Everywhere (through the App or the website) with your UCR email

Now, you have at least 90 seconds to answer the question!

Bard v.s. ChatGPT

- Comparing the experiments we have done with Bard and ChatGPT, how many of the following metrics does Bard outperforms ChatGPT?
  - ① Response time
  - ② Throughput
  - ③ End-to-end latency (i.e., total execution time)
  - ④ Quality of results
  - A. 0
  - B. 1
  - C. 2
  - D. 3
  - E. 4

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Performance

- The right metric — latency? throughput? quality of results?
- The same page — everyone needs to compare on the same metric under almost the same criteria — except for the one change you want to compare
- The quantitative comparison — A is better than B by “how much”

Let’s start with “end-to-end latency” as the default metric — how long it takes to execute a program?

CPU Performance Equation (X)

- Assume that we have an application composed with a total of **5,000,000,000** instructions, in which **20%** of them are "Type-A" instructions with an average **CPI of 4** cycles, **20%** of them are "Type-B" instructions with an average **CPI of 3** cycles and the rest instructions are "Type-C" instructions with average **CPI of 1** cycle. If the processor runs at **4 GHz**, how long is the execution time?
  A. 1.25 sec
  B. 2.5 sec
  C. 3.75 sec
  D. 7.5 sec
  E. 40 sec

CPU Performance Equation

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

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

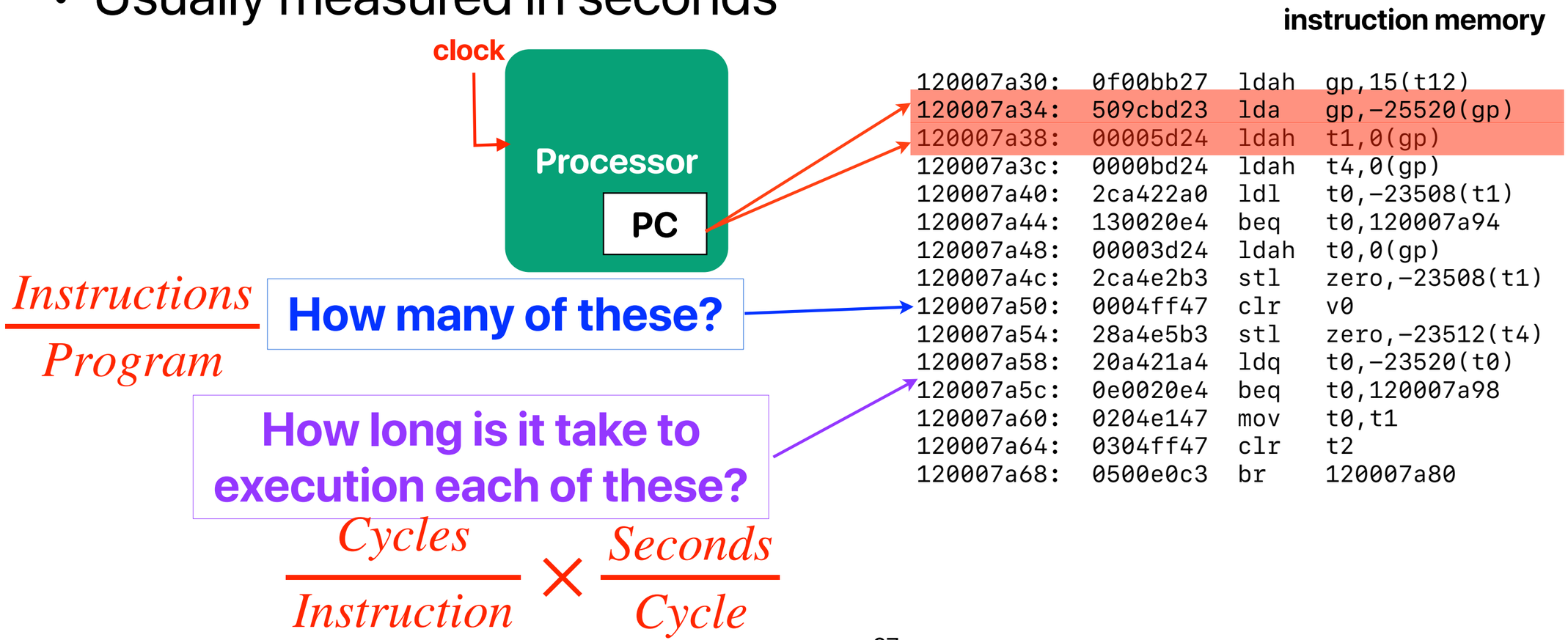
$$ET = IC \times CPI \times CT$$

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

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

Execution Time

- The simplest kind of performance
- Shorter execution time means better performance
- Usually measured in seconds



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  A. 1.25 sec

  B. 2.5 sec

  C. 3.75 sec

  D. 7.5 sec

  E. 40 sec

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

$$ET = (5 \times 10^9) \times \underbrace{(20\% \times 4 + 20\% \times 3 + 60\% \times 1)}_{\text{average CPI}} \times \frac{1}{4 \times 10^9}\ sec = 2.5\ sec$$

Performance equation (round 2)

- Consider the following c code snippet and x86 instructions implement the code snippet

C	x86

`for(i = 0; i < count; i++) {`
`  s += a[i];`
`}`
	`.L3:`
	`movslq  (%rdi), %rdx`
	`addq  $4, %rdi`
	`addq  %rdx, %tax`
	`cmpq  %rcx, %rdi`
	`jne  .L3`

If (1) count is set to 1,000,000,000, (2) a memory instruction takes 4 cycles, (3) a branch/jump instruction takes 3 cycles, (4) other instructions takes 1 cycle on average, and (5) the processor runs at 4 GHz, how much time is it take to finish executing the code snippet?

A. 0.5 sec
B. 1 sec
C. 2.5 sec
D. 3.75 sec
E. 4 sec

Performance equation (round 2)

- Consider the following c code snippet and x86 instructions implement the code snippet

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	`cmpq %rcx, %rdi`
	`jne .L3`

If (1) count is set to 1,000,000,000, (2) a memory instruction takes 4 cycles, (3) a branch/jump instruction takes 3 cycles, (4) other instructions takes 1 cycle on average, and (5) the processor runs at 4 GHz, how much time is it take to finish executing the code snippet?

A. 0.5 sec
B. 1 sec
C. 2.5 sec
D. 3.75 sec
E. 4 sec

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

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

total # of dynamic instructions

average CPI

https://www.pollev.com/hungweitseng close in 1:30

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%	3	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

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

- The speedup of Y over X

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

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	Instructions	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%	3	60%	1

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

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

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

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

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

What Affects Each Factor in Performance Equation

https://www.pollev.com/hungweitseng close in 1:30

What can programmers affect?

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

How many can a **programmer** affect?

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

Demo — 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** $O(n^2)$

Instruction Count?

Clock Rate

CPI

https://www.pollev.com/hungweitseng close in 1:30

Demo — 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];
  }
}
```

How many of the following make(s) the performance different between version A & version B?

① IC

② CPI

③ CT

A. 0

B. 1

C. 2

D. 3

Demo — 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
???	CPI	???

Use “performance counters” to figure out!

- Modern processors provides performance counters
  - instruction counts
  - cache accesses/misses
  - branch instructions/mis-predictions
- How to get their values?
  - You may use “perf stat” in linux
  - You may use Instruments —> Time Profiler on a Mac
  - Intel’s vtune — only works on Windows w/ intel processors
  - You can also create your own functions to obtain counter values

Demo — 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

Demo — 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];
  }
}
```

How many of the following make(s) the performance different between version A & version B?

① IC

② CPI

③ CT

A. 0

B. 1

C. 2

D. 3

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
C. CT
D. IC & CPI
E. CPI & CT

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

Announcement

- Reading quiz due next Tuesday before the lecture
  - We will drop one of your least performing reading quizzes
  - You have unlimited time
- Assignment #1 due this Thursday
  - You need to agree the course agreement to start — if you have done it late but haven't send us an e-mail explaining why, you're not allowed to start
- Assignment #2 up this evening and due next Thursday
- Office Hour tomorrow will be online — please find the link in the calendar
- Lecture this Thursday likely to be online — please find the link in the calendar
- Check our website for slides, gradescope for quizzes/assignments, piazza for discussions
- Youtube channel for lecture recordings: https://www.youtube.com/c/ProfUsagi/playlists

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