

# Memory & Caches I

CSE 351 Winter 2022

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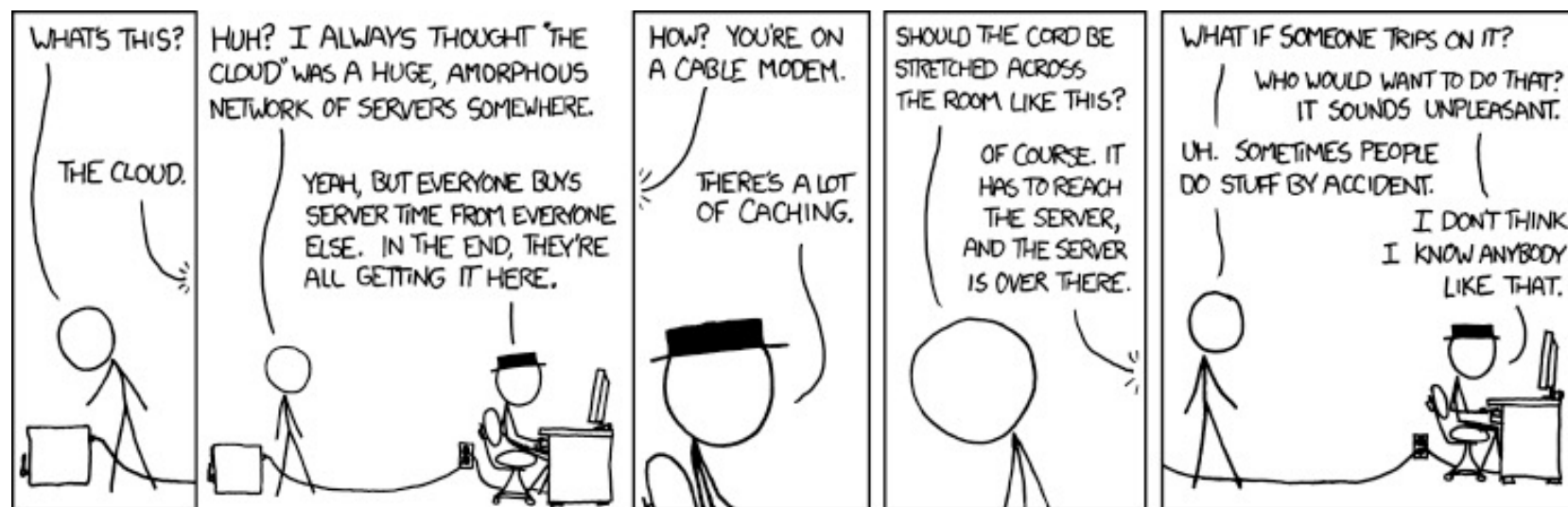
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Nick Durand



# Relevant Course Information

- ❖ Lab 3 due next Wednesday (2/16)
  - Tips in section this week
- ❖ Mid-Quarter Survey due next Monday (2/14)
  - Let us know how the course is going for you!
  - There are some questions about the midterm, so we recommend completing that first
- ❖ No lecture this Friday
  - Sam will hold office hours instead (location TBD)

# Midterm Details

- ❖ Released tomorrow at 11:59pm, due Friday 11:59pm
  - We will post on Ed discussion
  - Late submissions are not permitted
- ❖ Distributed as PDF that you will fill out and then submit via Gradescope
  - Print and hand-write, type with Adobe Reader, use e-ink with a tablet, whatever you prefer, as long as it's legible 😊
  - Many scanner apps available, please ensure that scans are clear and straight!
- ❖ I can print some copies and distribute them in lecture on Wednesday, if there's interest.

# Midterm Details

- ❖ Gilligan's Island Rule
  - You are allowed to meet with fellow students and discuss questions
  - Writing on a whiteboard or shared piece of paper is acceptable
  - However, you may not take any written record away from the meeting (electronic or otherwise)
  - After the meeting, engage in a half hour of mind-numbing activity, like watching an episode of Gilligan's Island, before working on the exam
- ❖ Course staff will be available on Ed or in office hours to answer clarifying questions (but cannot help you solve problems)
- ❖ Open book, open note, open Internet, open ( . ) \*
  - Designed such that critical thinking will still be required 😊

# The Hardware/Software Interface

## ❖ Topic Group 1: **Data**

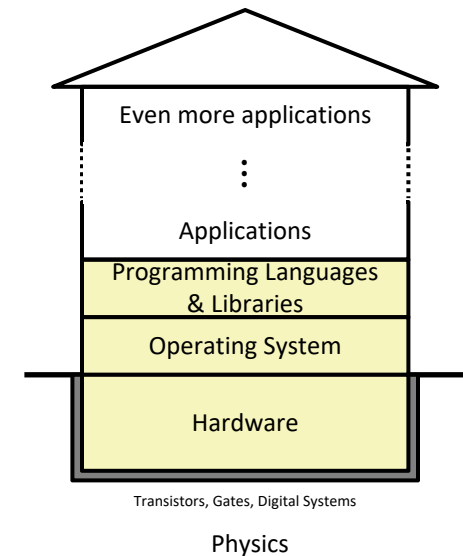
- Memory, Data, Integers, Floating Point, Arrays, Structs

## ❖ Topic Group 2: **Programs**

- x86-64 Assembly, Procedures, Stacks, Executables

## ❖ Topic Group 3: **Scale & Coherence**

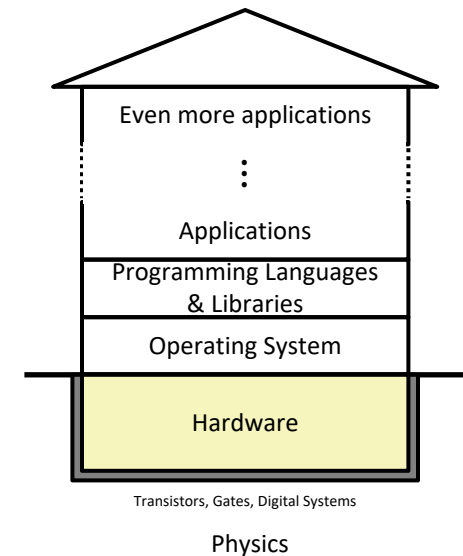
- Caches, Processes, Virtual Memory, Memory Allocation



# The Hardware/Software Interface

## ❖ Topic Group 3: **Scale & Coherence**

- **Caches**, Processes, Virtual Memory, Memory Allocation



- ❖ How do we maintain logical consistency in the face of more data and more processes?
  - How do we support control flow both within many processes and things external to the computer?
  - How do we support data access, including dynamic requests, across multiple processes?

# Aside: Units and Prefixes (Review)

- ❖ Here focusing on large numbers (exponents  $> 0$ )
- ❖ Note that  $10^3 \approx 2^{10}$
- ❖ SI prefixes are *ambiguous* if base 10 or 2
- ❖ IEC prefixes are *unambiguously* base 2

SIZE PREFIXES ( $10^x$  for Disk, Communication;  $2^x$  for Memory)

SI Size	Prefix	Symbol	IEC Size	Prefix	Symbol
$10^3$	Kilo-	K	$2^{10}$	Kibi-	Ki
$10^6$	Mega-	M	$2^{20}$	Mebi-	Mi
$10^9$	Giga-	G	$2^{30}$	Gibi-	Gi
$10^{12}$	Tera-	T	$2^{40}$	Tebi-	Ti
$10^{15}$	Peta-	P	$2^{50}$	Pebi-	Pi
$10^{18}$	Exa-	E	$2^{60}$	Exbi-	Ei
$10^{21}$	Zetta-	Z	$2^{70}$	Zebi-	Zi
$10^{24}$	Yotta-	Y	$2^{80}$	Yobi-	Yi

# How to Remember?

- ❖ Will be given to you on Final reference sheet
- ❖ Mnemonics
  - There unfortunately isn't one well-accepted mnemonic
    - But that shouldn't stop you from trying to come with one!
  - **K**iller **M**echanical **G**iraffe **T**eaches **P**et, **E**xtinct **Z**ebra to **Y**odel
  - **K**irby **M**issed **G**anondorf **T**erribly, **P**otentially **E**xterminating **Z**elda and **Y**oshi
  - xkcd: **K**arl **M**arx **G**ave **T**he **P**roletariat **E**leven **Z**eppelins, **Y**o
    - <https://xkcd.com/992/>
  - Post your best on Ed Discussion!



# Reading Review

- ❖ Terminology:
  - Caches: cache blocks, cache hit, cache miss
  - Principle of locality: temporal and spatial
  - Average memory access time (AMAT): hit time, miss penalty, hit rate, miss rate
- ❖ Questions from the Reading?

# Review Questions

❖ Convert the following to or from IEC:

- 512 Ki-books =  $\boxed{2^{19} \text{ books}}$   
 $2^9 \times 2^{10}$
- $2^{27}$  caches =  $\boxed{128 \text{ Mi-caches}}$   
 $2^7 \times 2^{20}$

❖ Compute the average memory access time (AMAT) for the following system properties:

- Hit time of 1 ns
- Miss rate of 1%
- Miss penalty of 100 ns

$$\begin{aligned} \text{AMAT} &= \text{HT} + \text{MR} \times \text{MP} \\ &= 1 \text{ ns} + 0.01(100 \text{ ns}) \\ &= 1 \text{ ns} + 1 \text{ ns} \end{aligned}$$

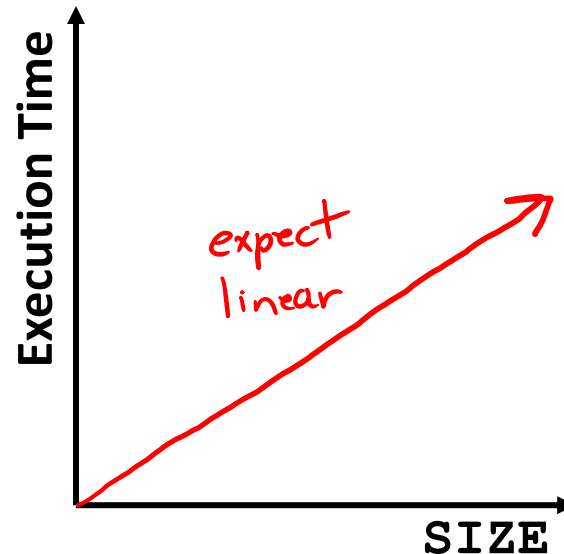
$$\boxed{\text{AMAT} = 2 \text{ ns}}$$

# How does execution time grow with SIZE?

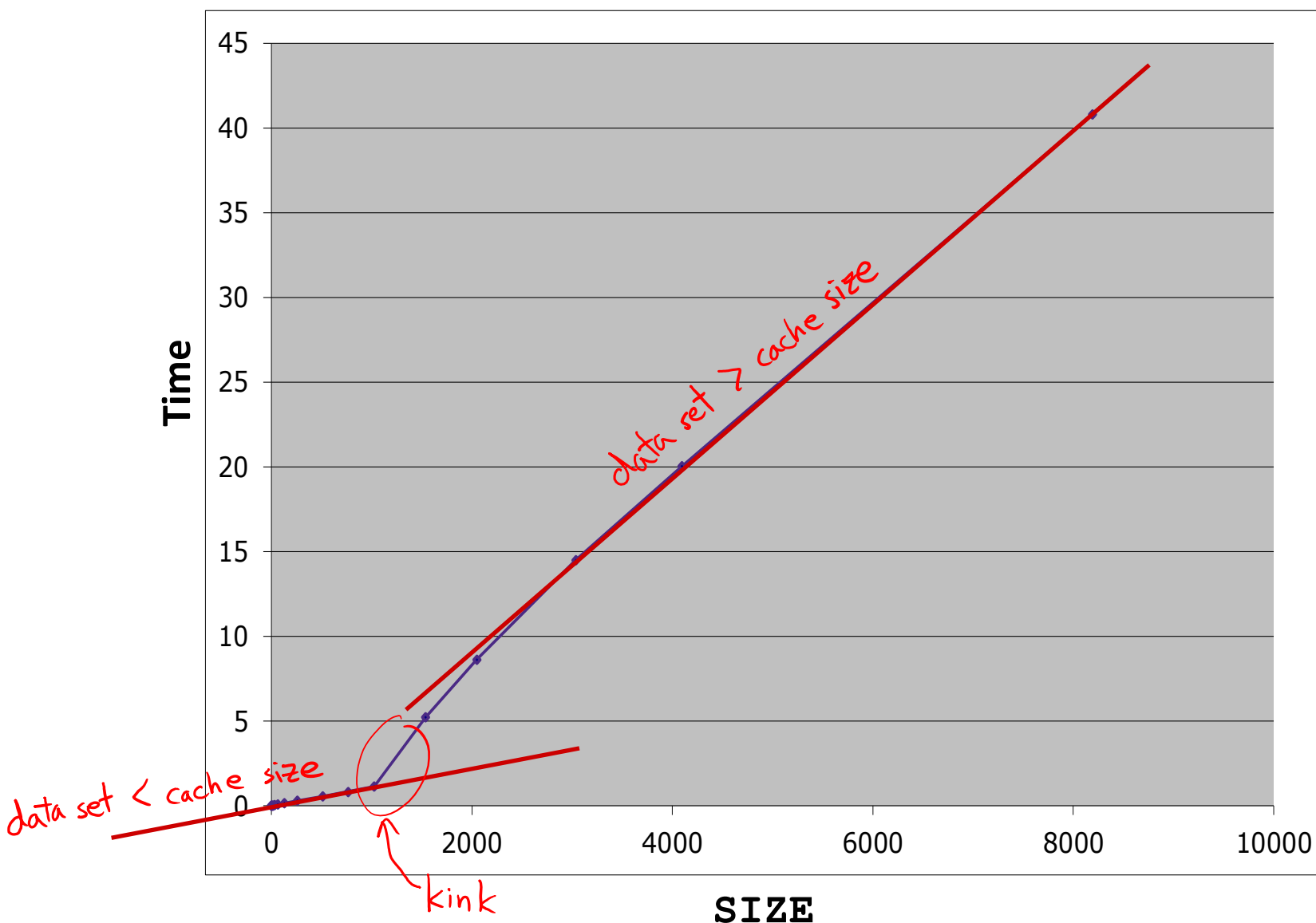
```
int array[SIZE];  
int sum = 0;  
  
for (int i = 0; i < 200000; i++) {  
    for (int j = 0; j < SIZE; j++) {  
        sum += array[j]; ← execute SIZE × 200,000 times  
    }  
}
```

repeat 200,000 times

Plot:



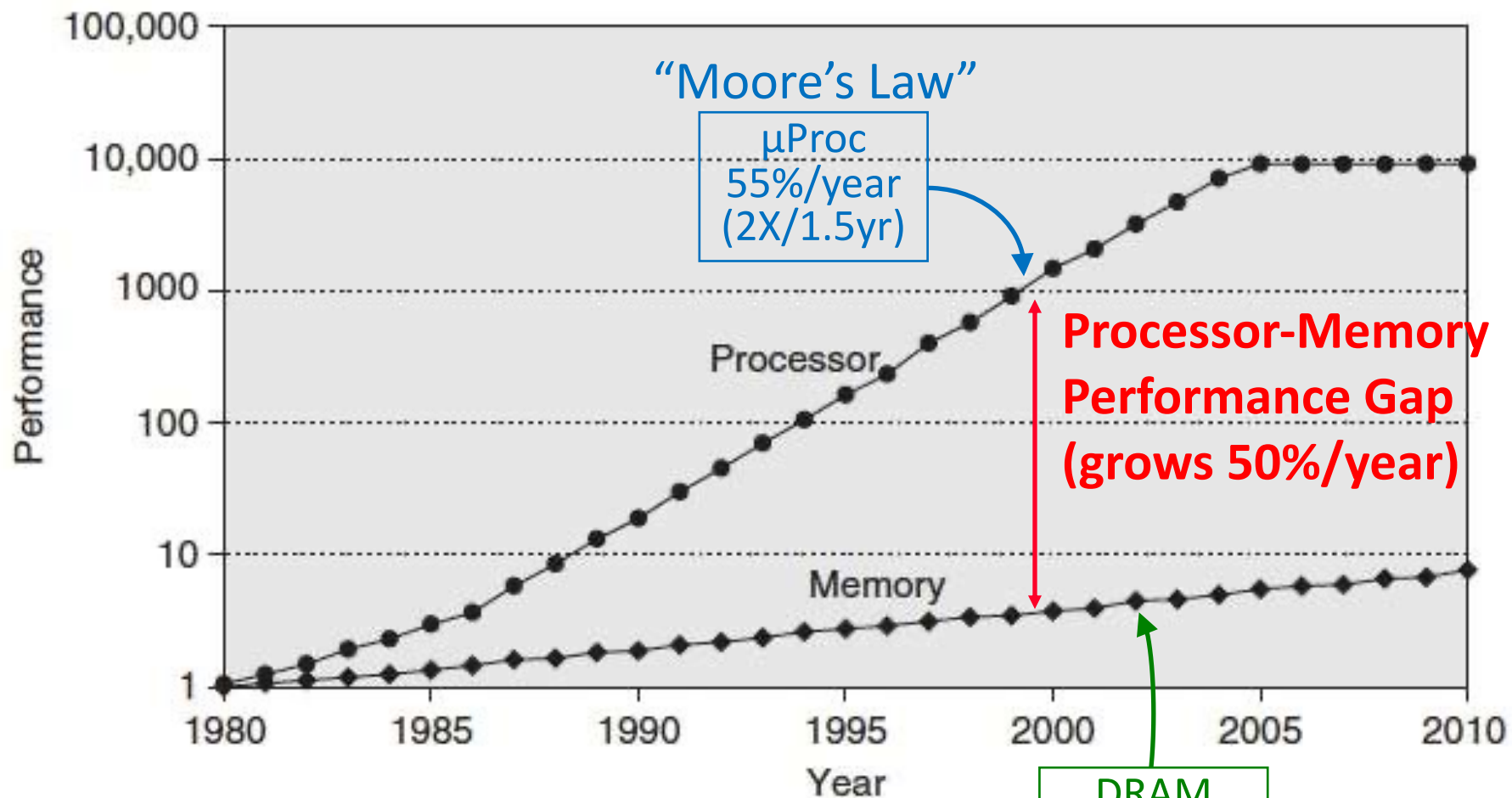
# Actual Data



# Making memory accesses fast!

- ❖ **Cache basics**
- ❖ **Principle of locality**
- ❖ **Memory hierarchies**
- ❖ Cache organization
- ❖ Program optimizations that consider caches

# Processor-Memory Gap

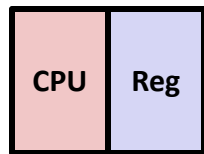


**1989** first Intel CPU with cache on chip

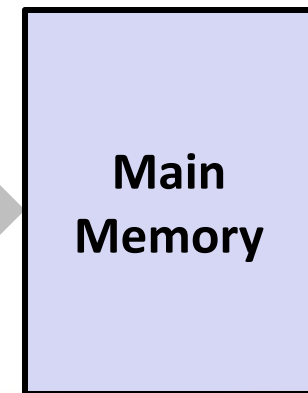
**1998** Pentium III has two cache levels on chip

# Problem: Processor-Memory Bottleneck

Processor performance  
doubled about  
every 18 months



Bus latency / bandwidth  
evolved much slower



**Core 2 Duo:**  
Can process at least  
256 Bytes/cycle

**Core 2 Duo:**  
Bandwidth  
2 Bytes/cycle  
Latency  
! 100-200 cycles (30-60ns)



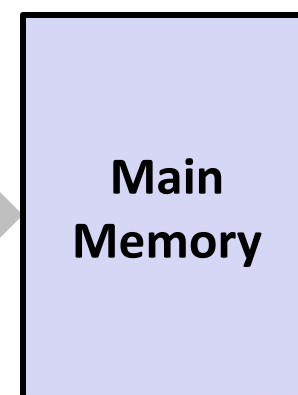
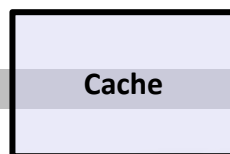
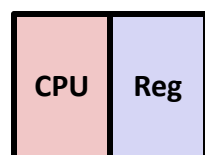
***Problem: lots of waiting on memory***

*cycle: single machine step (fixed-time)*

# Problem: Processor-Memory Bottleneck

Processor performance  
doubled about  
every 18 months

Bus latency / bandwidth  
evolved much slower



**Core 2 Duo:**

Can process at least  
256 Bytes/cycle



*fridge/  
pantry*

**Core 2 Duo:**

Bandwidth  
2 Bytes/cycle  
Latency

100-200 cycles (30-60ns)



*grocery store*

**Solution: caches**



*sandwich  
to mouth*

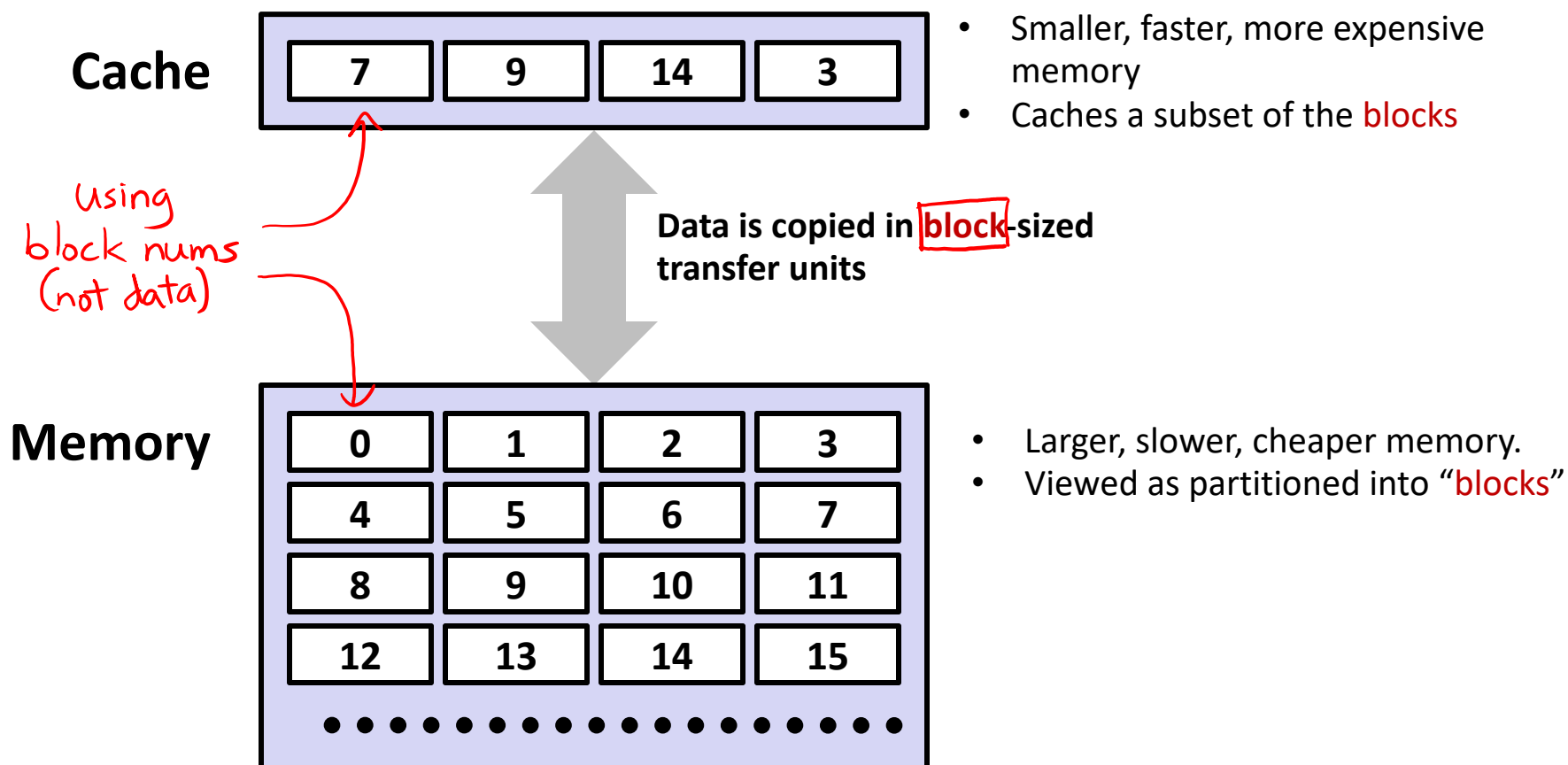
*cycle: single machine step (fixed-time)*



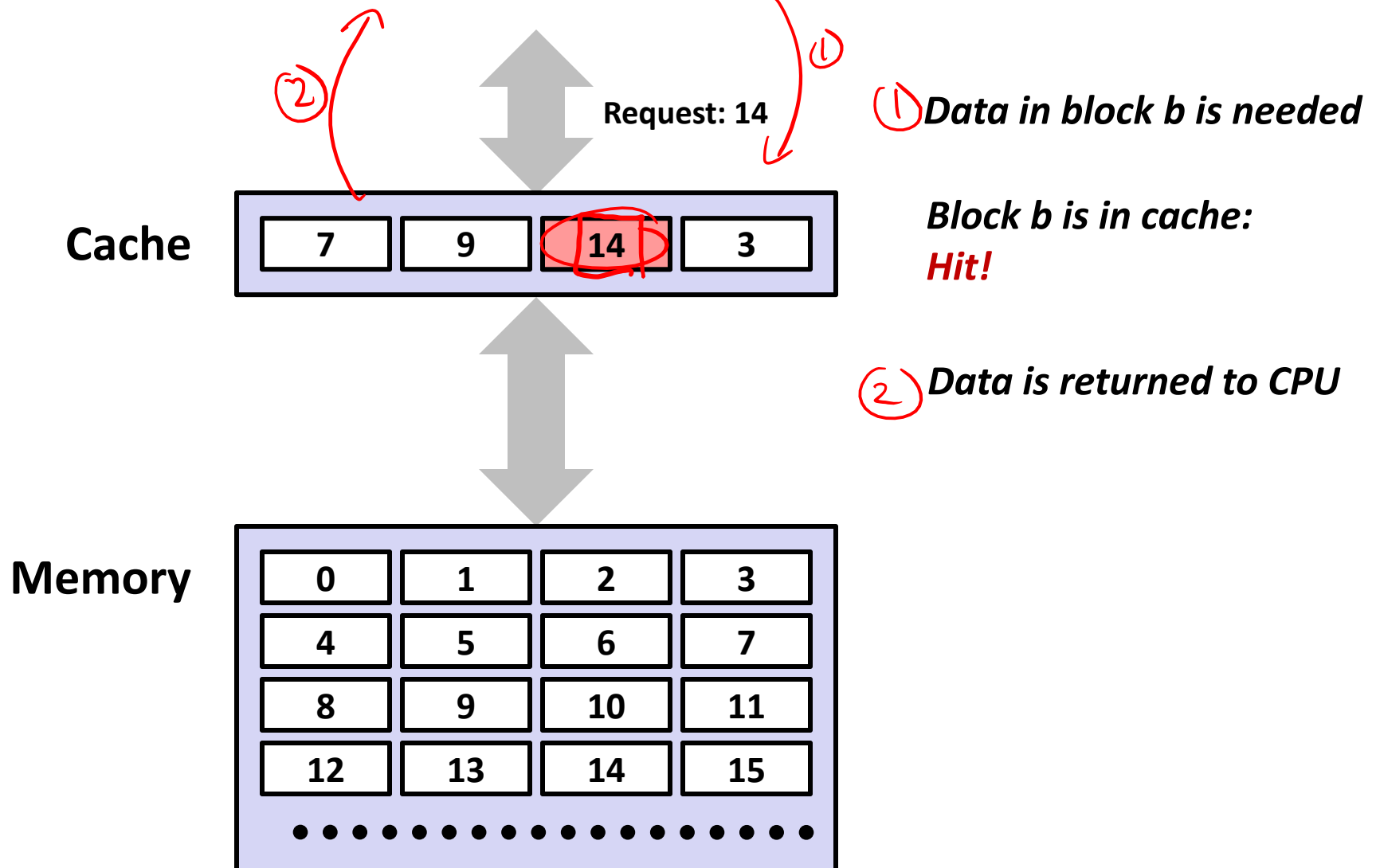
# Cache

- ❖ Pronunciation: “cash”
  - We abbreviate this as “\$”
- ❖ English: A hidden storage space for provisions, weapons, and/or treasures
- ❖ Computer: Memory with short access time used for the storage of frequently or recently used instructions (i-cache/I\$) or data (d-cache/D\$)
  - *More generally*: Used to optimize data transfers between any system elements with different characteristics (network interface cache, I/O cache, etc.)

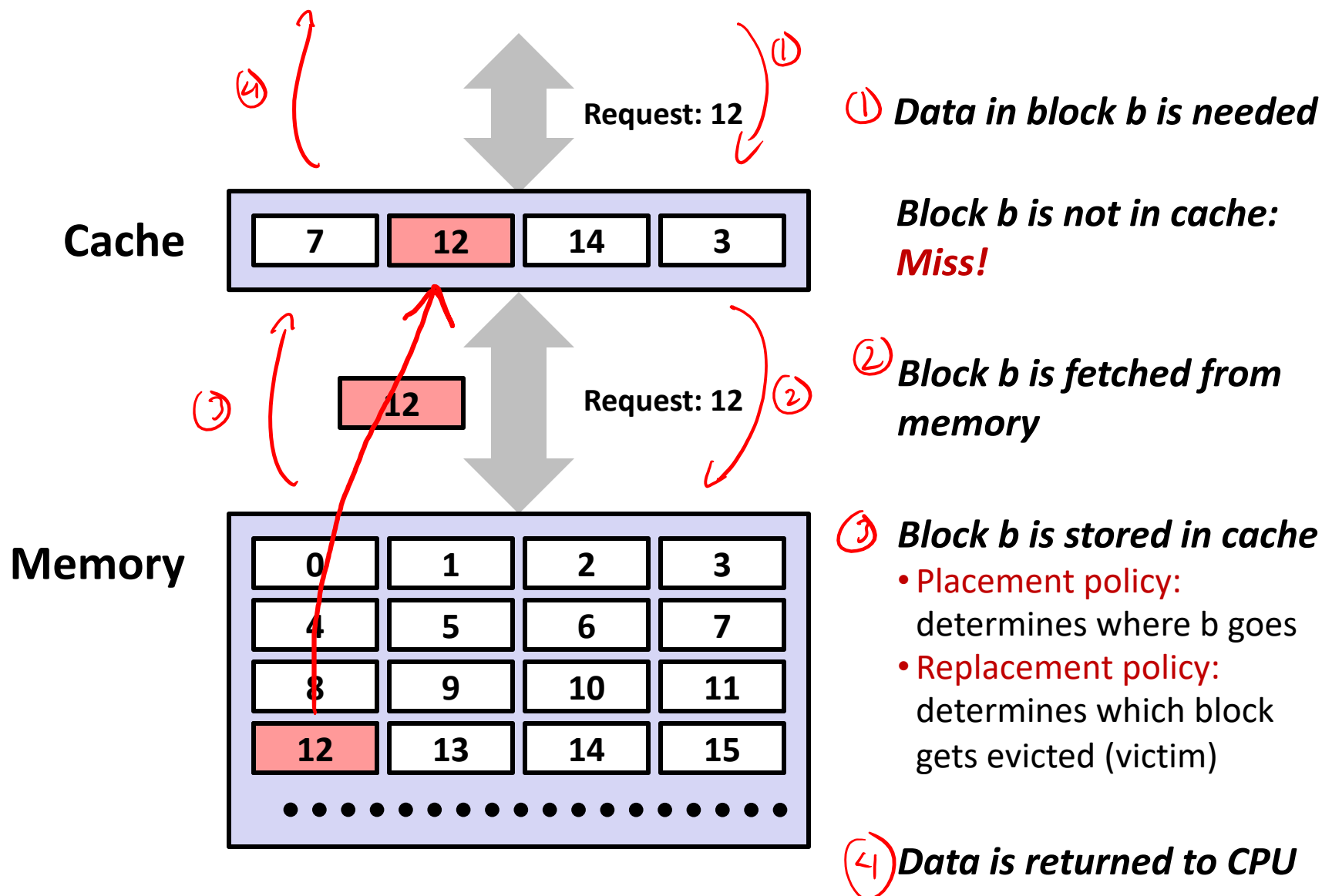
# General Cache Mechanics (Review)



# General Cache Concepts: **Hit** (Review)



# General Cache Concepts: **Miss** (Review)



# Why Caches Work (Review)

- ❖ **Locality:** Programs tend to use data and instructions with addresses near or equal to those they have used recently

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- ❖ **Locality:** Programs tend to use data and instructions with addresses near or equal to those they have used recently
- ❖ **Temporal locality:**
  - Recently referenced items are *likely* to be referenced again in the near future



# Why Caches Work (Review)

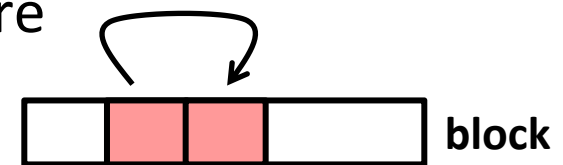
- ❖ **Locality:** Programs tend to use data and instructions with addresses near or equal to those they have used recently

- ❖ **Temporal locality:**

- Recently referenced items are *likely* to be referenced again in the near future

- ❖ **Spatial locality:**

- Items with nearby addresses *tend* to be referenced close together in time

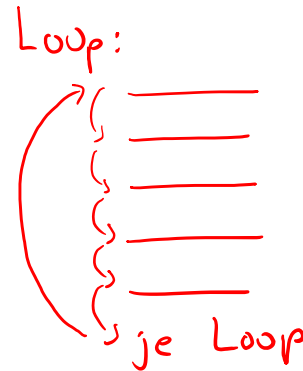


- ❖ How do caches take advantage of this?

# Example: Any Locality?

```
sum = 0;
for (i = 0; i < n; i++)
{
    sum += a[i];
}
return sum;
```

*a[0]  
a[1]  
a[2]*



## ❖ Data:

- Temporal: sum referenced in each iteration
- Spatial: consecutive elements of array `a [ ]` accessed

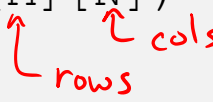
## ❖ Instructions:

- Temporal: cycle through loop repeatedly
- Spatial: reference instructions in sequence



# Locality Example #1

```
int sum_array_rows(int a[M][N])  
{  
    int i, j, sum = 0;  
  
    for (i = 0; i < M; i++)  
        for (j = 0; j < N; j++)  
            sum += a[i][j];  
  
    return sum;  
}
```



# Locality Example #1

```

int sum_array_rows(int a[M][N])
{
    int i, j, sum = 0;

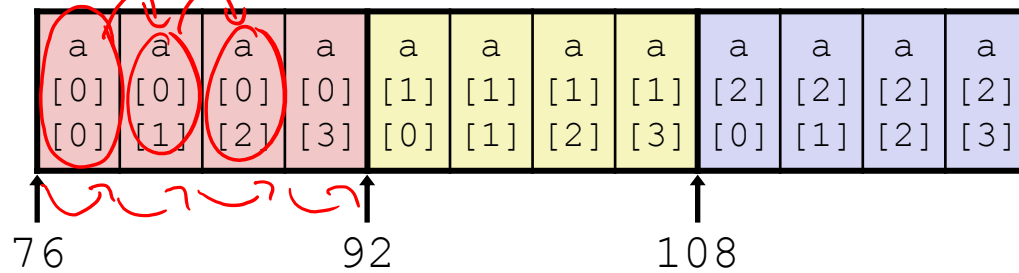
    for (i = 0; i < M; i++)
        for (j = 0; j < N; j++)
            sum += a[i][j];

    return sum;
}

```

$\begin{matrix} a[0][0] \\ 0 \quad 0 \\ 0 \quad 2 \end{matrix}$

## Layout in Memory



**Note:** 76 is just one possible starting address of array a

**M = 3, N = 4**

a[0][0]	a[0][1]	a[0][2]	a[0][3]
a[1][0]	a[1][1]	a[1][2]	a[1][3]
a[2][0]	a[2][1]	a[2][2]	a[2][3]

**Access Pattern:**  
stride = ?

"stride-1"  
1 int = 4B

- 1) a[0][0]
- 2) a[0][1]
- 3) a[0][2]
- 4) a[0][3]
- 5) a[1][0]
- 6) a[1][1]
- 7) a[1][2]
- 8) a[1][3]
- 9) a[2][0]
- 10) a[2][1]
- 11) a[2][2]
- 12) a[2][3]

# Locality Example #2

```
int sum_array_cols(int a[M][N])
{
    int i, j, sum = 0;

    for (j = 0; j < N; j++)
        for (i = 0; i < M; i++)
            sum += a[i][j];

    return sum;
}
```

# Locality Example #2

```

int sum_array_cols(int a[M][N])
{
    int i, j, sum = 0;

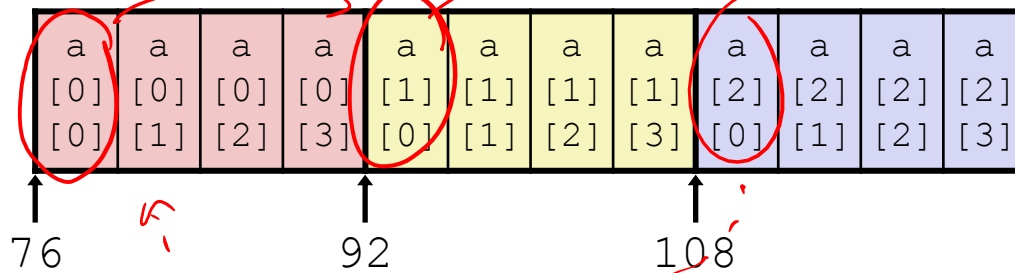
    for (j = 0; j < N; j++)
        for (i = 0; i < M; i++)
            sum += a[i][j];

    return sum;
}

```

6 0  
 1 0  
 2 0  
 : 0

## Layout in Memory



**M = 3, N = 4**

a[0][0]	a[0][1]	a[0][2]	a[0][3]
a[1][0]	a[1][1]	a[1][2]	a[1][3]
a[2][0]	a[2][1]	a[2][2]	a[2][3]

**Access Pattern:**

stride = ?

stride = 4  
stride = N

- 1) a[0][0]
- 2) a[1][0]
- 3) a[2][0]
- 4) a[0][1]
- 5) a[1][1]
- 6) a[2][1]
- 7) a[0][2]
- 8) a[1][2]
- 9) a[2][2]
- 10) a[0][3]
- 11) a[1][3]
- 12) a[2][3]

# Locality Example #3

```

int sum_array_3D(int a[X][Y][Z])
{
    int i, j, k, sum = 0;

    for (i = 0; i < Y; i++)
        for (j = 0; j < Z; j++)
            for (k = 0; k < X; k++)
                sum += a[k][i][j];

    return sum;
}

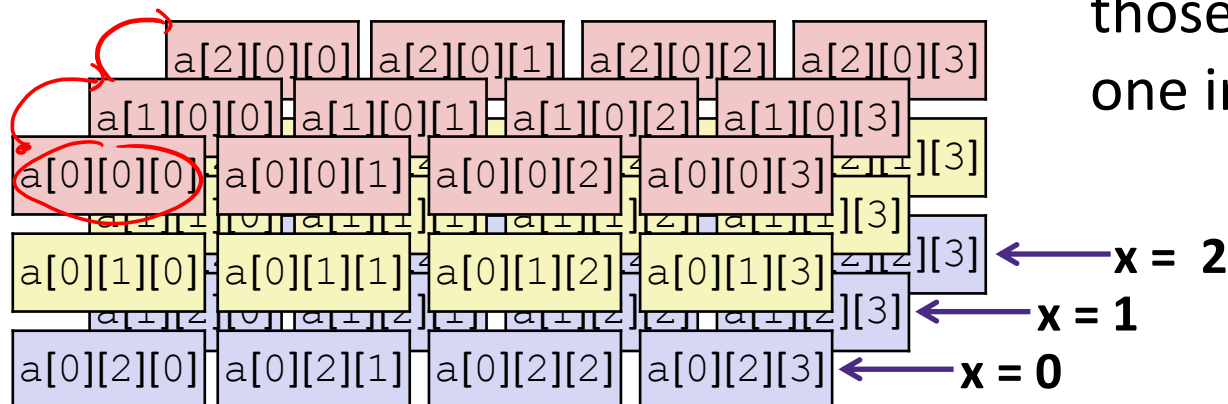
```

*Handwritten red annotations:*  
 - "rows" with an arrow pointing to the `Y` dimension in the function signature.  
 - "cols" with an arrow pointing to the `Z` dimension in the function signature.  
 - "grids" with an arrow pointing to the `X` dimension in the function signature.  
 - Red circles around the indices `k`, `i`, and `j` in the array access `a[k][i][j]`.  
 - Red numbers `0`, `1`, and `0` below the indices `k`, `i`, and `j` respectively, indicating the first iteration of the innermost loop.

❖ What is wrong with this code?

❖ How can it be fixed?

- Want inner loop to be `j`, since those are only one int apart



# Cache Performance Metrics (Review)

- ❖ Huge difference between a cache hit and a cache miss
  - Could be 100x speed difference between accessing cache and main memory (measured in *clock cycles*)

- ❖ Miss Rate (MR)

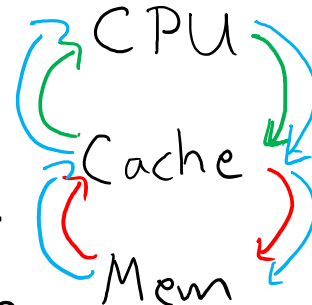
- Fraction of memory references not found in cache (misses / accesses) =  $1 - \text{Hit Rate}$

- ❖ Hit Time (HT)

- Time to deliver a block in the cache to the processor
    - Includes time to determine whether the block is in the cache

Hit takes HT

Miss takes HT + MP



- ❖ Miss Penalty (MP)

- Additional time required because of a miss

# Cache Performance (Review)

- ❖ Two things hurt the performance of a cache:
  - Miss rate and miss penalty
- ❖ *Average Memory Access Time (AMAT)*: average time to access memory considering both hits and misses

$$\text{AMAT} = \text{Hit time} + \text{Miss rate} \times \text{Miss penalty}$$

$$(\text{abbreviated AMAT} = \text{HT} + \text{MR} \times \text{MP})$$

$$\begin{aligned} & \text{HT} * \text{HR} + \text{MT} * \text{MR} \\ & \text{HT} * (1 - \text{MR}) + (\text{HT} + \text{MP}) * \text{MR} \\ & \text{HT} - \text{HT} * \text{MR} + \text{HT} * \text{MR} + \text{MP} * \text{MR} \end{aligned}$$

- ❖ 99% hit rate twice as good as 97% hit rate!
  - Assume HT of 1 clock cycle and MP of 100 clock cycles
  - 97%:  $\text{AMAT} = 1 + 0.03 * 100 = 4 \text{ clock cycles}$
  - 99%:  $\text{AMAT} = 1 + 0.01 * 100 = 2 \text{ clock cycles}$

# Practice Question

- ❖ **Processor specs:** 200 ps clock, MP of 50 clock cycles, MR of 0.02 misses/instruction, and HT of 1 clock cycle

$$\text{AMAT} = \text{HT} + \text{MR} * \text{MP} = 1 + 0.02 * 50 = 2 \text{ clock cycles} = 400 \text{ ps}$$

- ❖ Which improvement would be best?

**A. 190 ps clock** (overclocking, faster CPU)

$$2 \text{ clock cycles} = 380 \text{ ps}$$

**B. Miss penalty of 40 clock cycles** (reduced Mem size)

$$1 + 0.02 * 40 = 1.8 \text{ clock cycles} = 360 \text{ ps}$$

**C. MR of 0.015 misses/instruction** (write better code)

$$1 + 0.015 * 50 = 1.75 \text{ clock cycles} = 350 \text{ ps}$$



# Can we have more than one cache?

## ❖ Why would we want to do that?

- Avoid going to memory!

① optimize L1 for fast HT  
② optimize L2 for low MR

## ❖ Typical performance numbers:

### ■ Miss Rate

- L1 MR = 3-10%
- L2 MR = Quite small (e.g.,  $< 1\%$ ), depending on parameters, etc.

②

### ■ Hit Time

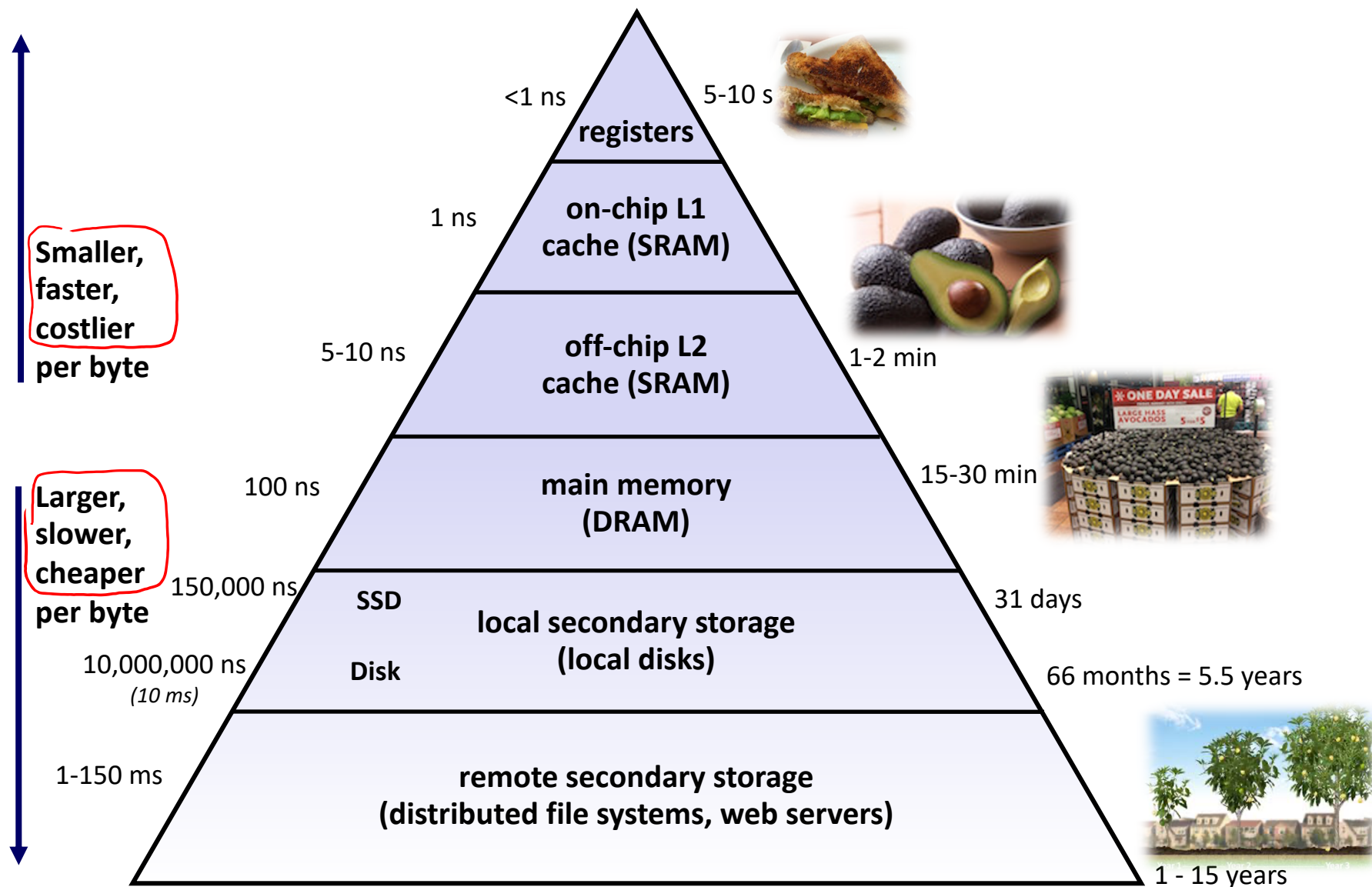
- L1 HT = 4 clock cycles
- L2 HT = 10 clock cycles

①

### ■ Miss Penalty

- P = 50-200 cycles for missing in L2 & going to main memory
- Trend: increasing!

# An Example Memory Hierarchy



# Summary

## ❖ Memory Hierarchy

- Successively higher levels contain “most used” data from lower levels
- Makes use of *temporal and spatial locality*
- Caches are intermediate storage levels used to optimize data transfers between any system elements with different characteristics

## ❖ Cache Performance

- Ideal case: found in cache (hit)
- Bad case: not found in cache (miss), search in next level
- Average Memory Access Time (AMAT) =  $HT + MR \times MP$ 
  - Hurt by Miss Rate and Miss Penalty