CS 261
Fall 2022

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Caching

(get it??)

Topics

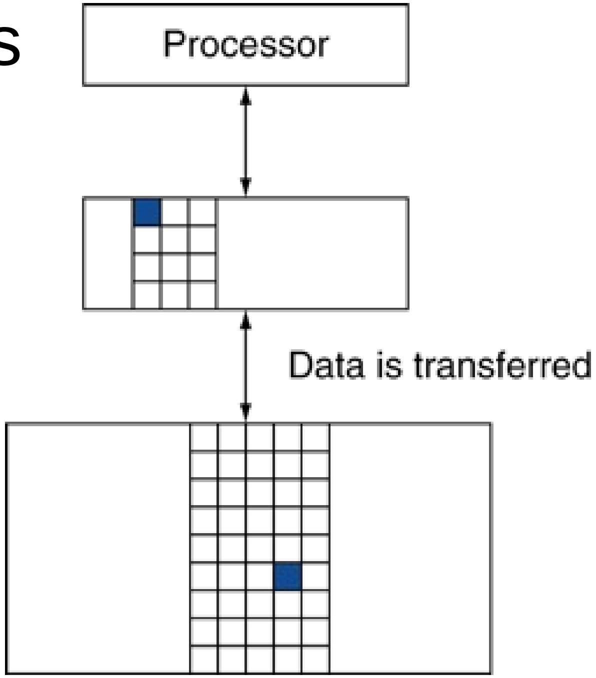
- Caching
- Cache implementations
- Cache policies
- Cache performance
- Performance improvement strategies

Motivation

- Caching is ubiquitous in modern computing:
  - L1-L3 memory
  - TLB and virtual memory (next week)
  - Disk controller buffers
  - Network controller buffers
  - Browser caches
  - Content delivery networks

Caching

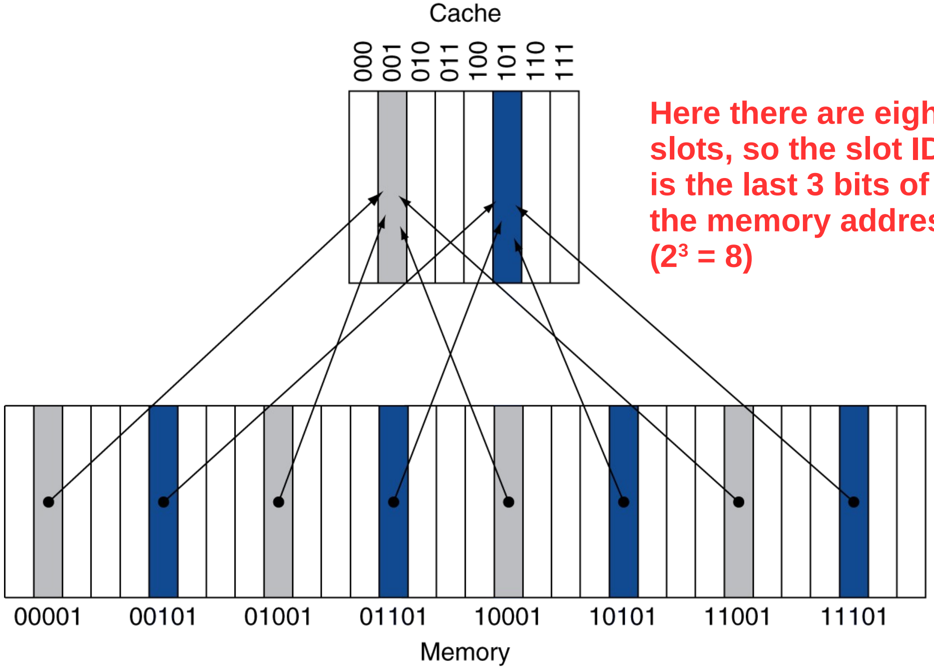
- A cache is a small, fast memory that acts as a buffer or staging area for a larger, slower memory
  - Fundamental CS system design concept
  - Data is transferred in blocks or lines
  - Slower caches use larger block sizes
  - Cache hit vs. cache miss
  - Hit ratio: # hits / # memory accesses



Cache implementations

- What data structure can we use to implement caches?
  - Need **FAST** lookups and containment checks
  - From CS 240: use a hash table!
  - Cache slot = "real address" % CACHE_SIZE

Multiple addresses may map to the same cache slot! (this is called a conflict)



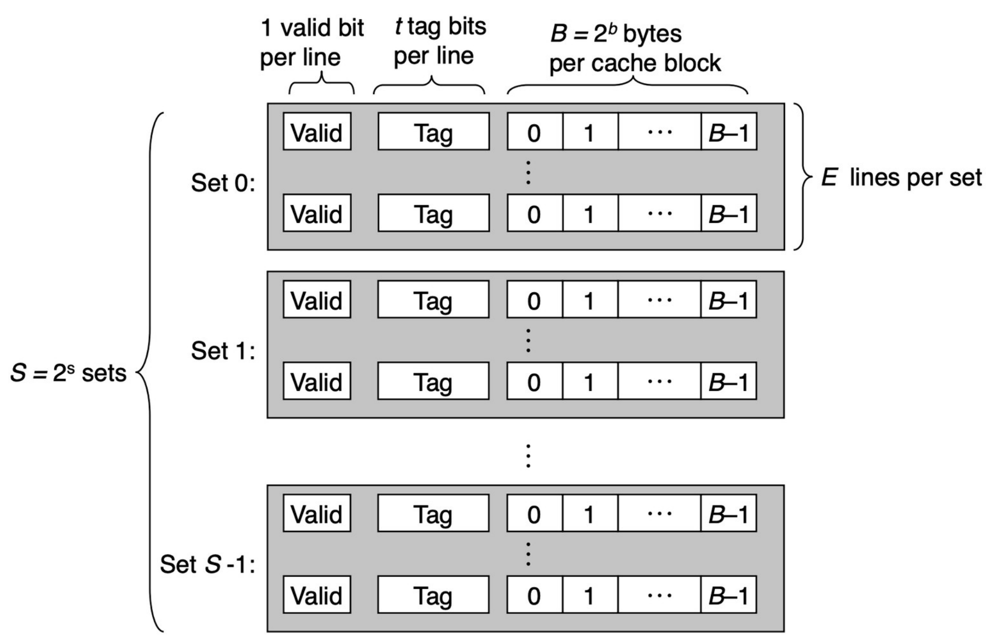
Here there are eight slots, so the slot ID is the last 3 bits of the memory address ($2^3 = 8$)

Question

- Suppose we have a sixteen-element cache, with slots labeled starting at zero. Which slot would we use to store a cached version of a data element stored at address 0x4d6?
  - Reminder: cache slot = "real address" % CACHE_SIZE
  - Hint: 2^4 = 16, and four bits = one hex digit

Cache implementations

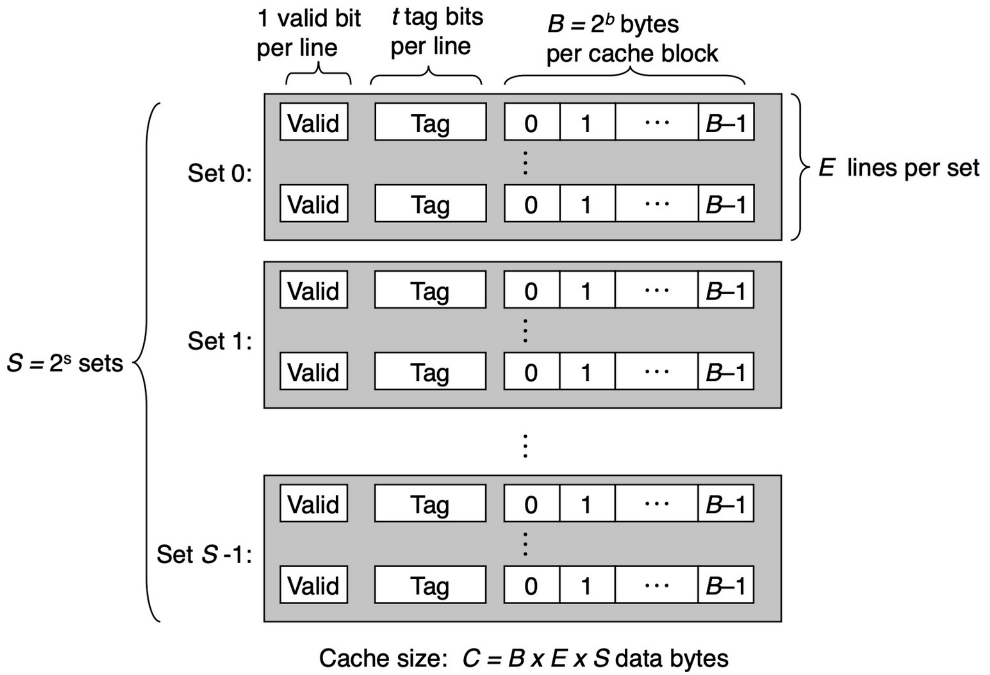
- A cache line is a block or sequence of bytes that is moved between memory levels in a single operation
- A cache set is a collection of one or more cache lines
  - Each cache line contains a tag to identify the source address and a valid flag/bit indicating whether the value is up-to-date

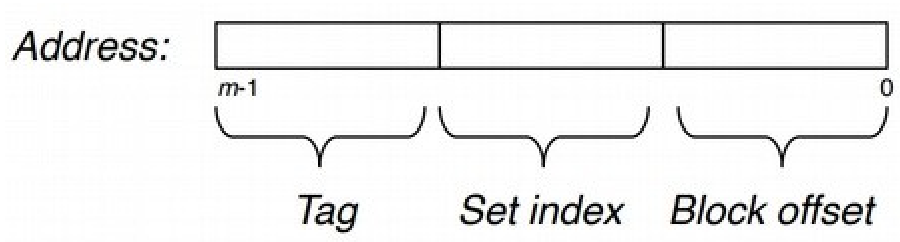


Cache size: $C = B \times E \times S$ data bytes

Cache implementations

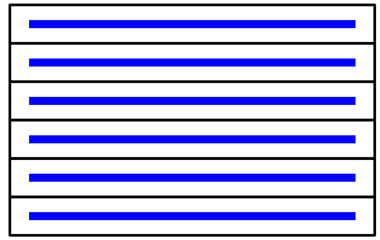
- General cache organization:
  - **S** = # of cache sets = 2^s
    - s = # of bits for set index
  - **E** = # of lines per cache set
    - Level of associativity
  - **B** = block (cache line) size = 2^b
    - Essentially bytes per line
    - b = # of bits for block offset
  - **m** = # of bits for memory address
    - M = size of memory in bytes = 2^m
  - C = total cache capacity = S x E x B
    - sets x lines/set x bytes/line
  - t = # of tag bits = m - s - b



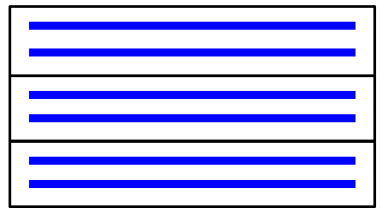


Types of caches

- Direct-mapped (E = 1)
  - One line per set

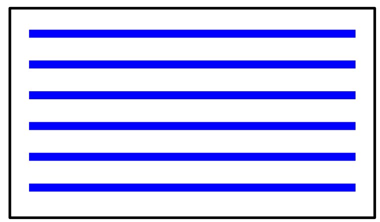


- Set-associative (1 < E < C/B)
  - Multiple lines per set



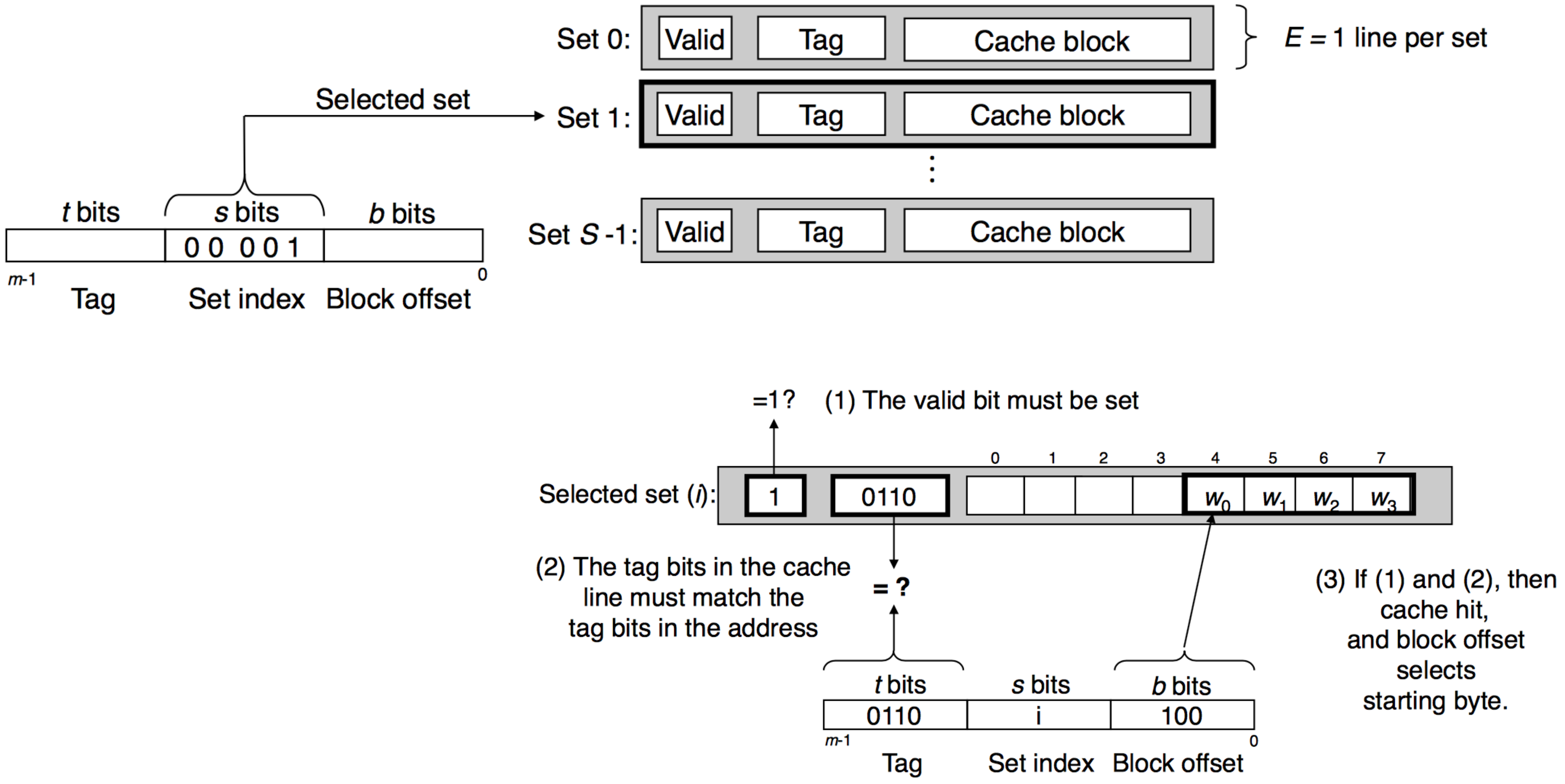
Here E = 2

- Fully-associative (E = C/B)
  - All lines in one set



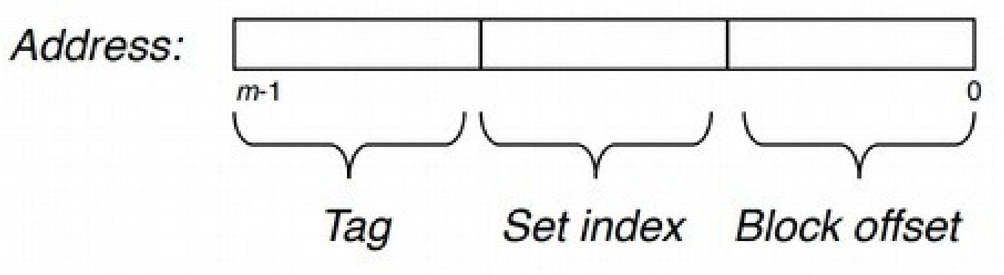
Cache implementations

- Direct-mapped (E = 1) caches



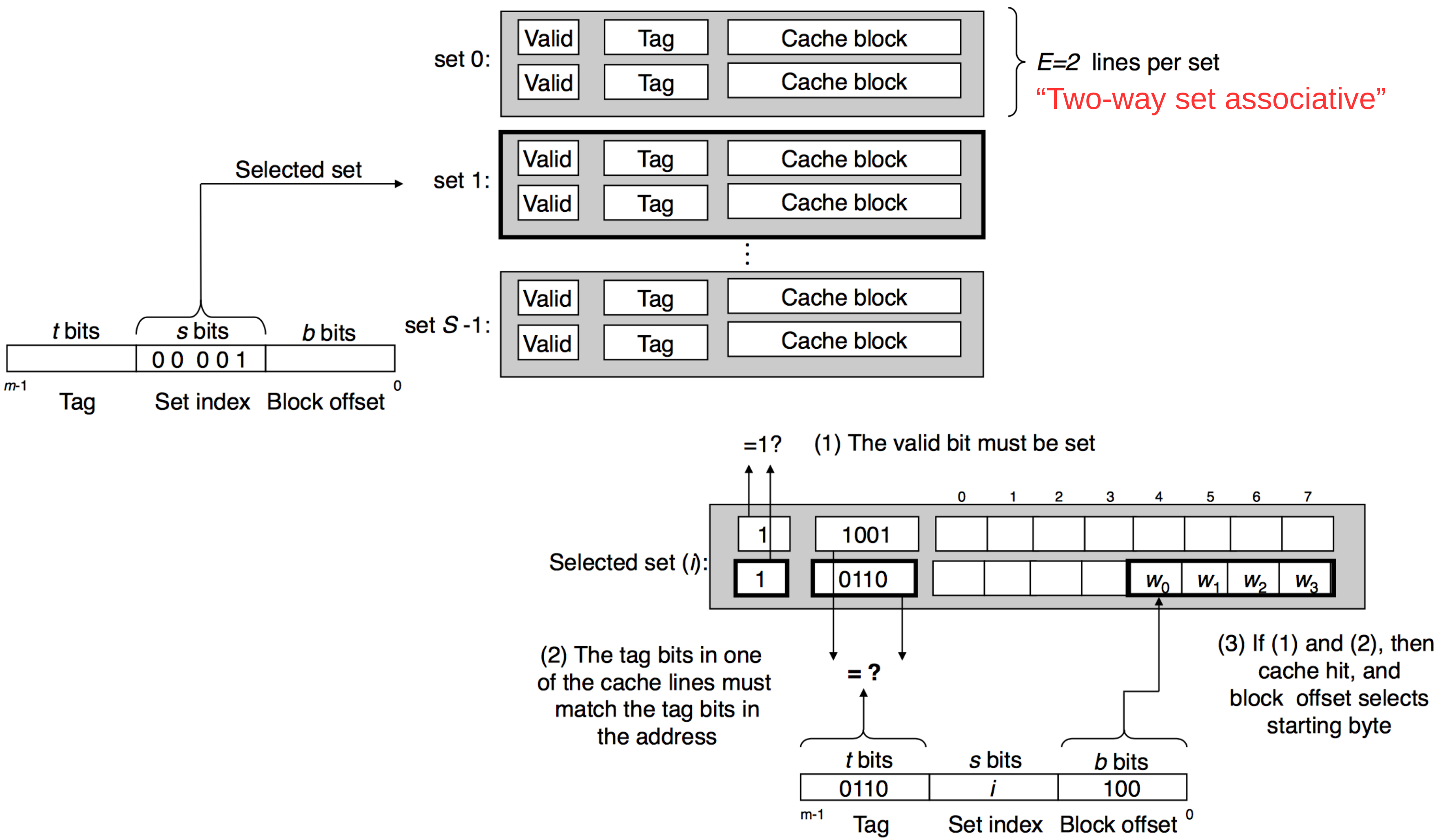
Question

- Suppose we have a direct-mapped cache (S=16, B=1), with sets labeled starting at zero. Which set would we use to store a cached version of a data element stored at address 0x4d6?
  - Hint: S=16 so the number of bits for the set index is four
  - Hint: B=1 so the number of bits for the block offset is zero



Cache implementations

- Set-associative (1 < E < C/B) caches

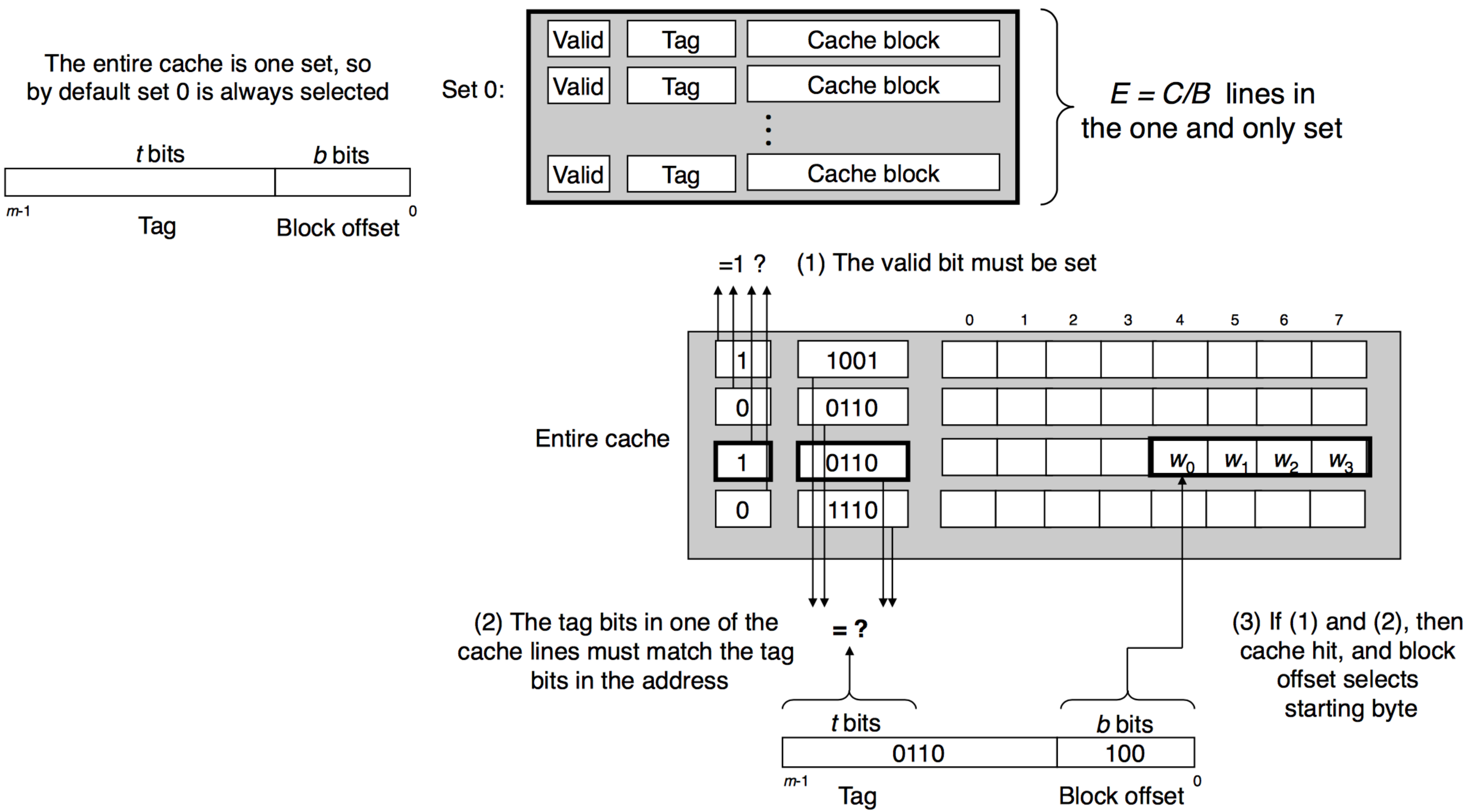


Question

- Suppose we have a four-way set-associative cache (S=16, E=4, B=1), with sets labeled starting at zero. Which set would we use to store a cached version of a data element stored at address 0x4d6?

Cache implementations

- Fully-associative (E = C/B) caches

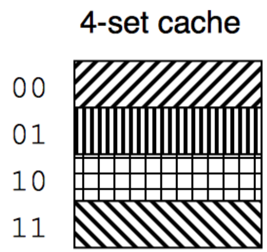


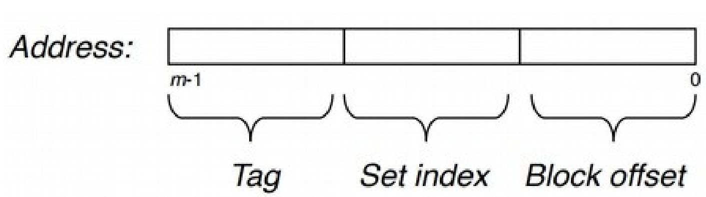
Question

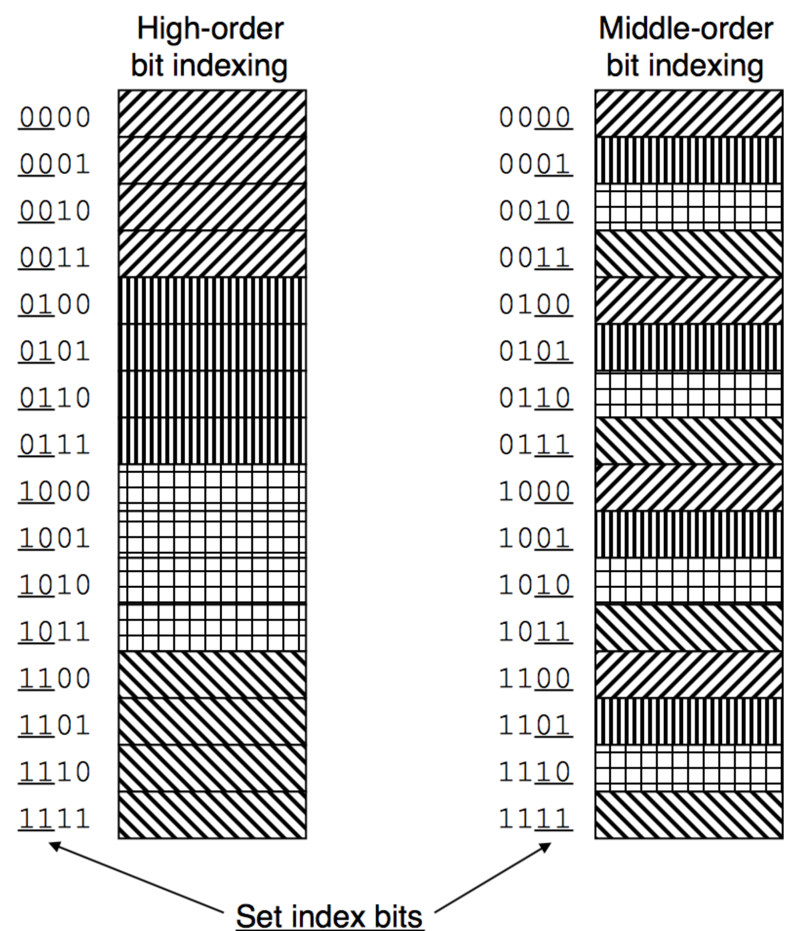
- Suppose we have a fully-associative cache (B=1) with sets labeled starting at zero. Which set would we use to store a cached version of a data element stored at address 0x4d6?

Cache implementations

- In general, we use the middle bits for the set index
  - Contiguous memory blocks should map to different cache sets







Cache misses ("Three C's")

- Compulsory / cold miss
  - First cache miss due to an "empty" cache
  - As the cache loads data, it is warmed up
- Conflict miss
  - Cache miss due to multiple lines in working set mapping to the same cache line
  - Repeated conflict misses for the same cache lines or blocks is called thrashing
- Capacity miss
  - The working set (amount of memory accessed in a given time interval) is too large to fit in cache

Cache policies

- If a cache set is full, a cache miss in that set requires lines to be replaced or evicted
- Policies:
  - Random replacement
  - Least recently used
  - Least frequently used
- These policies require additional overhead
  - More important for lower levels of the memory hierarchy

Cache policies

- How should we handle writes to a cached value?
  - Write-through: immediately update to lower level
    - Typically used for higher levels of memory hierarchy
  - Write-back: defer update until replacement/eviction
    - Typically used for lower levels of memory hierarchy
- How should we handle write misses?
  - Write-allocate: load then update
    - Typically used for write-back caches
  - No-write-allocate: update without loading
    - Typically used for write-through caches

Performance impact

- Metrics
  - Hit rate/ratio: # hits / # memory accesses (1 – miss rate)
    - Hit time: delay in accessing data for a cache hit
  - Miss rate/ratio: # misses / # memory accesses
    - Miss penalty: delay in loading data for a cache miss
  - Read throughput (or "bandwidth"): the rate that a program reads data from a memory system
- General observations:
  - Larger cache = higher hit rate but higher hit time
  - Lower miss rates = higher read throughput

Case study: matrix multiply

(a) Version *ijk*

code/mem/matmult/mm.c

```
for (i = 0; i < n; i++)
    for (j = 0; j < n; j++) {
        sum = 0.0;
        for (k = 0; k < n; k++)
            sum += A[i][k]*B[k][j];
        C[i][j] += sum;
    }
```

code/mem/matmult/mm.c

(b) Version *jik*

code/mem/matmult/mm.c

```
for (j = 0; j < n; j++)
    for (i = 0; i < n; i++) {
        sum = 0.0;
        for (k = 0; k < n; k++)
            sum += A[i][k]*B[k][j];
        C[i][j] += sum;
    }
```

code/mem/matmult/mm.c

(c) Version *jki*

code/mem/matmult/mm.c

```
for (j = 0; j < n; j++)
    for (k = 0; k < n; k++) {
        r = B[k][j];
        for (i = 0; i < n; i++)
            C[i][j] += A[i][k]*r;
    }
```

code/mem/matmult/mm.c

(d) Version *kji*

code/mem/matmult/mm.c

```
for (k = 0; k < n; k++)
    for (j = 0; j < n; j++) {
        r = B[k][j];
        for (i = 0; i < n; i++)
            C[i][j] += A[i][k]*r;
    }
```

code/mem/matmult/mm.c

(e) Version *kij*

code/mem/matmult/mm.c

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for (k = 0; k < n; k++)
    for (i = 0; i < n; i++) {
        r = A[i][k];
        for (j = 0; j < n; j++)
            C[i][j] += r*B[k][j];
    }
```

code/mem/matmult/mm.c

(f) Version *ikj*

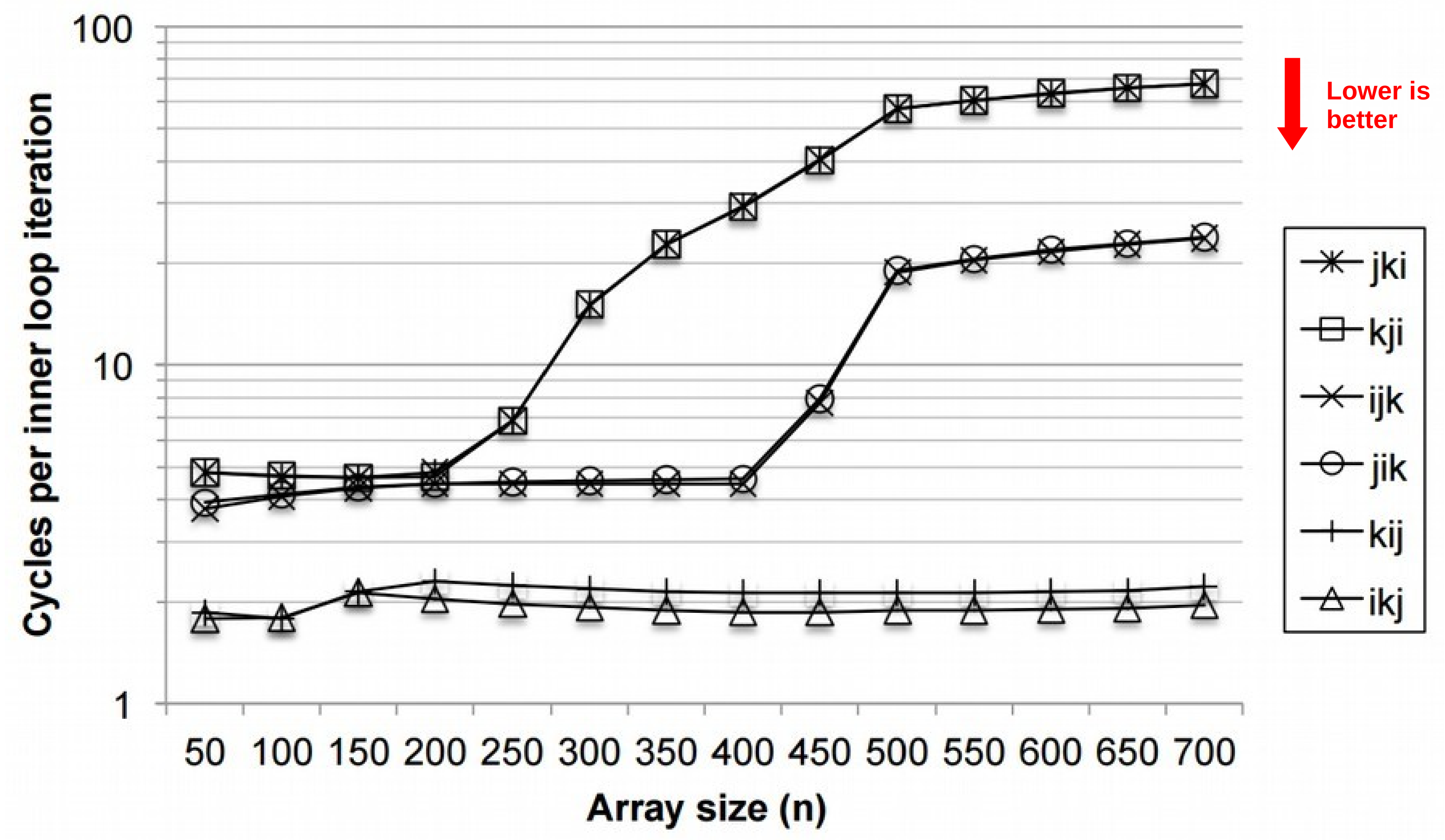
code/mem/matmult/mm.c

```
for (i = 0; i < n; i++)
    for (k = 0; k < n; k++) {
        r = A[i][k];
        for (j = 0; j < n; j++)
            C[i][j] += r*B[k][j];
    }
```

code/mem/matmult/mm.c

Figure 6.44 **Six versions of matrix multiply.** Each version is uniquely identified by the ordering of its loops.

Case study: matrix multiply



Optimization strategies

- Focus on the common cases
- Focus on the code regions that dominate runtime
- Focus on inner loops and minimize cache misses
- Favor repeated local accesses (temporal locality)
- Favor stride-1 access patterns (spatial locality)

Tip: You can use Valgrind to detect cache misses (look up a tool called cachegrind)

Core theme

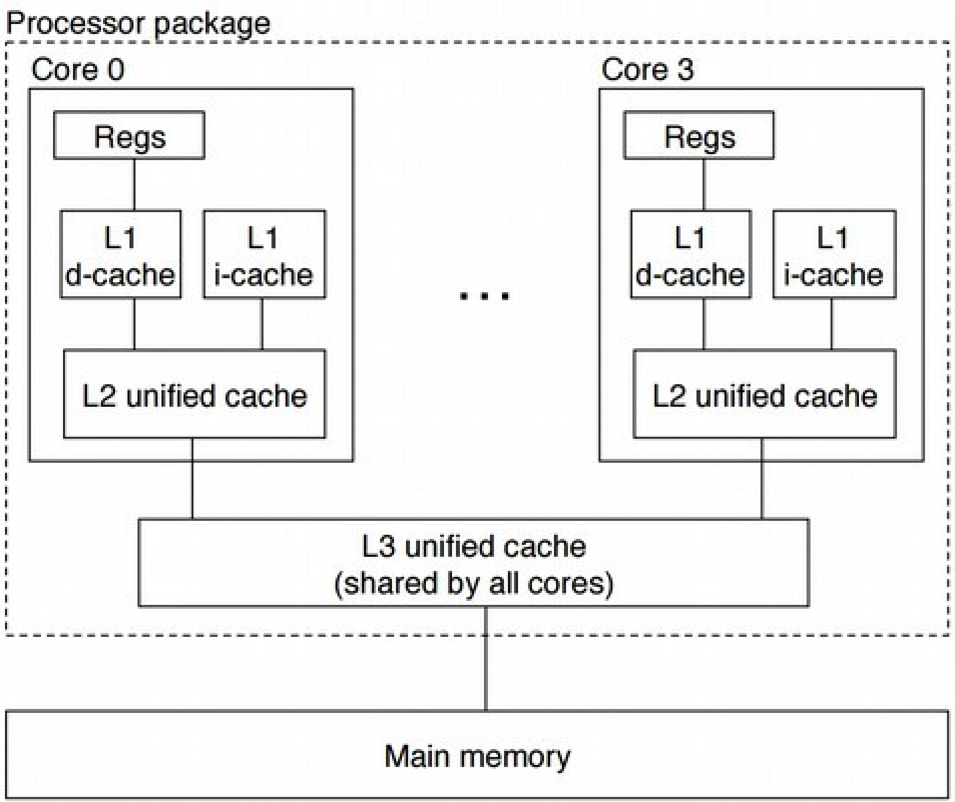
- ***Cache system design involves tradeoffs***
  - **Larger caches** => **higher hit rate** but **higher hit time**
    - Size vs. speed
  - **Larger blocks** => **higher hit rate** for programs with good spatial locality, but **lower hit rate** for others
    - Favor spatial vs. temporal locality
  - **Higher associativity** => **lower chance of thrashing** but **expensive to implement** w/ possibly **increased hit time**
    - Hit time vs. miss penalty
  - **More writes** => **simpler to implement** but **lower performance**
    - Write-through vs. write-back

Next time

- Virtual memory: an OS-level memory cache
  - Bridge between module 4 (machine architectures) and module 5 (operating systems)

Cache architecture

- Example: Intel Core i7
- Per-core:
  - Registers
  - L1 d-cache and i-cache
    - Data and instructions
  - L2 unified cache
- Shared:
  - L3 unified cache
  - Main memory

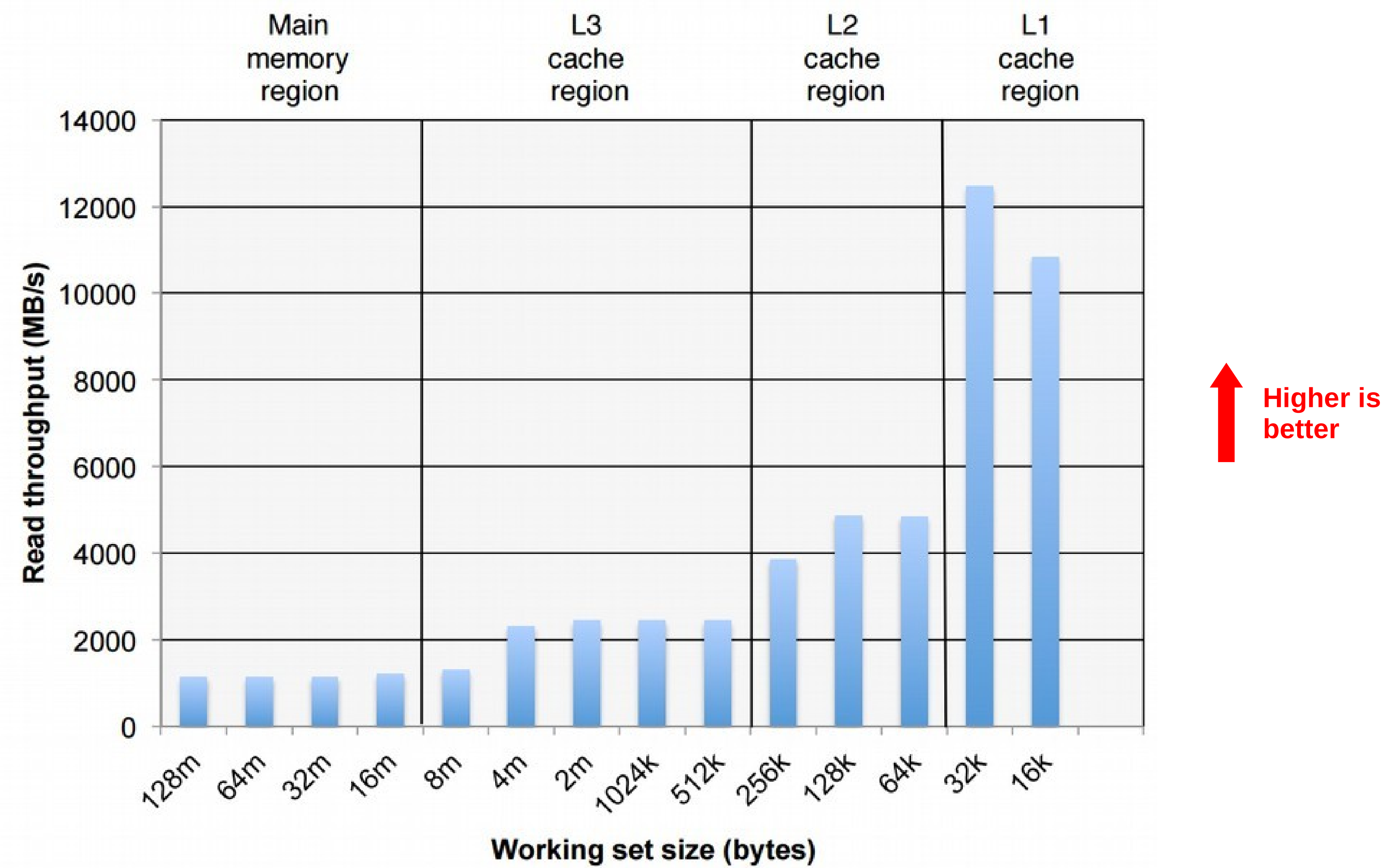


Question

- As the **working set size** of a loop decreases, what generally happens to the read throughput?
  - A) It increases
  - B) It decreases
  - C) It remains the same
  - D) There is no correlation
  - E) Not enough information to determine

Temporal locality

- Working set size vs. throughput

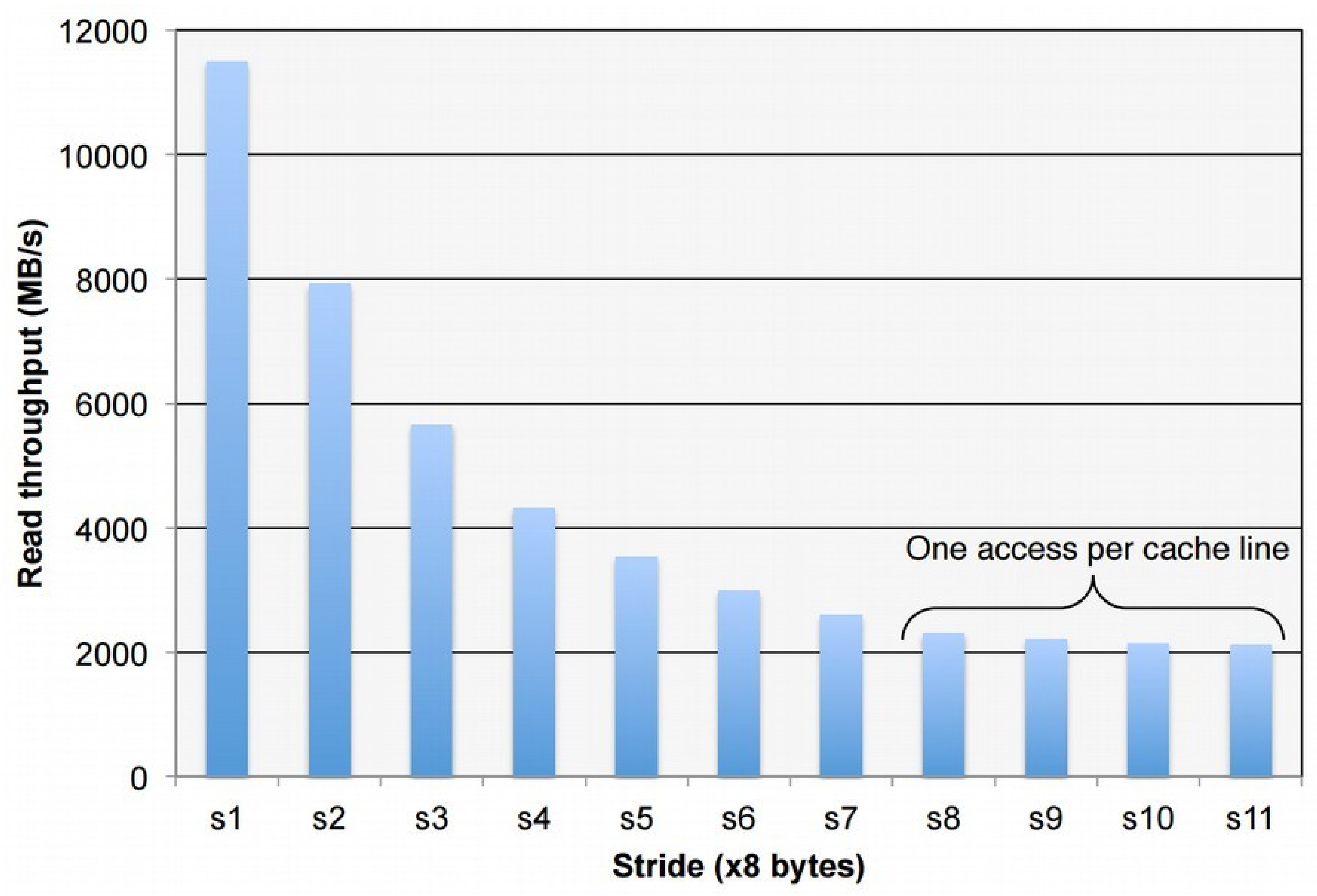


Question

- As the **stride** of a loop increases, what generally happens to the read throughput?
  - A) It increases
  - B) It decreases
  - C) It remains the same
  - D) There is no correlation
  - E) Not enough information to determine

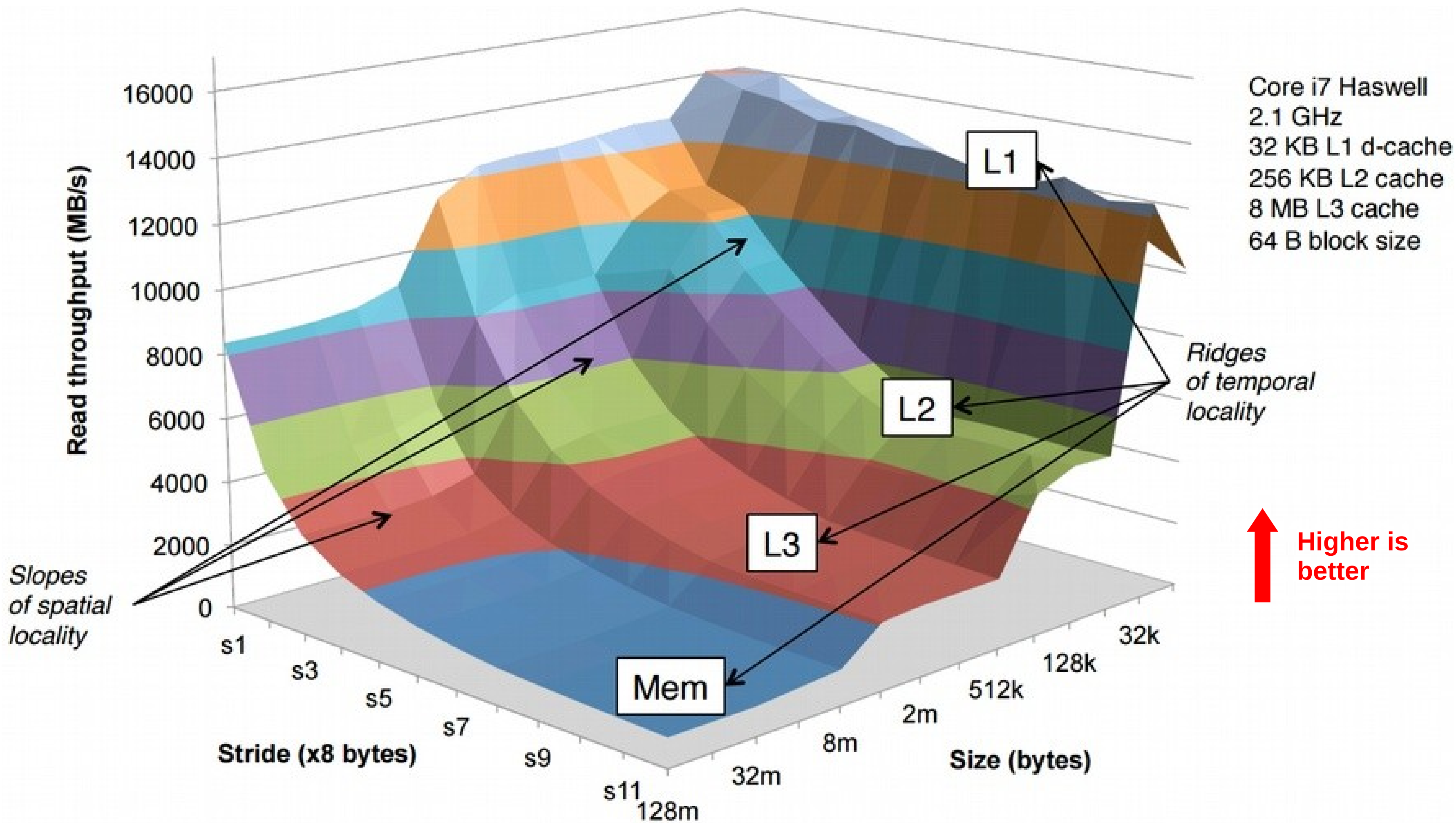
Spatial locality

- Stride vs. throughput

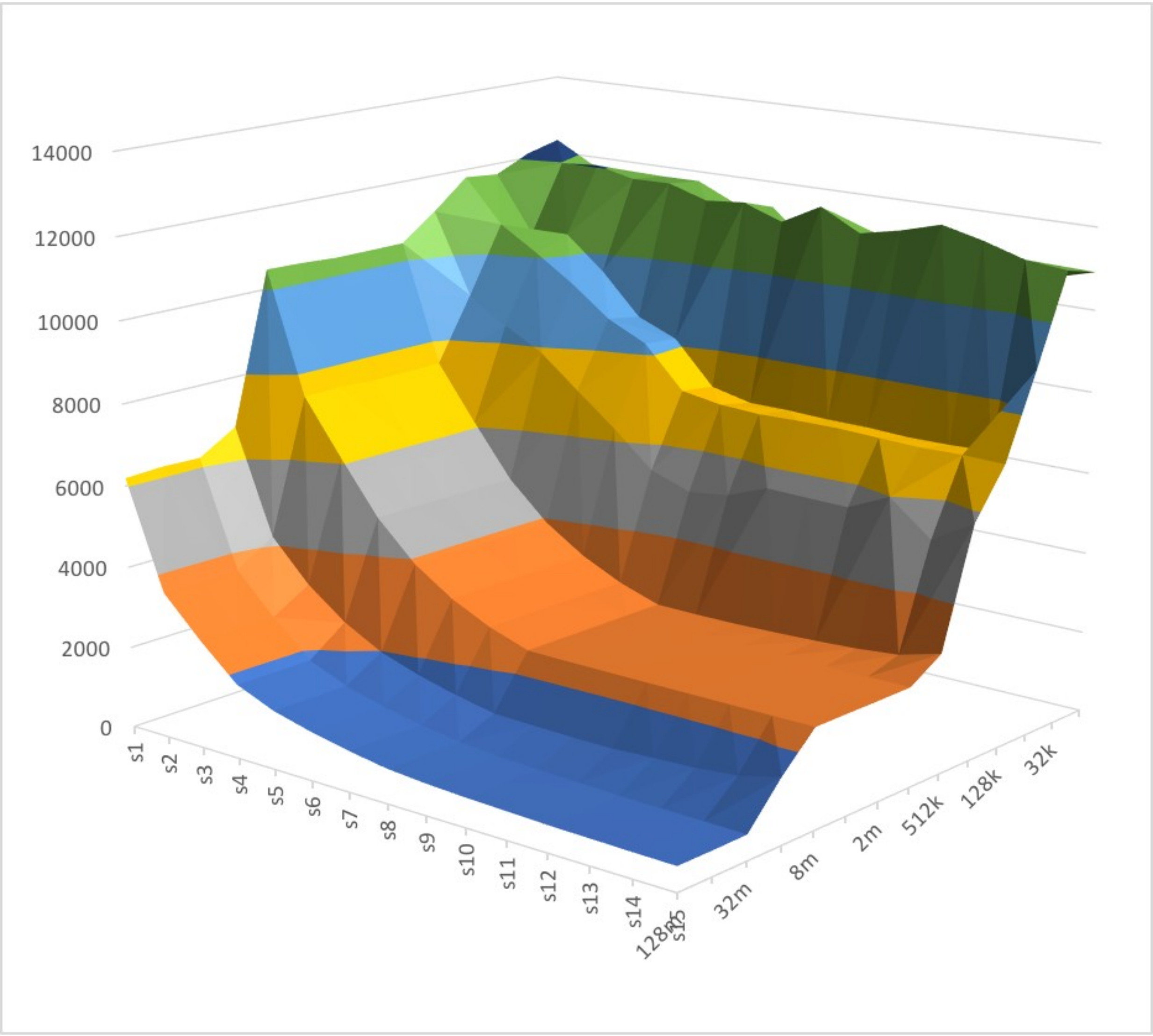


Memory mountain (CS:APP)

- Stride and WSS vs. read throughput



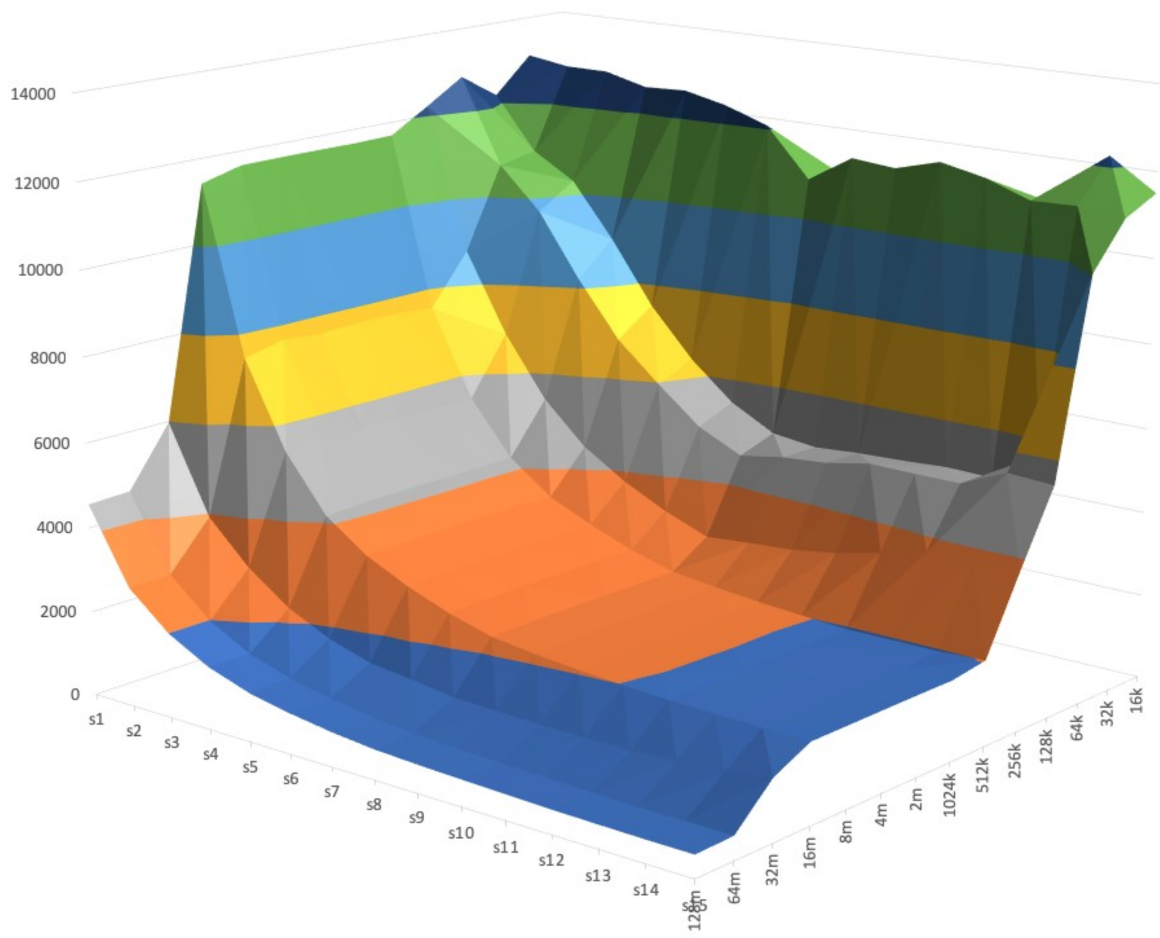
Memory mountain (stu, 2017)



Output of **lscpu**:

```
Architecture:          x86_64
Byte Order:            Little Endian
CPU(s):                24
Thread(s) per core:    2
Core(s) per socket:    6
Socket(s):             2
Vendor ID:             Intel
Model name:
Intel(R) Xeon(R) CPU E5-2640
CPU max MHz:           3000.0000
CPU min MHz:           1200.0000
L1d cache:             32K
L1i cache:             32K
L2 cache:              256K
L3 cache:              15360K
```

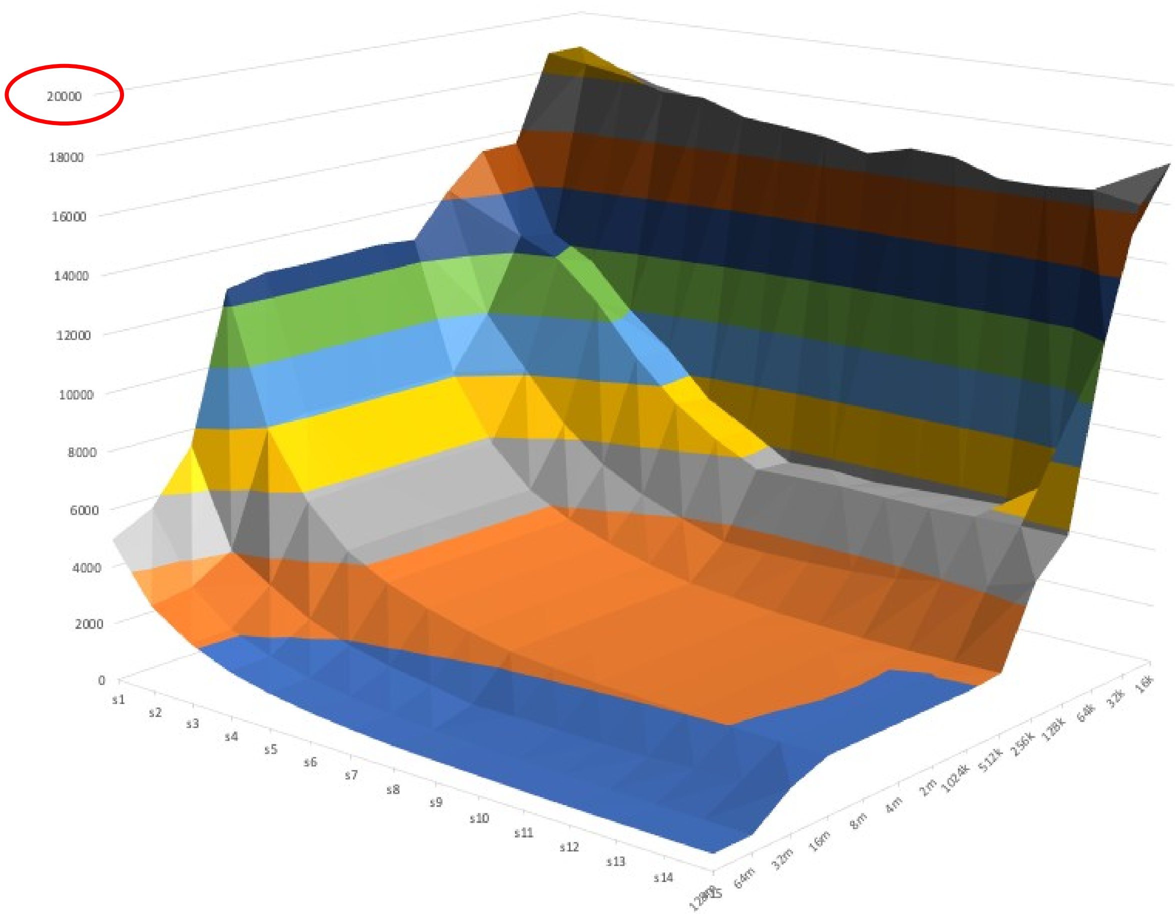
Memory mountain (stu, 2018)



Output of **lscpu**:

```
Architecture:          x86_64
Byte Order:            Little Endian
CPU(s):                48
Thread(s) per core:    2
Core(s) per socket:    12
Socket(s):             2
Vendor ID:             Intel
Model name:
Intel(R) Xeon(R) CPU E5-2680
CPU max MHz:           3300.0000
CPU min MHz:           1200.0000
L1d cache:             32K
L1i cache:             32K
L2 cache:              256K
L3 cache:              30720K
```

Memory mountain (stu, 2021)



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Socket(s):             2
Vendor ID:             Intel
Model name:
Intel(R) Xeon(R) CPU E5-2680 v3
CPU max MHz:           3300.0000
CPU min MHz:           1200.0000
L1d cache:             768K
L1i cache:             768K
L2 cache:              6M
L3 cache:              60M
```
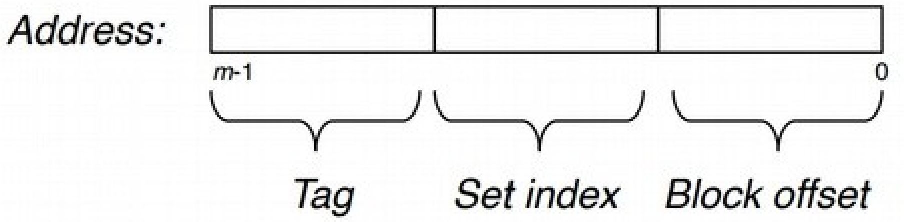

Note: new per-user resource limits put in place Fall 2021 may be interfering

Question

- Assume the following cache:
  - **S = 8** sets (so s=3 bits for set index)
  - **E = 1** line per set (so direct-mapped)
  - **B = 4** bytes per line (so b=2 bits for block offset)
- What is the set index, tag, and block offset for address 227?
  - Hint: 227 in binary is 11100011



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  - **S = 8** sets (so s=3 bits for set index)
  - **E = 1** line per set (so direct-mapped)
  - **B = 4** bytes per line (so b=2 bits for block offset)
- Address 227 (binary: 11100011)
  - Set index = 000_2 (0)
  - Tag = 111_2 (7)
  - Block offset = 11_2 (3)
  - **Is this a hit?**

No! Need to load the line into cache:

Set	Valid	Tag	block[0]	block[1]	block[2]	block[3]
0 (000)	1	111	m[224]	m[225]	m[226]	m[227]

Question

- Assume the following cache:
  - **S = 8** sets (so s=3 bits for set index)
  - **E = 1** line per set (so direct-mapped)
  - **B = 4** bytes per line (so b=2 bits for block offset)
- What is the set index, tag, and block offset for address 226? Is it a hit?
  - Hint: 226 in binary is 11100010