

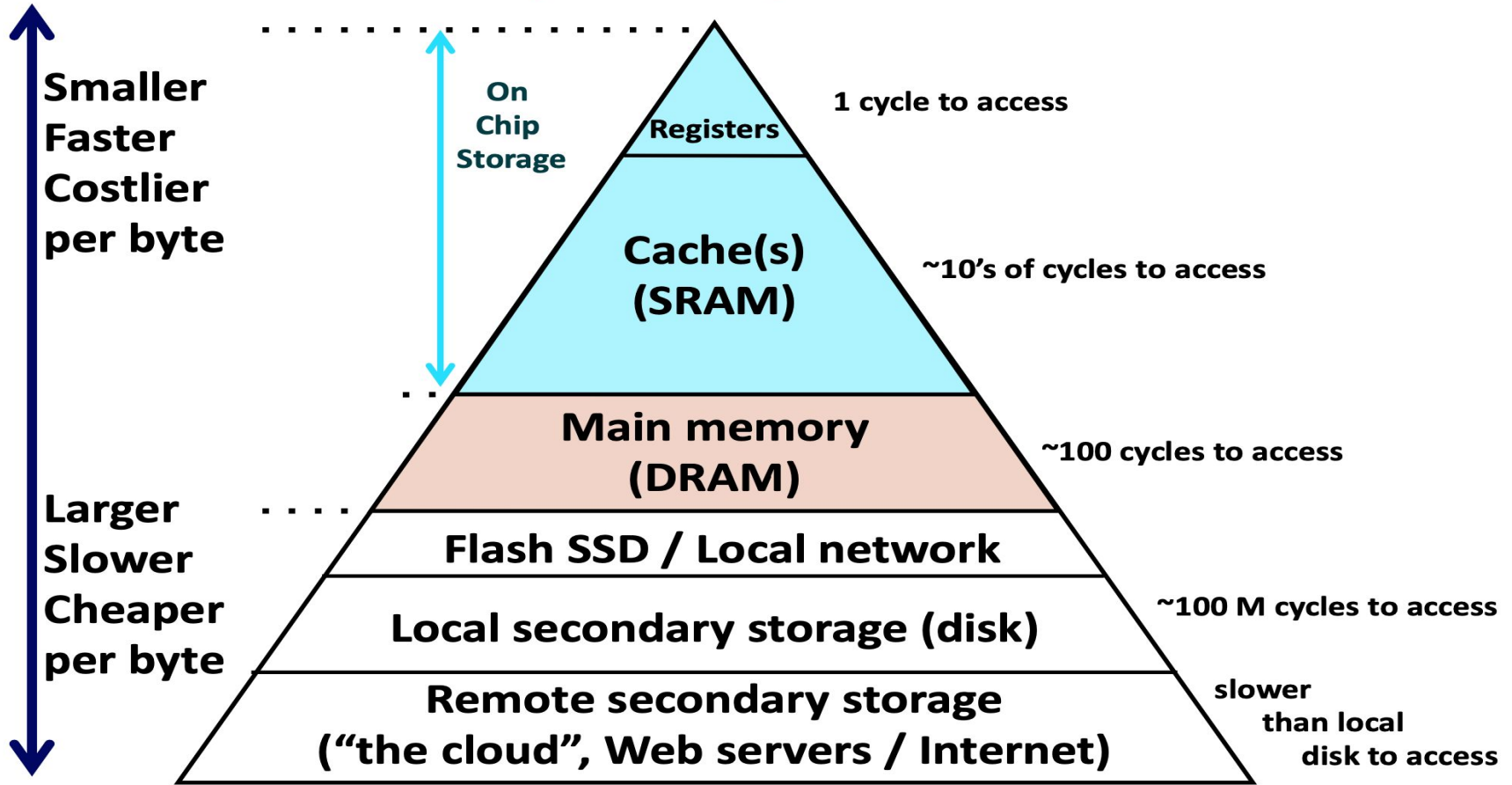
Memory Organization

COMP201 Lab Session
Spring 2021



**KOÇ
UNIVERSITY**

The Memory Hierarchy



Why do we need Memory Hierarchies?

Some fundamental properties of computer system

- Fast storage technologies cost more per byte, have less capacity, and require more power (heat!).
- The gap between CPU and main memory speed is widening.
- Well-written programs tend to exhibit good locality.

These fundamental properties of hardware and software suggest an approach for organizing memory and storage systems known as a memory hierarchy.

Fundamental idea of a memory hierarchy

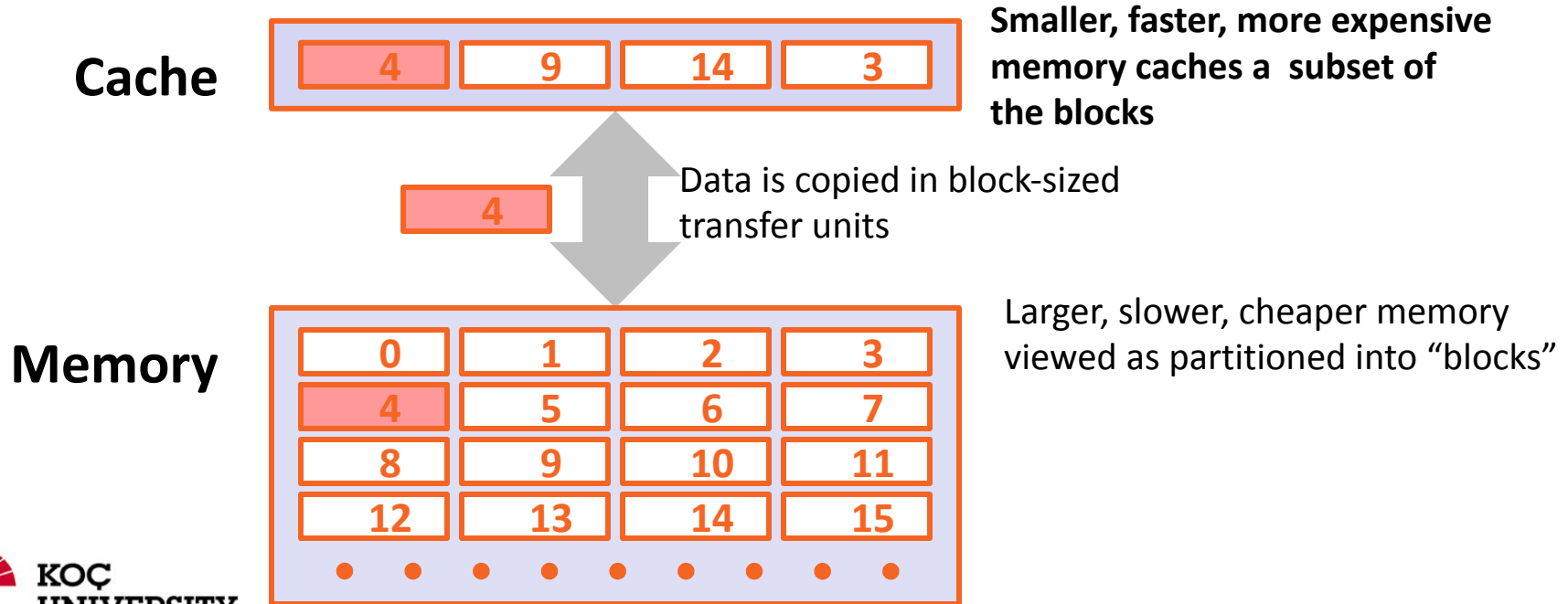
- For each k , the faster, smaller device at level k serves as a cache for the larger, slower device at level $k+1$.
- Because of locality, programs tend to access the data at level k more
- often than they access the data at level $k+1$.

(Ideal): The memory hierarchy creates a large pool of storage that costs as much as the cheap storage near the bottom, but that serves data to programs at the rate of the fast storage near the top.

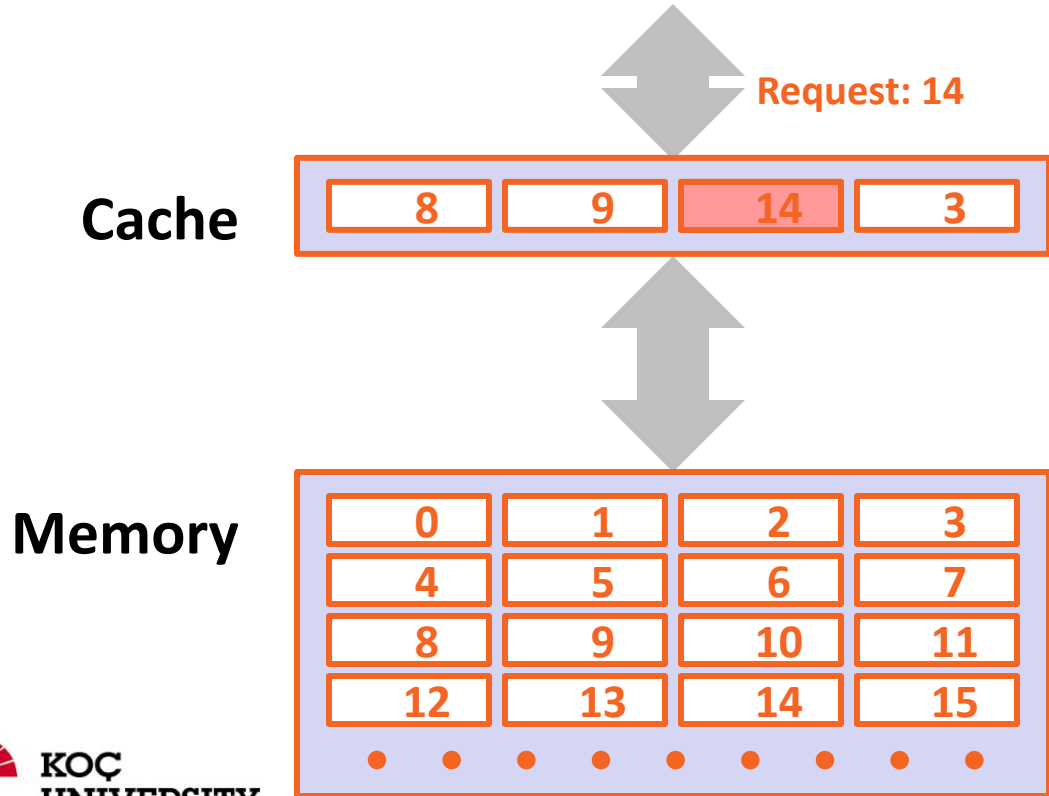
Examples of Caching in the Mem. Hierarchy

Cache Type	What is Cached?	Where is it Cached?	Latency (cycles)	Managed By
Registers	4-8 bytes words	CPU core	0	Compiler
TLB	Address translations	On-Chip TLB	0	Hardware MMU
L1 cache	64-byte blocks	On-Chip L1	4	Hardware
L2 cache	64-byte blocks	On-Chip L2	10	Hardware
Virtual Memory	4-KB pages	Main memory	100	Hardware + OS
Buffer cache	Parts of files	Main memory	100	OS
Disk cache	Disk sectors	Disk controller	100,000	Disk firmware
Network buffer cache	Parts of files	Local disk	10,000,000	NFS client
Browser cache	Web pages	Local disk	10,000,000	Web browser
Web cache	Web pages	Remote server disks	1,000,000,000	Web proxy server

Recall: General Cache Concepts



General Cache Concepts: Hit

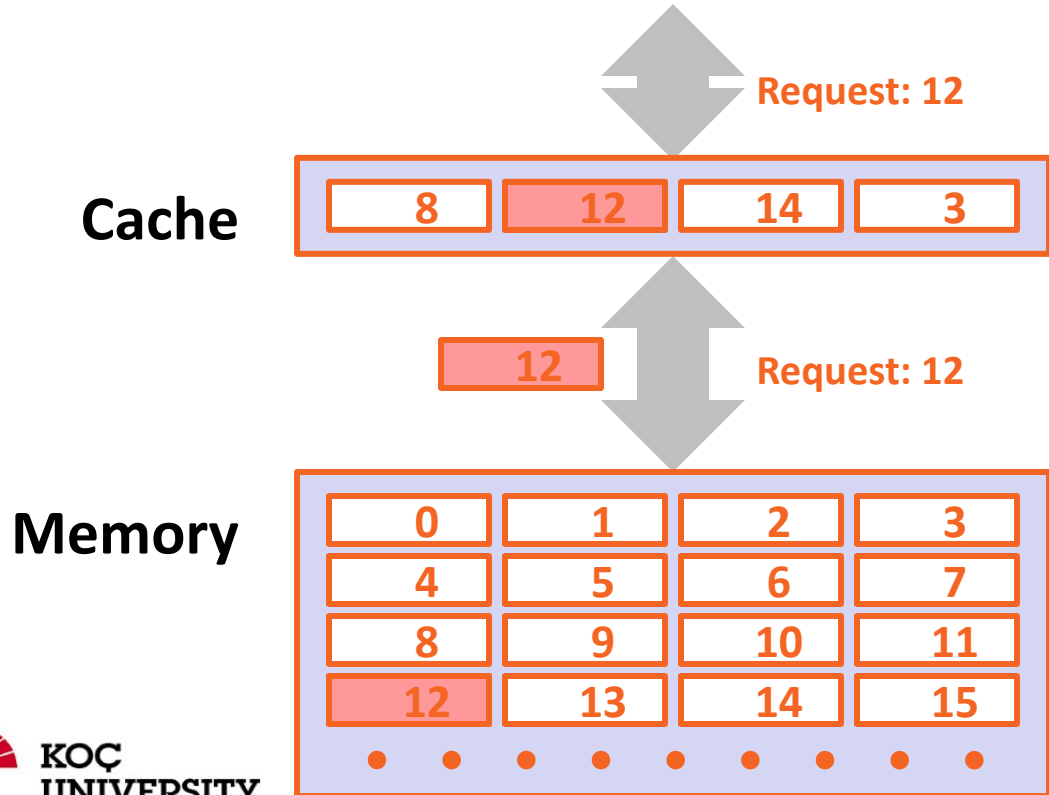


Data in block 14 is needed

Block 14 is in cache:

Hit!

General Cache Concepts: Miss



Data in block 12 is needed

Block 12 is not in cache:
Miss!

*Block 12 is fetched from
memory*

Block 12 is stored in cache

- **Placement policy:**
determines where b goes
- **Replacement policy:**
determines which block
gets evicted (victim)

Cache Simulator

- Simulates usage of Cache when there is read or write request
- Has feature of step-by-step explanation
- System parameters can be adjusted
- Cache Hits and Misses counts and History
- Physical Memory and Cache Memory can be visualized

Cache Simulator: Read Address 0x23

System Parameters:
Address width: bits
Cache size: bytes
Block size: ☐ 2 ☒ 4 ☐ 8 bytes
Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
Write Hit:
Write Miss:
Replacement:

☐ Explain

Manual Memory Access:
 Addr: 0x23
☒ Explain Addr: 0x, Byte: 0x

Tag	Index	Offset	Cache Hits	Cache Misses
000	0	00	0	0

Simulation Messages:

System Generated and Reset

History:

>

||

m = 6, C = 16
K = 4, E = 2
Write back
Write-allocate
Eviction: LRU

V D T Cache Data									
Set 0	0	0	-	-	-	-	-	-	-
	0	0	-	-	-	-	-	-	-
Set 1	0	0	-	-	-	-	-	-	-
	0	0	-	-	-	-	-	-	-

Physical Memory									
0x00	20	f6	ef	ea	a2	5e	9f	1a	
0x08	a2	d0	4f	c4	a0	0c	f7	27	
0x10	b8	bd	1a	ca	35	95	cb	80	
0x18	84	3f	02	4f	8e	f3	f6	e5	
0x20	cd	4a	f6	48	1a	6f	7e	63	
0x28	e9	36	ae	32	0d	37	bc	c9	
0x30	93	dc	b8	7a	3b	1a	b2	0c	
0x38	d3	a6	a4	71	e2	23	9c	59	

System Parameters:

Address width: 6 bits
Cache size: 16 bytes
Block size: ☐ 2 ☒ 4 ☐ 8 bytes
Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
Write Hit: Write back
Write Miss: Write-allocate
Replacement: Least Recently Used

Reset System

☐ Explain

Manual Memory Access:

Addr: 0x23
☒ Explain Addr: 0x, Byte: 0x

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	11	0	0

Simulation Messages:

Read: 0x23
Split address into TIO breakdown.

History:

> R(0x23) = ?

Load

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

Set 0	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	1
Set 1	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

System Parameters:

Address width: bits
Cache size: bytes
Block size: ☐ 2 ☒ 4 ☐ 8 bytes
Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
Write Hit:
Write Miss:
Replacement:

☐ Explain

Manual Memory Access:

Addr: 0x23
☒ Explain Addr: 0x, Byte: 0x

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	11	0	1

Simulation Messages:

Checking Set 0
Looking for Tag 4... MISS!
Invalid Line 0 chosen for replacement.

History:

> R(0x23) = M

||

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

Set 0	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	1
Set 1	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

System Parameters:

Address width: bits

Cache size: bytes

Block size: ☐ 2 ☒ 4 ☐ 8 bytes

Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)

Write Hit:

Write Miss:

Replacement:

Reset System

☐ Explain**Manual Memory Access:**

Addr: 0x23

☒ Explain Addr: 0x, Byte: 0x

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	11	0	1

Simulation Messages:

Invalid Line 0 chosen for replacement.
Block read into cache from memory at address 0x20.

History:

> R(0x23) = M

Load ||

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

Set 0	1	0	4	cd	4a	f6	48	2
	0	0	-	-	-	-	-	1
Set 1	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

System Parameters:

Address width: bits
 Cache size: bytes
 Block size: ☐ 2 ☒ 4 ☐ 8 bytes
 Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
 Write Hit:
 Write Miss:
 Replacement:

☐ Explain

Manual Memory Access:

Addr: 0x
☒ Explain Addr: 0x , Byte: 0x

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	11	0	1

Simulation Messages:

0x20.
 LRU statuses updated.
 Data: 0x48

History:

R(0x23) = M
 >

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

	1	0	4	cd	4a	f6	48	1
Set 0	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	2
Set 1	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

Cache Simulator: Writing 0x13 at 0x22

System Parameters:
Address width: bits
Cache size: bytes
Block size: ☐ 2 ☒ 4 ☐ 8 bytes
Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
Write Hit:
Write Miss:
Replacement:

☐ Explain

Manual Memory Access:
 Addr: 0x23
☒ Explain Addr: 0x22, Byte: 0x13

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	11	0	1

Simulation Messages:

Write: 0x13 at address 0x22

History:

R(0x23) = M
> W(0x22, 0x13) = ?

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

Set 0	1	0	4	cd	4a	f6	48	1
	0	0	-	-	-	-	-	2
Set 1	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

System Parameters:

Address width: bits
 Cache size: bytes
 Block size: ☐ 2 ☒ 4 ☐ 8 bytes
 Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
 Write Hit:
 Write Miss:
 Replacement:

Reset System

☐ Explain**Manual Memory Access:**

Read Addr: 0x23

☒ Explain

Next Addr: 0x22, Byte: 0x13

Flush

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	10	0	1

Simulation Messages:

Write: 0x13 at address 0x22
 Split address into TIO breakdown.

History:

R(0x23) = M
 > W(0x22, 0x13) = ?

Load ||

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

	1	0	4	cd	4a	f6	48	1
Set 0	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	2
Set 1	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

System Parameters:

Address width: 6 bits
Cache size: 16 bytes
Block size: ☐ 2 ☒ 4 ☐ 8 bytes
Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
Write Hit: Write back
Write Miss: Write-allocate
Replacement: Least Recently Used

Reset System

☐ Explain

Manual Memory Access:

Addr: 0x23
☒ Explain Addr: 0x22, Byte: 0x13

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	10	1	1

Simulation Messages:

Split address into TIO breakdown.
Checking Set 0
Looking for Tag 4... HIT in Line 0!

History:

R(0x23) = M
> W(0x22, 0x13) = H

Load

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data									
Set 0	1	0	4	cd	4a	f6	48	1	
	0	0	-	-	-	-	-	2	
Set 1	0	0	-	-	-	-	-	2	
	0	0	-	-	-	-	-	1	

Physical Memory									
0x00	20	f6	ef	ea	a2	5e	9f	1a	
0x08	a2	d0	4f	c4	a0	0c	f7	27	
0x10	b8	bd	1a	ca	35	95	cb	80	
0x18	84	3f	02	4f	8e	f3	f6	e5	
0x20	cd	4a	f6	48	1a	6f	7e	63	
0x28	e9	36	ae	32	0d	37	bc	c9	
0x30	93	dc	b8	7a	3b	1a	b2	0c	
0x38	d3	a6	a4	71	e2	23	9c	59	

System Parameters:

Address width: 6 bits
Cache size: 16 bytes
Block size: ☐ 2 ☒ 4 ☐ 8 bytes
Associativity: ☐ 1 ☒ 2 ☐ 4 way(s)
Write Hit: Write back
Write Miss: Write-allocate
Replacement: Least Recently Used

Reset System

☐ Explain

Manual Memory Access:

Addr: 0x23
☒ Explain Addr: 0x22, Byte: 0x13

Tag	Index	Offset	Cache Hits	Cache Misses
100	0	10	1	1

Simulation Messages:

Checking Set 0
Looking for Tag 4... HIT in Line 0!
LRU statuses updated.
Write back: set Dirty bit.

History:

R(0x23) = M
W(0x22, 0x13) = H
>

Load ||

m = 6, C = 16

K = 4, E = 2

Write back

Write-allocate

Eviction: LRU

V D T Cache Data

	1	1	4	cd	4a	13	48	1
Set 0	0	0	-	-	-	-	-	2
	0	0	-	-	-	-	-	2
Set 1	0	0	-	-	-	-	-	1

Physical Memory

0x00	20	f6	ef	ea	a2	5e	9f	1a
0x08	a2	d0	4f	c4	a0	0c	f7	27
0x10	b8	bd	1a	ca	35	95	cb	80
0x18	84	3f	02	4f	8e	f3	f6	e5
0x20	cd	4a	f6	48	1a	6f	7e	63
0x28	e9	36	ae	32	0d	37	bc	c9
0x30	93	dc	b8	7a	3b	1a	b2	0c
0x38	d3	a6	a4	71	e2	23	9c	59

Recall: General Caching Concepts:

3 Types of Cache Misses

- **Cold (compulsory) miss**
 - Cold misses occur because the cache starts empty and this is the first reference to the block.
- **Capacity miss**
 - Occurs when the set of active cache blocks (**working set**) is larger than the cache.
- **Conflict miss**
 - Most caches limit blocks at level $k+1$ to a small subset (sometimes a singleton) of the block positions at level k .
 - E.g. Block i at level $k+1$ must be placed in block $(i \bmod 4)$ at level k .
 - Conflict misses occur when the level k cache is large enough, but multiple data objects all map to the same level k block.
 - E.g. Referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time.

Principle of Locality

Principle of Locality:

- Programs tend to reuse data and instructions near those they have used recently, or that were recently referenced themselves.
- **Temporal locality:**
 - Recently referenced items are likely to be referenced in the near future.
- **Spatial locality:**
 - Items with nearby addresses tend to be referenced close together in time.

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

Locality Example:

- Data
 - Reference array elements in succession(stride-1 reference pattern): **Spatial locality**
 - Reference sum each iteration: **Temporal locality**
- Instructions
 - Reference instructions in sequence: **Spatial locality**
 - Cycle through loop repeatedly: **Temporal locality**

Locality Example

Does this function have a good locality?
How we can improve it?

Hint: C arrays are allocated in row-major

```
int sumarray3d(int a[M][N][N])
{
    int i, j, k, sum = 0;

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

    return sum
}
```

Concluding Observations

Programmer can optimize for cache performance

- How data structures are organized
- How data are accessed
 - Nested loop structure
 - Blocking is a general technique

All systems favor “cache friendly code”

- Getting absolute optimum performance is very platform specific
 - Cache sizes, line sizes, associatives, etc.
- Can get most of the advantage with generic code
 - Keep working set reasonably small (**temporal locality**)
 - Use small strides (**spatial locality**)

Callgrind



Code Profiling

- A **code profiler** is a tool to analyze a program and report on its resource usage
 - "resource" could be memory, CPU cycles, network bandwidth, and so on
- The program is run under control of a profiling tool
- During application development, a common step is to improve runtime performance using profiling tools.
- To not waste time on optimizing functions which are rarely used, one needs to know in which parts of the program most of the time is spent.
- Some example:
 - Callgrind, GProf, JConsol, CLR

Valgrind

the Valgrind framework supports a variety of runtime analysis tools

- **memcheck**
 - detects memory errors/leaks
- **massif**
 - reports on heap usage
- **helgrind**
 - detects multithreaded race conditions
- **callgrind/cachegrind**
 - profiles CPU/cache performance

Callgrind/cachegrind

- The Valgrind profiling tools are **cachegrind** and **callgrind**
- The **cachegrind** tool simulates the L1/L2 caches and counts cache misses/hits.
- The **callgrind** tool counts function calls and the CPU instructions executed within each call and builds a function callgraph
- The callgrind tool includes a cache simulation feature adopted from cachegrind, so you can actually use callgrind for both CPU and cache profiling.

Basic Usage of Callgrind

- First, we need to compile our program with debugging enabled
 - `gcc -g -ggdb name.c -o name.out`
- You first need to run your program under Valgrind and explicitly request the callgrind tool (if unspecified, the tool defaults to memcheck)
 - `valgrind --tool=callgrind [possible options] name.out program-arguments`
- The result will be stored on the files `callgrind.out.PID`, where PID will be the process identifier.

Process identifier

```
==22417== Events      : Ir
==22417== Collected : 7247606
==22417==
==22417== I   refs:      7,247,606
```

Number of Instruction read (Ir)

Basic Usage of Callgrind

Counting instructions with callgrind

- The callgrind output file is a text file, but its contents are not intended for you to read yourself.
- You can properly read the output using callgrind_annotate
 - callgrind_annotate --auto=yes callgrind.out.PID
- The --auto=yes option report counts for each C statement
- Do not forget to replace PID by the actual number.

This program sort a 1000-member array using selection sort

```
. void swap(int *a, int *b)
3,000 {
3,000     int tmp = *a;
4,000     *a = *b;
3,000     *b = tmp;
2,000 }

.
. int find_min(int arr[], int start, int stop)
3,000 {
2,000     int min = start;
2,005,000     for(int i = start+1; i <= stop; i++)
4,995,000         if (arr[i] < arr[min])
6,178             min = i;
1,000     return min;
2,000 }

. void selection_sort(int arr[], int n)
3 {
4,005     for (int i = 0; i < n; i++) {
9,000         int min = find_min(arr, i, n-1);
7,014,178 => sorts.c:find_min (1000x)
10,000         swap(&arr[i], &arr[min]);
15,000 => sorts.c:swap (1000x)
.     }
2 }
.
```

Basic Usage of Callgrind

Interpreting the results

- The Ir counts are basically the count of assembly instructions executed.
- By default, the counts are *exclusive*
 - The counts for a function include only the time spent in that function and not in the functions that it calls.
- By using exclusive counts you can detect the bottlenecks.
- For example, in the right code, the work is concentrated in the loop to find the min value
 - Conclusion: Caching the min array element is useful here.

```
. void swap(int *a, int *b)
3,000 {
3,000     int tmp = *a;
4,000     *a = *b;
3,000     *b = tmp;
2,000 }

.
. int find_min(int arr[], int start, int stop)
3,000 {
2,000     int min = start;
2,005,000     for(int i = start+1; i <= stop; i++)
4,995,000         if (arr[i] < arr[min])
6,178             min = i;
1,000     return min;
2,000 }

. void selection_sort(int arr[], int n)
3 {
4,005     for (int i = 0; i < n; i++) {
9,000         int min = find_min(arr, i, n-1);
7,014,178 => sorts.c:find_min (1000x)
10,000         swap(&arr[i], &arr[min]);
15,000 => sorts.c:swap (1000x)
.     }
2 }

.
```

Basic Usage of Callgrind

Adding in cache simulation

- Invoke valgrind by `--simulate-cache=yes` option
 - `valgrind --tool=callgrind --simulate-cache=yes name.out program-arguments`
- The cache simulator models a machine with a split L1 cache (separate instruction I1 and data D1), backed by a unified second-level cache (L2).
- Similar to the previous example, `callgrind_annotate` should be used to interpret the output.

Output example

```
==16409== Events      : Ir Dr Dw I1mr D1mr D1mw I2mr D2mr D2mw
==16409== Collected : 7163066 4062243 537262 591 610 182 16 103 94
==16409==
==16409== I   refs:      7,163,066
==16409== I1  misses:      591
==16409== L2i misses:      16
==16409== I1  miss rate:    0.0%
==16409== L2i miss rate:    0.0%
==16409==
==16409== D   refs:      4,599,505 (4,062,243 rd + 537,262 wr)
==16409== D1  misses:      792 (      610 rd +      182 wr)
==16409== L2d misses:      197 (      103 rd +       94 wr)
==16409== D1  miss rate:    0.0% (    0.0% +    0.0% )
==16409== L2d miss rate:    0.0% (    0.0% +    0.0% )
==16409==
==16409== L2 refs:      1,383 (    1,201 rd +      182 wr)
==16409== L2  misses:      213 (      119 rd +       94 wr)
==16409== L2  miss rate:    0.0% (    0.0% +    0.0% )
```

It sounds like we have a cache friendly code.

Ir: I cache reads (instructions executed)

I1mr: I1 cache read misses (instruction wasn't in I1 cache but was in L2)

I2mr: L2 cache instruction read misses (instruction wasn't in I1 or L2 cache, had to be fetched)

Dr: D cache reads (memory reads)

D1mr: D1 cache read misses (data location not in D1 cache, but in L2)

D2mr: L2 cache data read misses (location not in D1 or L2)

Dw: D cache writes (memory writes)

D1mw: D1 cache write misses (location not in D1 cache, but in L2)

D2mw: L2 cache data write misses (location not in D1 or L2)

Output example

--- Auto-annotated source: sorts.c

	Ir	Dr	Dw	I1mr	D1mr	D1mw	I2mr	D2mr	D2mw	
	.	.	.	.	.	.	.	.	.	void swap(int *a, int *b)
3,000	0	1,000	1	0	0	1	.	.	.	{
3,000	2,000	1,000	.	.	.	.	.	.	.	int tmp = *a;
4,000	3,000	1,000	.	.	.	.	.	.	.	*a = *b;
3,000	2,000	1,000	.	.	.	.	.	.	.	*b = tmp;
2,000	2,000	.	.	.	.	.	.	.	.	}
.	
.	.	.	.	.	.	.	.	.	.	int find_min(int arr[], int start, int st
op)	.	.	.	.	.	.	.	.	.
3,000	0	1,000	1	0	0	1	.	.	.	{
2,000	1,000	1,000	0	0	1	0	0	1	.	int min = start;
2,005,000	1,002,000	500,500	.	.	.	.	.	.	.	for(int i = start+1; i <= st
op; i++)	.	.	.	.	.	.	.	.	.
4,995,000	2,997,000	0	0	32	0	0	19	.	.	if (arr[i] < arr[m
in])	.	.	.	.	.	.	.	.	.
6,144	3,072	3,072	.	.	.	.	.	.	.	min = i;
1,000	1,000	.	.	.	.	.	.	.	.	return min;
2,000	2,000	.	.	.	.	.	.	.	.	}
.	.	.	.	.	.	.	.	.	.	void selection_sort(int arr[], int n)
3	0	1	1	0	0	1	.	.	.	{
4,005	2,002	1,001	.	.	.	.	.	.	.	for (int i = 0; i < n; i++) {
9,000	3,000	5,000	.	.	.	.	.	.	.	int min = find_min(arr, i, n
-1);	.	.	.	.	.	.	.	.	.
7,014,144	4,006,072	505,572	1	32	1	1	19	1	.	=> sorts.c:find_min
(1000x)	.	.	.	.	.	.	.	.	.
10,000	4,000	3,000	.	.	.	.	.	.	.	swap(&arr[i], &arr[min]);
15,000	9,000	4,000	1	0	0	1	.	.	.	=> sorts.c:swap (1000x)
.	}
2	2	.	.	.	.	.	.	.	.	}

Ir: I cache reads (instructions executed)

I1mr: I1 cache read misses (instruction wasn't in I1 cache but was in L2)

I2mr: L2 cache instruction read misses (instruction wasn't in I1 or L2 cache, had to be fetched)

Dr: D cache reads (memory reads)

D1mr: D1 cache read misses (data location not in D1 cache, but in L2)

D2mr: L2 cache data read misses (location not in D1 or L2)

Dw: D cache writes (memory writes)

D1mw: D1 cache write misses (location not in D1 cache, but in L2)

D2mw: L2 cache data write misses (location not in D1 or L2)

Additional Points

- L2 misses are much more expensive than L1 misses, so pay attention to passages with high D2mr or D2mw counts.
- Even a small number of misses can be quite important, as a L1 miss will typically cost around 5-10 cycles, an L2 miss can cost as much as 100-200 cycles
- Callgrind cannot detect the bottleneck of your program if it is related to file I/O
- Try to examine different path of your program

References

1. Some of the slides are borrowed from materials in Stanford CS107, CMU15-213 and CS201, Portland State University
2. <https://stackoverflow.com/questions/16699247/what-is-a-cache-friendly-code>
3. <https://www.valgrind.org/docs/manual/manual.html>
4. The Cache Simulator and its demos are borrowed from materials in University of Washington, CSE 351